

# Managing Time–Cost–Sustainability Trade-offs in Metro Rail Construction Projects

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**Abstract** - Construction of metro rail projects have proven to be an essential element of sustainable urban transportation in cities that experience rapid growth. Nevertheless, the inclusion of sustainability into the construction process brings about a number of problems related to the balance of time and cost during the development of the metro rail system. This research focuses on the analysis of the complex relationships between the factors of time, cost, and sustainability in the process of metro rail construction. Based on the review of relevant literature and real-world practice, this research concludes that the introduction of sustainable approaches to construction, for instance, the usage of environmentally friendly materials and energy-efficient constructions as well as compliance with environmental laws, leads to higher costs and longer construction periods. On the other hand, sustainability yields considerable benefits in the form of lower running costs, greater efficiency, and minimal environmental footprint.

**Key Words:** Sustainable construction, metro rail projects, time-cost trade-off, infrastructure management, project performance, sustainability.

## 1. INTRODUCTION

Due to rapid urbanization, there is an increased need for efficient and environmentally-friendly transport systems in major cities. Metro rail systems play a crucial role in solving problems associated with urbanization due to their effectiveness in alleviating traffic jams, cutting down greenhouse gas emissions, and improving transport efficiency. With more organizations and governments adopting the principle of environmental sustainability, construction processes in infrastructure development have been transformed to adopt sustainable processes.

Sustainable construction refers to a process whereby an effort is made to minimize environmental impacts while at the same time remaining economically feasible and socially responsible. Sustainability in the construction process in metro rail systems involves adopting environmentally-friendly construction techniques, energy conservation, among other techniques. Nonetheless, achieving sustainability in mega projects such as the metro rail system poses a number of challenges.

Traditionally, project management has been guided by the time-cost trade-off paradigm, whereby the shortening of project times usually means the raising of costs, while conversely, lowering the costs results in the elongation of

project times. In the new scenario of sustainability, there comes in another variable in addition to the two that have been used traditionally. The three dimensions of time, cost, and sustainability make the project manager's task very difficult. The purpose of this paper is to examine the interplay between time, cost, and sustainability in the context of metro rail construction projects.

## 2. METHODOLOGY

Within the context of this paper, the methodology used is that of qualitative and comparative case studies in order to analyze the impact of time, cost, and sustainability on metro rail construction projects. In contrast with merely theoretical considerations, the current research uses real-world data and practices to provide useful conclusions on the issues raised.

The research process consists of three steps: First, the scientific literature review and industry reports are performed in order to establish the relationship between the considered parameters based on theoretical assumptions. Such an action allows us to set up the theoretical basis of knowledge regarding the factors which might affect our variables. Second, a number of cases will be analyzed within the scope of multiple case studies. For this purpose, four important metro rail projects in India are selected: Delhi Metro, Bengaluru Metro, Nagpur Metro, and Mumbai Metro. Such a choice is made based on varying performance regarding project realization, costs, and sustainable construction. The following elements will be examined:

- [1] Difference in the planned and actual realization periods of projects
- [2] Differences in terms of costs and management
- [3] Use of sustainability in projects

Thirdly, an approach of comparative analysis will be used in order to use information obtained from the two cases. This involves the identification of similarities and differences, especially with regard to the performance of projects. Based on the results obtained during this analysis process, a model that shows the relationship between time, cost, and sustainability will be proposed. It is important to note that this approach is meant to do more than making judgements about specific projects; rather, it should produce general conclusions regarding metro projects.

### 3. LITERATURE REVIEW

To begin with, a comprehensive literature review will be carried out in order to establish the connections between the concepts of time, cost, and sustainability in the construction process of metro rail projects. Sources of literature for this purpose include academic journals and peer-reviewed articles about the management of time, cost, and sustainability in the development of metro rail infrastructures. Other sources of literature may be industry-based literature, studies, reports, etc. by metro rail authorities such as Delhi Metro Rail Corporation, Bangalore Metro Rail Corporation Limited, MahaMetro, and Mumbai Metropolitan Region Development Authority, and other case studies of projects developed for metro rail projects.

For instance, the literature review will include literature on the following dimensions. The first dimension will be that of time. In this regard, literature on project scheduling causes of delays, such as land acquisition and regulation and performance issues with contractors among others, will be included in this part of the review. Besides, literature on how different techniques of project management impact schedule compliance will also be considered in the study. The second dimension will entail literature on issues concerning cost. For example, literature will be obtained concerning the cost estimates of projects, causes of cost overruns, e.g., delays and inflation, and risk management issues.

Not only does this literature review focus on the identification of the parameters in question but on the relationship among the three parameters in focus. Earlier studies have revealed that time delays are often associated with increased cost, whereas sustainability measures, which will be included in a project, will raise its initial cost and prolong it because of added compliance processes. On the other hand, sustainable measures will provide benefits in the long run, both economically and environmentally speaking. In addition, industry publications are assessed for information about problems and implementation techniques used in metro construction projects. Such aspects include stakeholder coordination, restrictions related to urban construction, risk management measures, as well as use of digital technologies like Building Information Modelling and project management systems.

Ultimately, the result obtained through this literature review is a conceptual framework that identifies the factors affecting project performance and provides a theoretical background for the study.

### 4. CASE STUDIES

#### 4.1 Delhi Metro Rail Project

The Delhi Metro Rail Project is considered among the most successful projects in the field of transportation infrastructure development in India. Launched under the auspices of Delhi Metro Rail Corporation (DMRC), the Delhi Metro Rail Project was distinguished by such key features as timeliness of execution, efficiency of expenditures, and

sustainability of the project. Regarding the timeliness of execution of the project, the Delhi Metro Rail Project can be described as a project completed in accordance with schedule thanks to proper planning, contracting, and use of project management techniques. The Delhi Metro Rail Project succeeded to meet all necessary deadlines without causing any problems in terms of time delays despite the fact that the project was carried out in a highly congested city.

As for cost management, the Delhi Metro Rail Project deserves special praise since proper cost management was ensured by the project. Though the use of sustainable technologies involved certain additional expenses, no cost overruns were noticed throughout the project.

Sustainability formed part of the important components of the project rather than an additional one. Some of the components included solar energy, water conservation and sustainable development assessment tools which were incorporated in the construction processes. As a result, the Delhi Metro was the first railroad transport project to earn carbon credits via the Clean Development Mechanism.



Fig -1: Delhi Metro

The example of the Delhi Metro shows the importance of taking into account sustainability and management of the project in order to find equilibrium between time, cost and sustainability.

Table -1: Optimal Balance for Delhi Metro

Parameter	Result
Time	Reduced project delays using advanced construction methods
Cost	Controlled lifecycle cost through efficient planning
Sustainability	Improved environmental performance using green technologies

#### 4.2 Bengaluru Metro Rail Project

Bengaluru Metro or Namma Metro is a complex project that was constructed under dynamic growth conditions of the city. There were several issues that arose during the construction process related to land acquisition, traffic

control, and utility relocation that affected the project's efficiency. Regarding the time, there were medium delays in all stages of the project implementation. They were caused by the bureaucracy, high urbanization, and coordination among the stakeholders. In contrast to the Delhi Metro project, where the implementation period was quick, Bengaluru Metro experienced some difficulties in adhering to the schedule. The delay had a negative effect on the cost performance since the project's long implementation period resulted in higher costs for labor, material, and administration. The cost overrun was insignificant but demonstrated the relationship between the project's time and cost performance.



Fig -2: Bengaluru Metro

Sustainability initiatives have been incorporated via efficient energy use and improved integration of public transport. However, the level of incorporation of these initiatives does not match that of other new metro systems such as the Nagpur Metro. Sustainability has been considered, but sustainability has not been the motivating factor for the project. This metro project is a perfect illustration of performance effects resulting from sustainable integration with urban challenges.

Table -2: Optimal Balance for Bengaluru Metro

Parameter	Result
Time	Project delays observed due to land acquisition issues, traffic management challenges, and coordination complexities in dense urban areas
Cost	Increased project cost due to extended timelines, escalation in material prices, and additional administrative expenses
Sustainability	Moderate implementation of sustainability practices such as energy-efficient systems and improved public transport integration

### 4.3 Nagpur Metro Rail Project

Nagpur Metro Rail Project can be regarded as one of the most sustainable projects in India. The initiation of this project has been undertaken by Maharashtra Metro Rail Corporation Limited (MahaMetro). This project takes into account not only its effective realization but also sustainability and environment-friendly approaches. Considering sustainability aspect, it may be emphasized that Nagpur Metro deserves to be mentioned since it makes extensive use of renewable energy sources such as solar energy generation. Certain stations in this project are recognized as green buildings, while other sustainable methods are used in the project. Speaking about time performance aspect, it should be pointed out that even with all sustainable approaches taken into account, it was realized quite effectively. Such result could be achieved due to proper planning of sustainability from the very beginning.

The cost performance shows an increased amount of initial investment due to sustainable technology used, but this can be compensated by lower costs for energy and maintenance during its operation. The case of Nagpur Metro makes it evident that incorporating sustainability into the project does not cause any delays if it is implemented at the earliest stage of the project development.



Fig -3: Nagpur Metro

Table -3: Optimal Balance for Nagpur Metro

Parameter	Result
Time	Efficient project execution achieved through early planning and integration of sustainability measures, resulting in minimal delays
Cost	Higher initial investment due to adoption of solar energy systems and green building technologies, offset by long-term operational savings
Sustainability	High sustainability performance with extensive use of renewable energy, green certifications, and environmentally friendly design practices

#### 4.4 Mumbai Metro Rail Project

The Mumbai Metro Rail Project is an example of a complicated and difficult situation in the infrastructure industry that involves trade-offs among time, cost, and sustainability.

In this case, there have been several issues that have led to the delay and rise in cost associated with the project. There have been delays in terms of time performance, caused by difficulties related to land acquisition, environmental clearances, and opposition from the general public, especially concerning environmentally fragile sites like Aarey. The cost overruns have been a result of the delays in time performance. The increase in cost was mainly because of the higher costs involved in the delayed projects.



Fig -4: Mumbai Metro

Positive and negative effects from sustainability issues were seen in this project. They showed the relevance of sustainable development on the positive side. But they also resulted in conflicts, resulting in the postponement of the project implementation process. As such, sustainability issues can be considered as potential risks if not appropriately addressed concerning stakeholder management. In this specific example of the Mumbai Metro, there is an application of the conflict model wherein sustainability was wrongly incorporated in stakeholder management.

Table -4: Optimal Balance for Mumbai Metro

Parameter	Result
Time	Significant delays due to land acquisition issues, environmental clearances, and stakeholder conflicts
Cost	Substantial cost overruns caused by prolonged project duration, legal challenges, and design modifications
Sustainability	Sustainability considerations present but led to conflicts and delays due to environmental concerns and public opposition

#### 5. RESULTS

The conclusions of the study conducted indicate that time, cost, and sustainability are interrelated parameters which jointly affect the performance of metro rail projects. It has been seen through the comparison of case studies undertaken those changes in any one parameter affect the other two, creating trade-offs in terms of their performance within the metro rail project. From the perspective of time vs. cost, it can be seen that delays in the construction process tend to result in an increased cost of the total project. An increase in the time period means an increased cost in terms of labor costs, escalation of materials, and overhead costs. Projects with a long delay period due to complex urban settings have seen huge cost overruns. However, attempts to reduce the time period will involve increasing costs due to advanced methods and more resources being needed for the job. It has been seen from the perspective of sustainability vs. cost that using sustainable practices in the construction process tends to create high capital outlays at the outset of the project. This is because of measures like use of efficient energy, renewable energy, and environmentally friendly designs. However, this results in economic gains in the long term.

Sustainability-time relationship implies that due to the inclusion of environmental compliance issues, permits and design changes, projects can be prolonged. The earlier projects include sustainability issues in their early planning stage, the easier it is for them to handle the above effects; otherwise, projects that integrate sustainability in other stages face delay and coordination problems.

As for the comparative assessment of metro projects, it turns out that successful project results are achieved by integrating sustainability into the process at the project's early stage, using proper management techniques and coordination. Those projects that face some external factors, like land procurement or environmental problems, show great difficulties in handling time, cost, and sustainability.

#### 6. CONCLUSION

In conclusion, the research indicates that time, cost, and sustainability in the context of metro rail construction projects cannot be viewed as separate and distinct factors. Instead, they are related variables that should be addressed together. This means that an effort to optimize any of them could have negative implications on the other two parameters under consideration. The findings from the comparative case studies suggest that metro rail construction projects with an optimal performance in terms of these parameters are those that involve good planning, early incorporation of sustainability considerations, and efficient coordination of participants. In contrast, projects that are missing these characteristics may fail to meet their objectives and encounter problems related to delays, cost overruns, and implementation difficulties.

Based on these conclusions, it may be stated that successful performance of a project depends on the balanced optimization of the three parameters – time, cost, and sustainability – depending on the characteristics of the particular project.

## 7. RECOMMENDATIONS

From the results of this study, the following recommendations are presented regarding the ways in which time/cost sustainability trade-offs could be improved during the management of the metro rail project.

- [1] Firstly, the sustainability consideration should be considered right from the beginning of the project planning and design in order to prevent risks associated with time delays and cost overruns.
- [2] Secondly, the technology should be employed in the course of project management to facilitate the risk assessment for activities within the project management process.
- [3] Thirdly, coordination of the roles of all parties involved in the project should be ensured so that challenges affecting the project development could be addressed.
- [4] Finally, the approach used in project management should be flexible to incorporate any necessary changes.

## REFERENCES

- 1) <https://delhimetrorail.com/otherdocuments/Sustainability-Report.pdf>
- 2) <https://www.indiatoday.in/environment/story/delhi-metro-group-clean-energy-renewables-clean-energy-climate-change-global-warming-emissions-2802228-2025-10-13>
- 3) <https://www.mercomindia.com/mumbai-metro-rooftop-solar-projects>
- 4) <https://frontline.thehindu.com/social-issues/general-issues/article29766681.ece>
- 5) <https://indiainfrahub.com/news/nagpur-metro-rail-phase-1-project-completed-to-be-inaugurated-on-11-december/>
- 6) <https://metrorailnews.in/nagpur-metro-2/>
- 7) [https://x.com/updates\\_tn/status/1643809888425099267](https://x.com/updates_tn/status/1643809888425099267)
- 8) [https://www.researchgate.net/publication/355017526\\_Sustainable\\_Development\\_of\\_Urban\\_Metro\\_System\\_Perspective\\_of\\_Coordination\\_between\\_Supply\\_and\\_Demand](https://www.researchgate.net/publication/355017526_Sustainable_Development_of_Urban_Metro_System_Perspective_of_Coordination_between_Supply_and_Demand)
- 9) [https://www.researchgate.net/publication/349332951\\_An\\_overview\\_of\\_recent\\_developments\\_in\\_China's\\_metro\\_systems](https://www.researchgate.net/publication/349332951_An_overview_of_recent_developments_in_China's_metro_systems)
- 10) [https://www.researchgate.net/publication/392160508\\_Time-Cost-Quality-Environmental\\_Impact\\_Social\\_Impact\\_Trade-Off\\_for\\_Infrastructure\\_Projects\\_A\\_Review](https://www.researchgate.net/publication/392160508_Time-Cost-Quality-Environmental_Impact_Social_Impact_Trade-Off_for_Infrastructure_Projects_A_Review)

- 11) [https://www.researchgate.net/publication/373643439\\_An\\_Analysis\\_of\\_What%27s\\_Delaying\\_the\\_Metro\\_Rail\\_Projects\\_of\\_India](https://www.researchgate.net/publication/373643439_An_Analysis_of_What%27s_Delaying_the_Metro_Rail_Projects_of_India)
- 12) <https://timesofindia.indiatimes.com/city/kanpur/solar-plant-at-metro-depot-saved-2-crore-in-two-years/articleshow/123476025.cms>