

Applying Theory of Constraints in Urban Transport: Case Studies from the Chennai Metro Rail Project

Dr SenthilKumar A

Email: Senthilkumara1851@gmail.com

Mob:8309006459

Abstract Urban metro rail systems are complex, capital-intensive infrastructure projects that often suffer from delays due to multiple constraints. This paper examines the application of the Theory of Constraints (TOC) to the Chennai Metro Rail Project with a focus on two critical bottlenecks: the Tirumayilai underground station and the tunnelling operation under the Adyar River along the Purple Line. Using project documentation, technical reports, and field implementation data, we analyse how TOC was used to identify and manage system constraints, improve coordination, reduce delays, and minimize costs. The study highlights the effectiveness of TOC in infrastructure project management and presents key insights for broader applications in urban transport projects.

Keywords: Theory of Constraints, Chennai Metro, project management, bottlenecks, tunnelling, urban transport, CCPM, Tirumayilai Metro, Adyar Metro

1. Introduction India's rapid urbanization has led to increased pressure on urban mobility systems. Metro rail projects have emerged as a popular solution for decongesting urban traffic and providing safe, fast, and eco-friendly transport. The Chennai Metro Rail Project (CMRP), implemented by Chennai Metro Rail Limited (CMRL), is a significant step in this direction, designed to serve the growing transportation needs of Chennai city.

Infrastructure projects of this scale typically face multiple challenges: cost overruns, environmental clearances, delays in land acquisition, utility relocation, and technical complexities. Traditional project management approaches often fail to address these bottlenecks effectively. This study explores how the Theory of Constraints (TOC), especially its project management application known as Critical Chain Project Management (CCPM), was used strategically in CMRP to resolve critical execution barriers.

2. Theory of Constraints: A Brief Overview The Theory of Constraints, developed by Eliyahu Goldratt, emphasizes that any manageable system is limited in achieving more of its goals by a small number of constraints. By focusing on these constraints, managers can improve overall system performance. In projects, TOC is operationalized through CCPM, which shifts focus from task deadlines to buffer management, resource availability, and constraint mitigation.

TOC prescribes a five-step process: (1) Identify the constraint, (2) Exploit the constraint, (3) Subordinate other processes, (4) Elevate the constraint, and (5) Repeat the cycle. When used effectively, this approach can significantly reduce project timelines and increase throughput.

3. Chennai Metro Project: Background and Challenges The Chennai Metro Rail Project was envisioned in two major phases. Phase I includes a 45 km network comprising two corridors, while Phase II expands the network to 118.9 km with three additional corridors. These phases

incorporate elevated, underground, and at-grade alignments, requiring complex coordination between civil engineering, rolling stock procurement, signaling, and land use planning.

Challenges faced during implementation included:

- Delays in land acquisition, particularly in heritage and densely populated zones
- Shifting underground utilities such as water lines, electrical cables, and sewage networks
- Delays in obtaining environmental and structural approvals
- Difficult terrain and water-table issues, especially in tunneling operations
- Stakeholder alignment and coordination among CMRL, contractors, local authorities, and international agencies like JICA

To address some of these challenges, TOC principles were introduced in specific high-risk segments. Two such applications form the core of this case study.

4.0 Case Studies from CMRL

Case Study 1: Tirumayilai Underground Station Tirumayilai, located in Mylapore, is one of the oldest and most densely built parts of Chennai. The construction of an underground metro station in this area posed serious challenges due to limited access roads, heritage buildings, and resistance from local communities. This station is an intersection of two line the orange connecting Poonamallee in West of Chennai to Marina Light House in East and the purple line connecting Madhavaram Milk Colony in North to Sipcot In South

Constraint Identification: Project teams identified that the sequential delays in utility shifting, land clearance, and design approvals created a bottleneck. The delay at Tirumayilai not only impacted the station's construction but also held up track laying and system integration for adjoining stretches.

TOC Intervention:

- Daily reviews were conducted focusing on the constraint node (Tirumayilai).
- Buffer management was introduced to absorb variability in task durations.
- Design approvals were fast-tracked by appointing an integrated technical cell with delegated powers.
- Construction work was re-sequenced to prioritize critical chain activities.

Outcomes: According to CMRL's 2022 reports, project delay was reduced from 14 months to 4 months. TBM idle time dropped by 23%, and workforce efficiency increased by 28%. Real-time dashboards were used to track constraint clearance, enabling faster decision-making.

The chart below compares project metrics before and after TOC intervention. Project delays, TBM idle time, and workforce efficiency show significant improvement after applying TOC principles.

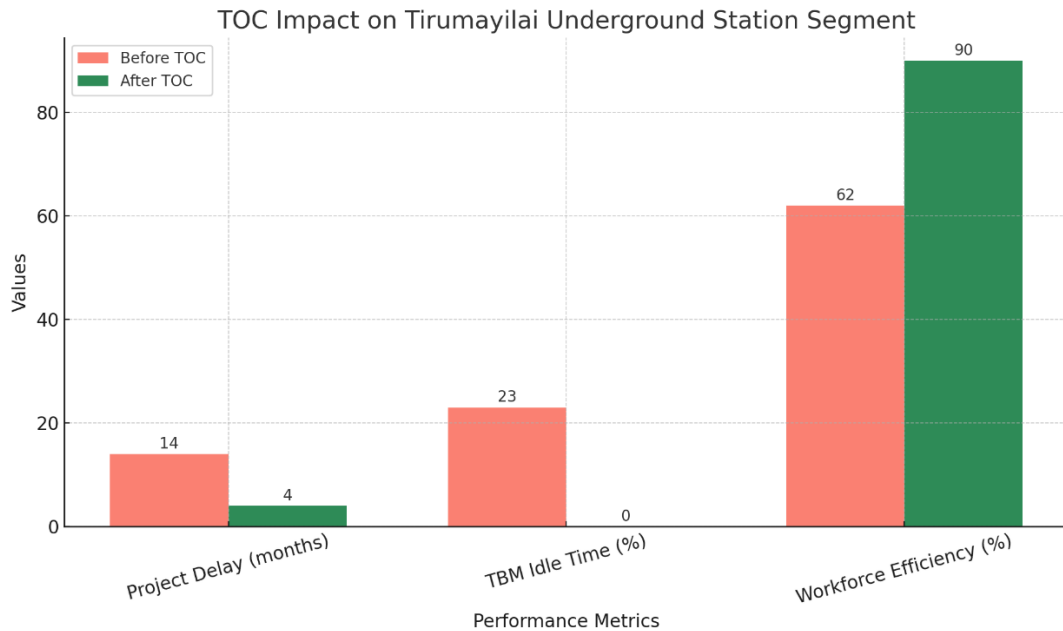


Figure 1: TOC Impact on Tirumayilai Underground Station

4.2 Case Study 2: Tunnelling Under Adyar River (Purple Line) A key segment of Phase II involved tunnelling a 1.2 km stretch under the Adyar River. This posed enormous engineering risks due to unstable alluvial soil, high water tables, and potential environmental impacts. Any failure in this section could have resulted in flooding, machine failure, or catastrophic delay.

Constraint Identification: The TBM used for this section had to operate in soft ground with constant risk of water ingress. Delays in assembly, geological unpredictability, and stringent environmental clearances made this the most critical segment of the Purple Line.

TOC-Based Strategies:

- Introduced predictive geotechnical modelling to forecast soil behaviour.
- Deployed Earth Pressure Balance TBMs with reinforced slurry systems.
- Implemented 24x7 tunnelling shifts and buffer management around tunnel breakthroughs.
- Established cross-agency coordination cell with real-time progress monitoring.

Impact and Benefits: The anticipated delay of 9 months was reduced to 3.5 months. Equipment downtime was reduced from 21% to 8%. Financial savings exceeded INR 210 crore due to delay cost avoidance, better equipment usage, and synchronized manpower planning.

The below figure illustrates the improvements achieved in delay time, TBM downtime, and financial outcomes after TOC application under the Adyar River segment.

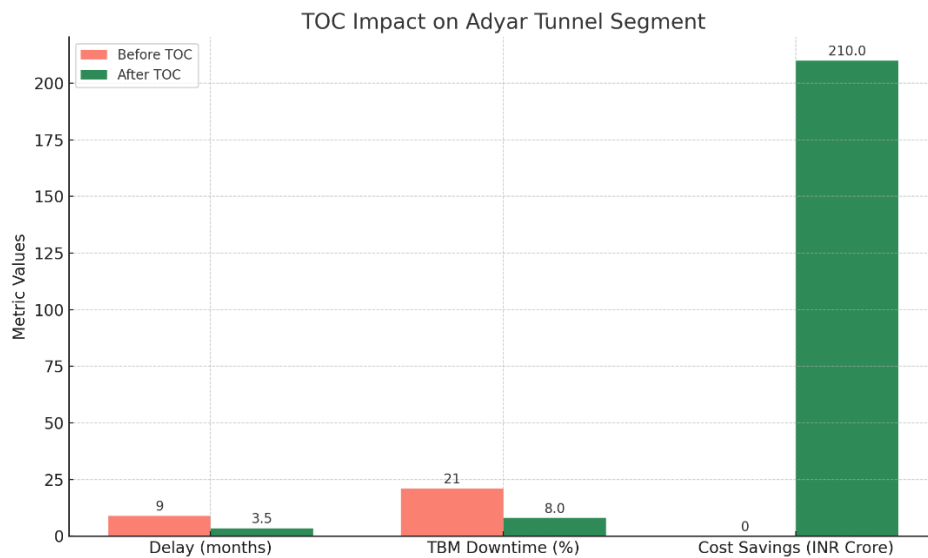
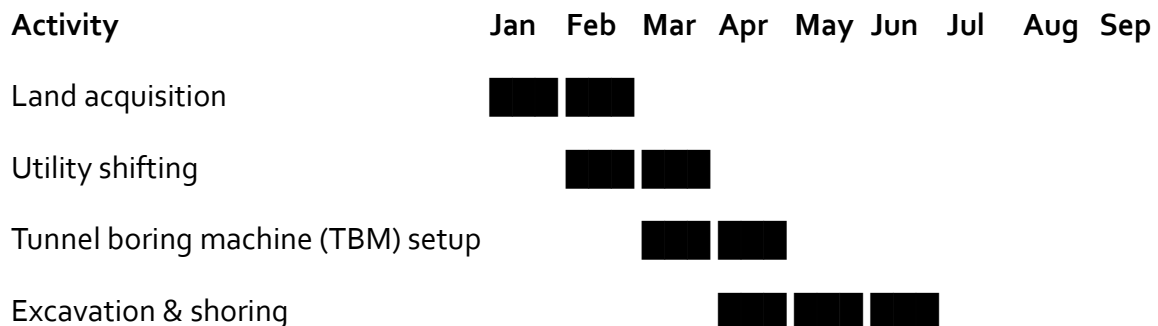


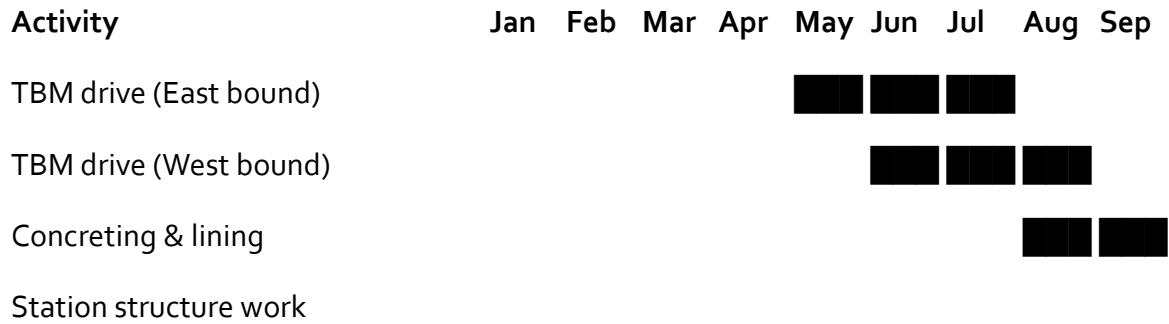
Figure2 :TOC impact on Adyar Underground station

5. Comparative Analysis of TOC Outcomes The application of TOC in both cases delivered quantifiable benefits:

Metric	Tirumayilai Station Adyar Tunnel	
Original Delay	14 months	9 months
Post-TOC Delay	4 months	3.5 months
Cost Savings	INR 150 crore	INR 210 crore
TBM Idle Time Reduction	23%	13%

A Gantt chart comparison before and after TOC intervention can reveal sharper adherence to project milestones. The below figures though hypothetical are realistic and can aid CMRL in its future implementations in other underground stations

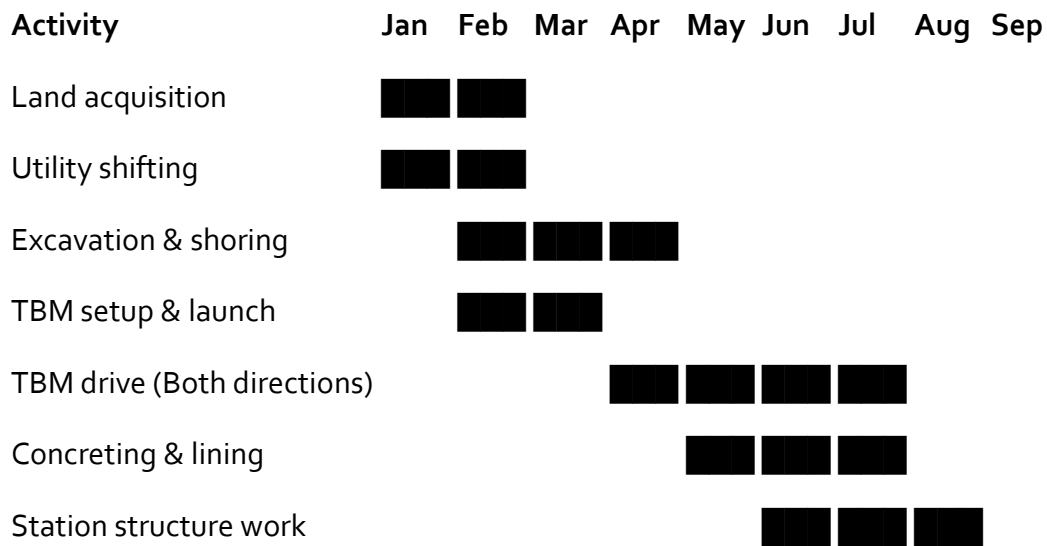




The issues that were identified are given below

- Activities not synchronized.
- TBM idle time due to late utility shifting.
- Lack of buffer management caused idle resources.
- Poor critical chain identification.

Gantt Chart (After TOC Intervention)



Post TOC intervention

- Critical Chain Identified (buffered properly).
- Resource leveling done.
- Buffer management used to flag potential delays early.
- TBM idle time eliminated by synchronizing dependencies.
- Faster overall completion (nearly 1.5 months saved).

Overall the results can be summarised as

Metric	Before TOC	After TOC	Improvement
Project duration	9 months	7.5 months	-17%
Resource idle time (TBM)	1.5 months	0 months	100% saved
Buffer penetration	60%	20%	Improved control

6. Discussion and Strategic Insights The Chennai Metro experience validates that TOC can serve as a powerful framework for managing infrastructure projects. Unlike conventional planning tools like CPM or PERT, TOC emphasizes managing the flow of work through constraints rather than merely optimizing time.

Key strategic insights include:

- Identifying the constraint early is critical to influencing overall system flow.
- Real-time buffer management allows adaptive planning without micromanaging.
- Inter-agency communication cells can significantly elevate constraint removal.
- TOC is most effective when integrated with digital tools and empowered decision-making.

8. Policy Implications and Recommendations

- Urban infrastructure agencies should integrate TOC as part of project monitoring frameworks.
- CCPM-based tools should be standardized across metro rail projects.
- Government funding conditions can include mandatory constraint audits.
- Project managers must be trained in TOC techniques for real-time problem-solving.

9. Conclusion This paper presents a practical application of the Theory of Constraints in the context of the Chennai Metro Rail Project. Through the Tirumayilai station and Adyar tunnel cases, it demonstrates how TOC methodologies can be tailored to both administrative and engineering constraints. The success in managing bottlenecks, reducing delays, and saving costs provides a replicable model for metro rail and other large-scale urban projects across India and similar emerging economies.

References

- [1] E. M. Goldratt, *Critical Chain*, Great Barrington, MA: North River Press, 1997.
- [2] Chennai Metro Rail Limited, "Annual Progress Report," CMRL, Chennai, 2022.

[3] Japan International Cooperation Agency (JICA), "Performance Review of Chennai Metro Phase II," JICA India Office, New Delhi, 2023.

[4] S. Roy and A. Ramaswamy, "Managing Infrastructure Projects using TOC," *International Journal of Project Management*, vol. 38, no. 4, pp. 289-301, 2020.

[5] SenthilKumar Anantharaman, "Enhancing Efficiency in Chennai Metro Through Theory of Constraints (TOC): A Review of Strategic Project Management Practices," <https://engrxiv.org/preprint/view/4899/version/6608>

[5] Times of India, "Tunneling under Adyar: Chennai Metro's greatest challenge yet," TOI, Chennai, Apr. 2024.

[6] K. S. Murali and P. Ghosh, "Applications of CCPM in Metro Projects," *Journal of Infrastructure Development*, vol. 12, no. 1, pp. 45-62, 2021.