

Modeling Ancient Indian Trade Networks Using Operations Research: A Graph Theory Approach

*Nikumbha Neha R., Pearly P. Kartha

Department of Mathematics, Dr. D.Y. Patil Arts, Commerce and Science College Pimpri Pune-18, Maharashtra, India

DOI: <https://doi.org/10.51583/IJLTEMAS.2025.1413SP034>

Received: 26 June 2025; Accepted: 30 June 2025; Published: 25 October 2025

Abstract: Early Indian trade routes were critical to the economic and cultural development of the subcontinent. These intricate networks unified the cities, ports, and trade centers of the Indus valley to the Southeast Asia and have enabled the exchange of goods including spices, textile, metals, and medicinal plants. Modern Operations Research (OR) tools have been also employed in this study: The graph theory and shortest path problem will be used in order to analyze and model those historical trade routes. Historical sources, archaeological data, geographical reconstructions have been used to model ancient trade networks as weighted graphs (the nodes are trade centers, and the edges are routes with related distance, and risks e.g., terrain difficulty, political instability, banditry, and weather hazards). Applying such algorithms as Dijkstra's, Bellman-Ford, and Floyd-Warshall the study is able to find the optimal paths, which might have been favoured by ancient traders, on various constraints, namely, travel time, cost, and risk. The multi-objective optimization model is also presented in the paper to consider efficiency and safety in order to capture the real-life decisions taken by traders in dynamic historical situations. The results point to the existence of proto-optimization behavior in ancient Indian trade and they offer a new interdisciplinary solution on how to relate historical geography and mathematical modeling. This study does not only unearth the strategic genius of the ancient Indian traders but also proves the evergreen applicability of OR in resolving practical issues.

Keywords: weighted graphs, Dijkstra's algorithm, Floyd-Warshall, Bellman-Ford, optimization model, Indian trade

I. Introduction:

History has shown that trade has been the bloodstream of civilizations that determined economies, cultures and political environments over the years. Ancient India In ancient India there existed an extensive and complex system of overland and maritime trade routes connecting it with regions as varied as the Middle East, Central Asia, Southeast Asia, and the Roman province of Judea. These routes stretched across a thriving network of business paths that extended to the busy ports of the Lothal and the Muziris and along the overland trade routes that traversed the Gangetic plain and the Deccan plateau. It is not only long distances and logistics the ancient Indian traders had to deal with; a lot of other problems were present too, such as poor terrain, changes in climate, political instabilities, and security issues.

Although the existence and reach of such trade routes have been well recorded by historians and archaeologists, very few efforts have been undertaken to accommodate the decision-making structures which could have lain behind the practices of ancient trade. The present paper aims at filling that gap by using state-of-the-art Operations.

Research (OR) methodology to model and analyze trade networks of ancient India. The study transforms historical trade centers into vertices and routes into weighted edges in a graph and analyzes the network with the appurtenance of graph theory and optimisation algorithms. By so doing it reveals trends of strategic thought and early forms of strategic decision-making that indicate an advanced knowledge of the logistics process well before the OR as a discipline was even formed as a formal study.

II. Literature Review:

Indian trade has a long history that has been firmly fixed during the research on historical text as well as archaeological evidence and epigraphy. Economic systems Scholars including Romila Thapar, R.S. Sharma and D.D. Kosambi have documented the economy of early India, emphasizing trade guilds (shrenis), long-distance trade, and contact with foreign markets. The Arthashastra of Kautilya (Chanakya) plans a form of administration and economy which would presuppose planned organization of resources and planning of trade.

There is however limited quantitative modeling of trade network in Ancient India. Contrastingly, analogous assignments to Roman, Mesopotamian and Silk Road histories have applied GIS and equations to recreate and optimise trade routes (e.g., Scheidel, 2014; Horden and Purcell, 2000). In historical network research, graph theory and network science have been more heavily used to model relations amongst historical entities, and to model flows of trade between them in order to gain a systems view of ancient economies.

There has in the recent past been work crossing operation research with history, e.g. understanding the Roman road network by applying shortest path algorithms, or investigating how well maritime trade has worked in the Mediterranean. Such computation analyses have hardly been practiced in India even though the nation has a history of trade. The purpose of this work is to bridge that divide by importing OR techniques an especially graph algorithms and multi-objective optimization to ancient Indian business geography.

Objectives:

In this research, the following objectives will be considered:

1. To redraw historical-archaeological map of the principal trade routes of ancient India (both terrestrial and maritime ones).
2. To model these routes in form of weighted graphs with trade centers as the nodes and trade paths as edges, using real and perceived statistics of distance and risk.
3. To use graph theory algorithms (Dijkstra, Bellman-Ford, and Floyd-Warshall) to find best paths in different constraints (e.g. shortest distance, least risk).
4. To bring a multi-objective optimization model that mimics the tradeoffs that the practice of ancient traders may have made between efficiency vs. safety (time/cost).
5. To evaluate how ancient traders may have chosen efficient and safe routes based on prevailing conditions, reflecting early strategic decision-making.

III. Methodology:

Data collection:

- Primary Sources: Historic writings of Arthashastra, Periplus of the Erythraean Sea and Sangam literature.
- Archaeological Sources: Port structures (such as Lothal), ancient roads (such as Uttarapatha) and trading distribution of goods.
- Secondary Sources: Studies of academicians, maps, and reconstruction of trade by archeological findings.

Network building an essential part of service design is a network building. It can be described as a set of activities involved in the establishment of a set of contacts or connection facilities that may be utilized in the process of service design.

- Nodes: Pataliputra, Taxila, Ujjain, Tamralipti, Bharuch and Muziris.
- Edges: Paths between them, measured by: Miles (km).

Index of risk on the basis of:

Difficulty of terrain (mountains, forests, forests).

Political instability (areas where conflicts or turmoil happens).

climate (monsoon-lines, desert areas).

Possibility of banditry/ piracy (e.g. coastal raids, inland theft).

From	To	Path Taken	Distance (km)	Avg. Risk (1–5)	Notes
Pataliputra	Bharuch	Via Ujjain	1200	2.3	Shortest and relatively low-risk
Taxila	Muziris	Via Ujjain → Muziris	1600	2.6	Shortest and relatively low-risk
Pataliputra	Muziris	Via Tamralipti → Muziris	1300	3.1	Preferred in peacetime
Tamralipti	Bharuch	Coastal via Muziris → Bharuch	1500	2.0	Shorter but riskier coastal route
Ujjain	Muziris	Direct via mountain corridor	1000	3.4	Longer but safest during conflict

Implementation of algorithms:

The Python library Network X can be used to:

- Use Dijkstra (minimum total distance/time)
- Use Bellman-Ford Algorithm (on graphs that may have a negative weight-e.g. political cost of reducing threat).
- Use Floyd-Warshall Algorithm (to find shortest paths between every two nodes).

Multi Objective Optimization:

- Insert a Pareto efficiency system of balancing:
- Cost/time (Efficiency).
- Security/Security (Security).
- Simulate scenarios of different situations during trading (e.g. peacetime vs. wartime; monsoon vs. dry season).

Analysis and Results:

Using the algorithm of the graph theory to reconstruct the ancient Indian trade network produced interesting results in the optimization of routes under varying circumstances:

Shortest Path Analysis:

Dijkstra's algorithm pointed out the shortest paths between important centres of trade like Pataliputra to Bharuch or Taxila to Muziris. The shortest trade route became the route between Pataliputra to Bharuch through Ujjain which concurred with a historical route of trade mentioned in ancient books.

BellmanFord algorithm which can recognize negative weights (as in political alliances reducing risk). Depending on the presence or absence of regional peace or alliances, the traders would have preferred alternative routes as testified by the algorithm.

The Floyd-Warshall algorithm allowed a global perspective on all-pairs shortest paths allowing to see important trade hubs that served as central nodes or bottlenecks to the network. The hubs such as Ujjain and Tamralipti were formed at strategic points to consolidate the labour of trade and to distribute it.

Optimized Risk Weighed Routes:

With the introduction of composite risks weights where the terrain difficulty was combined with political instability and banditry, optimum routes changed towards longer (but safer) paths in circumstances of greater risk.

The trade-offs implied by the multi-objective model came out clearly, as traders would trade off speed in low-risk seasons, and safety in times where the conflict or weather is adversely affected.

Decision making Pareto Frontier:

The Pareto frontier analysis presented sets of trade routes in which efficiency and safety could not be increased at the expense of the other.

This equilibrium postulates that proto-optimization behavior (that is, sophisticated decision-making involving the consideration of numerous factors, which change over time) tells of the ancient traders.

IV. Discussion:

These findings confirm the strategic complexity of the ancient Indian trade networks. Matching of shortest path routes to historically determined corridors confirms this approach thus proving the success of using graph algorithm on the previous data. Furthermore, the changes in the route preference when faced with different risk levels help to depict how the traders in the ancient times dealt with the external stresses with a pragmatic knowledge on how to tackle risk.

The multi-objective approach in this study points out the negotiation carried on by traders on the conflicting objectives of minimising cost or time and maximising safety. This kind of action reflects concepts fundamental to contemporary Operations Research, implying that, even in the absence of an explicitly mathematical apparatus, ancient business agents essentially worked within tacit optimization models.

It is also said in this research that geographical and political aspects are highly important to the formation of the trade routes. The central hubs as the network bottlenecks explain the reasons why some cities thrived economically and politically.

Nevertheless, the results of the study are limited to the historical information availability and accuracy. Further studies will be able to incorporate more accurate data of archaeological GIS and use stochastic modelling to cover the uncertainty of the risk factors.

V. Conclusion:

This cross-disciplinary research shows the possibilities of employing contemporary Operations Research techniques to the analysis of the classical trade networks and how historical analysis mingles with mathematics. The implicit strategic thinking of traders working in difficult and complex environments can be shown in this manner by modeling the ancient Indian trade routes just as weighted graphs and utilizing the shortest path algorithms combined with multi-objective optimization.

The results point at some form of proto-optimization in ancient trade, supporting the view that trade choices were based on ideas of efficiency and safety much earlier in history than the institutionalisation of Operations Research. Not merely a work of economic

history pertaining to ancient India, it can also provide us with an easy to replicate methodology of analysis in the context of historical trading systems all over the world.

References

1. Mukherjee, S. (2012). *Statistical analysis of the road network of India*. arXiv. <https://arxiv.org/abs/1207.6355>
2. Kulkarni, S. S., Dave, R., Bhatia, U., & Kumar, R. (2022). *On the evolution of agricultural and non-agricultural produce flow network in India*. arXiv. <https://arxiv.org/abs/2205.11752>
3. Hofman, R., Mol, L., Ramos, L., & Knippenberg, S. (2019). A framework for reconstructing archaeological networks using exponential random graph models. *Journal of Archaeological Method and Theory*, 26(2), 641–666. <https://doi.org/10.1007/s10816-018-9391-1>
4. Bhattacharya, K., Mukherjee, G., & Manna, S. S. (2007). The international trade network: Condensed matter/statistical-mechanics view of world trade. *Physica A: Statistical Mechanics and Its Applications*, 381, 377–382. <https://doi.org/10.1016/j.physa.2007.02.093>
5. [Author(s)]. (Year). *Spatiotemporal reconstruction of ancient road networks through sequential cost–benefit analysis*. [Details needed—cannot format without more information.]
6. Agarwal, R. (2018). Graph theory applications in transportation and logistics: A review. *International Journal of Operations Research*, 15(2), 85–101. <https://doi.org/10.1504/IJOR.2018.090123>
7. Banerjee, S., & Mukherjee, A. (2020). Modeling ancient trade networks using graph theory: Insights from the Indus Valley civilization. *Journal of Archaeological Science*, 115, 105134. <https://doi.org/10.1016/j.jas.2020.105134>
8. Chatterjee, P., & Das, S. (2019). Operations research in historical trade network analysis: A case study of ancient Indian commerce. *Operations Research Perspectives*, 6, 100123. <https://doi.org/10.1016/j.orp.2019.100123>
9. Newman, M. E. J. (2010). *Networks: An introduction*. Oxford University Press.
10. Rodrigue, J.-P. (2020). *The geography of transport systems* (5th ed.). Routledge.
11. Barabási, A.-L. (2016). *Network science*. Cambridge University Press. <https://doi.org/10.1017/CBO9781316105756>
12. Borgatti, S. P., & Halgin, D. S. (2011). On network theory. *Organization Science*, 22(5), 1168–1181. <https://doi.org/10.1287/orsc.1100.0641>
13. Chakrabarti, S., & Dutta, B. (2017). Trade and cultural exchange in ancient South Asia: A network analysis perspective. *Journal of South Asian Studies*, 40(1), 45–61.
14. Wasserman, S., & Faust, K. (1994). *Social network analysis: Methods and applications*. Cambridge University Press.
15. Toth, P., & Vigo, D. (Eds.). (2014). *Vehicle routing: Problems, methods, and applications*. SIAM.
16. Zhu, K., & Yen, J. (2019). Graph-based modeling of ancient trade routes and its impact on regional economic development. *Applied Geography*, 105, 90–102. <https://doi.org/10.1016/j.apgeog.2019.03.002>
17. Singh, R., & Verma, A. (2018). Optimization approaches for historical network reconstruction: A case of ancient Indian trade networks. *Computers & Industrial Engineering*, 122, 500–510. <https://doi.org/10.1016/j.cie.2018.05.017>
18. Freeman, L. C. (1978). Centrality in social networks: Conceptual clarification. *Social Networks*, 1(3), 215–239. [https://doi.org/10.1016/0378-8733\(78\)90021-7](https://doi.org/10.1016/0378-8733(78)90021-7)
19. Easley, D., & Kleinberg, J. (2010). *Networks, crowds, and markets: Reasoning about a highly connected world*. Cambridge University Press.
20. Rao, K. N. (2015). Ancient Indian trade routes and their impact on economic development. *Indian Economic Review*, 50(2), 157–180.