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Key Factors in the Design of Urban Underground Metro Lines

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Abstract: Designing sustainable underground metro lines in dense urban environments is a highly challenging task that requires the collaboration of numerous stakeholders and consultants to make crucial decisions influenced by several factors. While it is impossible to address every issue influencing the decision-making process, identifying key factors and their interdependencies is essential for optimal design. This study focuses on six critical aspects of the reference design of metro systems: (1) track alignment, (2) tunneling strategy, (3) station typology, (4) operations and maintenance, (5) procurement strategy, and (6) environmental aspects. Amongst these aspects, we identify track alignment as the primary driving factor that influences the other factors. We analyze the decision between shallow and deep alignments as an engineering choice that necessitates balancing conflicting factors and constraints. Our contribution lies in mapping these factors and their dependencies, thus offering policymakers, project managers, and designers a framework to navigate the design process. Our discussion also provides guidance to public agencies in tendering for design teams more efficiently. Drawing from lessons learned by experienced design managers, this study aims to fill the gap in the literature by offering a generalist perspective on metro design.

Keywords: metro design; underground space; subway construction; urban development; megaproject management

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1. Introduction

With the rapid global trend towards urbanization, cities are increasingly facing challenges related to traffic congestion, pollution, and inefficient public transport systems. As a result, metro systems are becoming a critical solution, designed to provide reliable transportation to millions of city dwellers and tourists. Sustainable metro design is essential not only for operational efficiency but also for long-term environmental and social benefits, such as lower carbon emissions, improving social equality, and increasing connectivity for economic growth [1]. Given their immense cost and the fact that they are built for a service life spanning several decades, it is crucial to ensure that their design is optimal and efficient from the outset.

The design process of a metro project involves a number of critical stages, each with its unique set of challenges. Typically, the first stage is conceptual transport planning, based on an analysis of key aspects of urban life, transportation, and economic impact [2]. The second stage is basic design, which involves foundational decisions such as train routes and station locations. The third stage, reference design, progresses the preliminary plans and specifications to a detailed level of design that enables issuing tenders to contractors. Depending on the bidding method, a final optional stage allows the winning contractor to propose a detailed design of their own, incorporating innovative solutions and optimizations based on their expertise and capabilities. Hence the term "reference design", as the contractors' designs must rely on this preceding design. In this paper, we will focus specifically on the initial phase of the reference design stage. This phase is highly challenging because conceptual and preliminary plans must be promoted to actual design, while considering several interdependent structures and systems.

Khosravi and Kähkönen [3] discuss the challenges in metro project design. They note the limited number of such projects compared to other civil engineering ventures. Consequently, many designers lack specific experience in metro projects, especially given the recent surge in metro designs worldwide.

Another challenge is the lengthy process of metro line design and construction, typically spanning a decade. This prolonged timeline involves managing a complex array of stakeholders, including government agencies, local communities, and investors, who often change throughout the project. This dynamic environment is further complicated by rapid technological advancements, which require a well-planned design process that anticipates change. Additionally, metro projects are high-cost and high-risk. For instance, the Espoo metro extension in Finland (Lansimetro project) saw costs escalate from EUR 400 million to almost EUR 1 billion [4]. Such financial stakes can lead to stakeholders being reluctant to make prompt decisions, hindering the design team's progress.

Moreover, metro design requires expertise across various disciplines, each with its specific needs that often conflict with other elements of the railway. This interdependency creates a scenario where different design teams are constrained by one another, impeding overall progress. Teams may also promote their own design interests without recognizing interdependencies, leading to rework and schedule delays. Communication challenges are exacerbated by the involvement of multiple companies, including local and international firms.

Given these challenges, identifying key interdependencies between critical aspects is essential for project success. Drawing from practical experience and insights, we attempt to address the following questions: (1) How can metro design in the early reference design stage incorporate and balance numerous critical aspects? (2) What are the key factors that can most effectively guide the decision-making process during this stage, and how are they interrelated?

Figure 1 illustrates the key factors in underground metro design, which include track alignment, tunneling strategy, station typology, operations and maintenance, procurement strategy, and environmental aspects. These factors are interrelated, as illustrated in the figure. While the issues highlighted do not cover all potential considerations, they are representative of many metro projects. A deeper understanding of these key topics and their interplay is particularly crucial during the initial design phase, where significant decisions must be made to advance the project. At this stage, there is a heightened risk of getting lost in the details, making it essential to focus on the broader issues to ensure that the design progresses in a cohesive and effective manner. This understanding can ultimately lead to the development of more effective design teams, workflows, and decision-making processes.

A notable example of a project that suffered from a misguided design process is the Hyderabad Metro in India [5]. This megaproject faced significant technological and environmental challenges that influenced project outcomes, highlighting the importance of understanding key factors and their interdependencies during the design phase. Land acquisition delays, utility relocations, and geological conditions affected both the track alignment and tunneling strategy, leading to a three-year project delay. The relocation of older utility infrastructure further complicated the station typology and overall construction workflow. Additionally, the interface issues between stakeholders and the use of new technologies underscored the need for effective procurement strategy and collaboration across teams. This case illustrates the importance of addressing these interconnected factors early in the design process to minimize risks during construction and ensure project success.

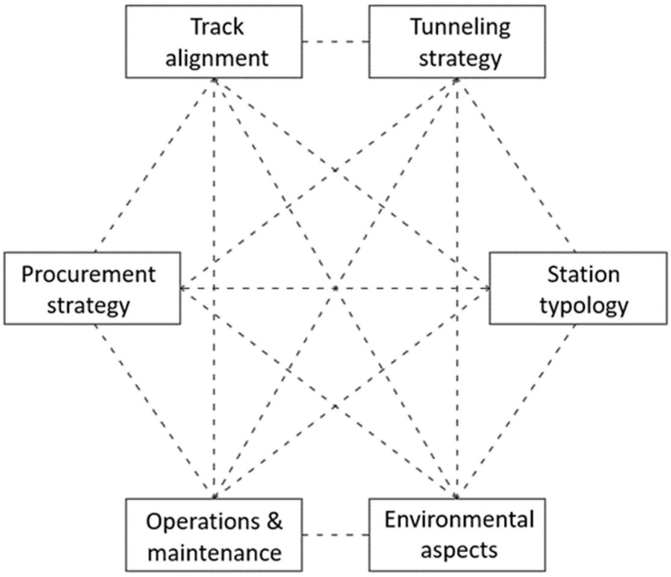


Figure 1. Key aspects and interdependencies in the design of an underground metro line.

It is important to emphasize that, throughout our discussion, where we use the term "decision", this does not imply a simple choice between multiple options. Instead, most decisions in metro design are heavily influenced, if not entirely dictated, by constraints. For instance, when an existing basement clashes with the proposed tunnel alignment, it may become necessary to deepen the tunnel, which in turn requires adjustment to other design elements, such as station typology. In other cases, existing structures that clash with the proposed alignment could be expropriated and demolished as part of the enabling works. This necessitates a thorough process of studies and analyses to identify and address the constraints effectively. Understanding this nuanced decision-making process is crucial for developing robust design teams and workflows that can navigate the complexities of metro projects.

The available research and engineering literature on metro system design focuses on highly technical topics, and there are only a few studies that discuss metro projects in a broader context [6]. Our discussion aims to bridge this gap by identifying and discussing the key aspects of the design process. Our discussion is based on three sources: (1) the authors' first-hand experience, (2) insights from discussions with experienced designers and managers, and (3) published case studies and reports. Accordingly, our study encompasses lessons learned over many years and multiple metro projects. Hereinafter, this paper is organized according to the following structure: each of the key factors highlighted in Figure 1 are discussed separately, as well as various examples of interdependencies. Finally, we focus on the decision of track alignment level, i.e., shallow vs. deep alignment and stations. This fundamental design decision provides a useful example where influencing factors and trade-offs must be identified and balanced.

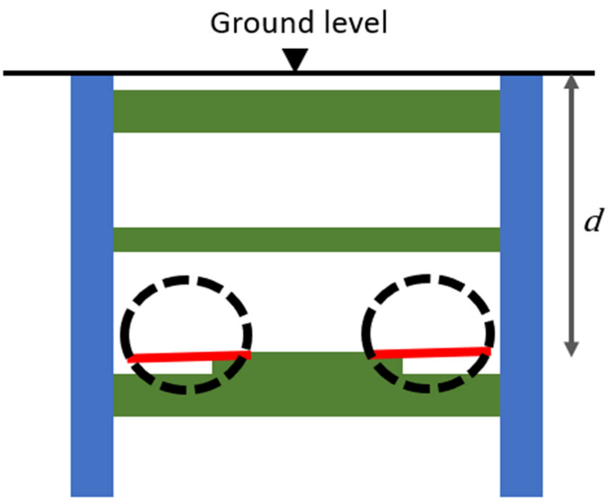
2. Track Alignment

Track alignment involves selecting the optimal three-dimensional path for the tunnels, considering factors such as type of train (often referred to as rolling stock), passenger comfort, maximum gradients, and geological conditions. The maximum allowable gradients and curves are constrained by the performance capabilities of the rolling stock and the need to provide a comfortable ride for passengers. The track alignment is designed to connect between stations, while avoiding physical clashes with underground structures and utilities. Optimizing track alignments to balance costs with operational and user requirements throughout the system's life cycle is crucial for a sustainable metro line [7].

While the key aspects of metro design are interdependent, track alignment stands out as the primary driver influencing the other factors. Track alignment decisions are closely linked with station typology. Figure 2 illustrates the impact of track alignment depth (denoted by *d*) on station typology, showing typical cross sections for stations at varying depths. Figure 2a shows a shallow track alignment, which dictates a two-story station. If the depth increases, a three-story station box may be a better choice, as shown in Figure 2b. Alternatively, for a deep alignment, a mined cavern can be considered for the station, as shown in Figure 2c. Clearly, the number of stories has a major influence on the station architecture and structure. As can be inferred from Figure 2b,c, the construction method may also change depending on different factors, as cut-and-cover boxes and mined caverns are valid options for deep stations. This topic will be discussed in the Station Typology section.

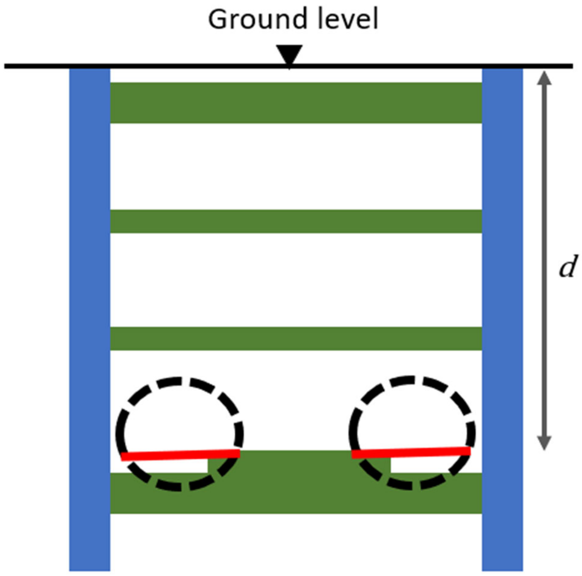
Interdependencies with other key factors are crucial as well in track alignment decisions. For example, the alignment affects the tunneling strategy, as the chosen tunneling method is constrained by the alignment depth and curves. Track alignment decisions must account for geological conditions. This involves assessing soil and rock stability, groundwater levels, and other geological risks, which significantly influence tunneling methods and costs. In many cases. balancing between constraints is necessary. For example, the tunneling strategy may require reaching a certain depth where there is a soil layer with greater strength for tunnel physical stability. In turn, this may require adjusting vertical curves to reach a desired station platform level, to a degree that passenger comfort is reduced. In Section 8, we discuss in detail the question of alignment depth as a common example in metro design that requires effective decision-making processes. The operations and maintenance team must verify that the track alignment allows the operational framework of the metro to comply with safety regulations, service reliability standards, and efficiency requirements. This includes ensuring that the alignment supports the timely movement of trains and accommodates necessary maintenance activities without disrupting regular service. The alignment must provide suitable locations with adequate space and geometric conditions for placing train crossovers and stabling facilities.

The interplay between track alignment and procurement strategy is essential for ensuring the metro system's efficiency. The selection of rolling stock must come first for the alignment to adhere to, as the type of train influences parameters such as minimum curve radius and tunnel dimensions. For example, a heavier train requires a larger curve radius, due to larger centrifugal forces. Thus, design of an alignment with tight curves may not allow for certain train types to be procured. Early involvement of procurement teams is therefore essential to ensure that the chosen technologies and suppliers align with the project's technical and operational requirements.



(**a**)

Figure 2. *Cont.*



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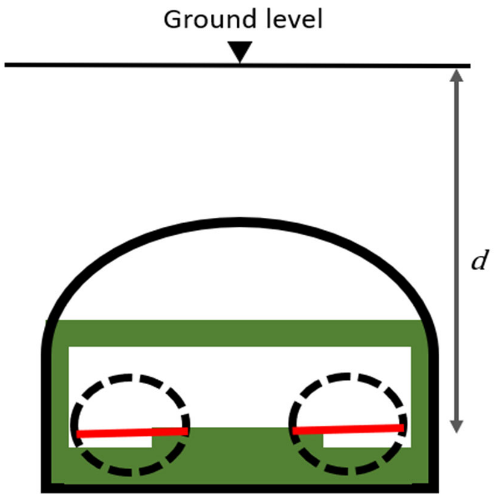


(**c**)

Figure 2. Illustration of typical station cross sections, for (**a**) shallow 2-storey station box, (**b**) deep 3-storey station box, and (**c**) deep mined station. The red lines denote track level, *d* denotes the alignment depth, and the dashed circles represent the tunnels. The dashed circles represent twin tunnels, the red lines represent the track level, the green lines represent slabs, and *d* denotes the alignment depth measured from ground to track level.

General track alignment must be decided upon early in the initial design and fine-tuned according to an iterative process based on these interdependencies. Hence, it is crucial that a proper workflow is set up to ensure that alignment updates are coordinated with the relevant design teams. In summary, the track alignment is a multifaceted decision that requires careful consideration of rolling stock capabilities, passenger comfort, geological conditions, and interdependencies with other key factors. A well-planned alignment enhances the overall efficiency, safety, and sustainability of the metro system.

3. Tunneling Strategy

In an underground metro project, the primary civil engineering tasks include tunneling and train station construction. The choice of tunneling method is a major decision that has a significant impact on project cost and schedule. For most modern metro projects, mechanized tunneling operations via tunnel boring machines (TBMs) are the generally preferred method. TBMs are machines that drive underground and are designed to excavate, transfer mucked soil backwards, and erect support elements through a sequenced and automated process. Compared to conventional tunneling, TBMs perform at higher advance rates and with considerably less human labor [8]. Smaller tunneling tasks, such as excavation of cross passage tunnels and crossovers, are typically executed using mining methods.

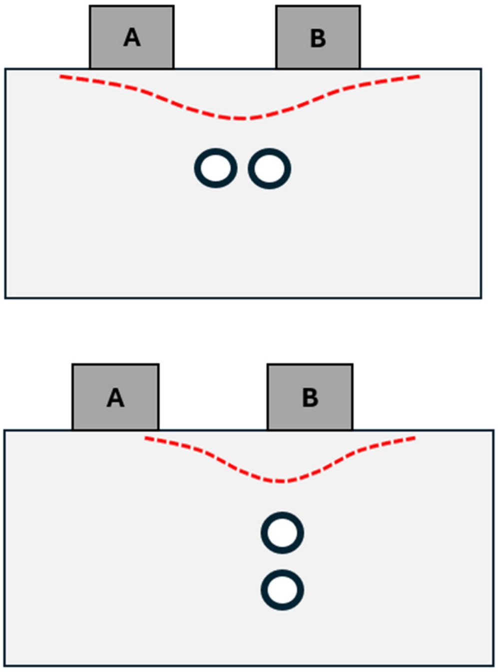
When considering a two-lane train configuration, the choice between constructing a single large tunnel with two lanes or opting for twin tunnels requires careful evaluation. Due to geometric principles, as the diameter of a tunnel increases, the cross-sectional area grows proportionally to the square of the radius, resulting in a significant increase in the volume of excavated soil. Consequently, a single large bore demands considerably more excavation than two smaller twin tunnels. Additionally, the advance rate of a large TBM is typically slower compared to smaller TBMs, which further extends the excavation period. In terms of cost, a single bore requires only one TBM, but this machine must be larger, more expensive, and specialized. On the other hand, twin tunnels allow for the use of smaller and more affordable TBMs that are often more available. Moreover, twin tunnels are generally considered more efficient in terms of space usage, as the smaller bores are better suited to the typical space requirements for two lanes, minimizing wasted cross-sectional area. Despite these considerations, a single-bore tunnel does offer some advantages, such as eliminating the need for the interconnecting cross passages that are required for safety in twin tunnels. A single bore can also better streamline systems like ventilation, where the larger cross section accommodates higher airflow capacities, improving overall efficiency.

The twin tunnels are regularly positioned horizontally one to the other, although a vertical configuration has also been implemented [9]. The vertical twin-tunnel configuration offers the advantage of reducing surface settlement impacts. Figure 3a,b illustrates the differences in surface settlement between the horizontal and vertical tunnel configurations, respectively. Note that the settlement contours, depicted in dashed red lines, are exaggerated for clarity. As shown, in the horizontal configuration, both buildings A and B are subject to differential settlement as a result of tunneling. In contrast, the vertical configuration primarily affects only building B, and the differential settlement it experiences is significantly reduced. Thus, in dense urban areas where the are many buildings, a vertical layout may be preferred. The main disadvantage of the vertical configuration is that it increases passenger travel time within the stations, as it requires travelling through an additional set of escalators or lifts. These tunnel–building interactions may require enabling works and statutory approvals, where buildings are strengthened prior to tunneling works.

Additional factors that can have a significant impact on tunneling-induced surface displacements are related to the TBM operation. For example, systematic field tests conducted during the TBM operation at the Beijing Metro Line 12 studied the effect of tail grouting under different types of grout. Tail grouting is the action of injecting grout into the void between the TBM concrete support segments and the surrounding ground. This study found that grout properties under varying ground conditions had a significant impact on surface displacements [10]. Another such factor is TBM speed and face pressure. For example, during the Athens Line 2 metro project, researchers analyzed field data and found that by controlling these parameters surface settlements can be reduced [11].

Tunneling strategy decisions have a critical impact on other aspects of design. For example, the tunnels are connected to the stations, and, therefore, station typology is dependent, as discussed in the previous section, on knowledge of the tunnel cross section and configuration.

The tunneling strategy must rely on geotechnical information, thus, it is crucial that at least a preliminary site investigation is conducted in advance to the major decisions regarding tunneling strategy. For example, if tunneling is to occur through altering geological formations, specialized and more expensive multi-mode TBMs may be needed [8]. The uncertainties inherent to geological materials must be accounted for using a combination of engineering judgment and probabilistic methods [12]. It is crucial that there is enough geotechnical data available to establish the general tunneling strategy. For example, the identification of soil layers and their main characteristics, as well as the groundwater level, are vital, whereas detailed laboratory strength tests can be conducted during later stages of design. At the completion of the reference design stage, it is important to have sufficient geotechnical data to allow for TBM contractors to make accurate bids. It is worth noting that, while geotechnical engineers often prioritize obtaining numerous test results, monitoring data from previous tunneling projects in the vicinity of the current metro project can be equally, if not more, valuable. Monitoring data from actual projects often provides a more accurate representation of the ground conditions and real-world performance. In contrast, laboratory test results are typically empirically correlated with important performance metrics, such as TBM advance rate or tunneling-induced settlement, and these correlations can sometimes be weak [8].



(**a**)

(**b**)

Figure 3. A comparison of tunneling-induced surface settlement and its impact on above-ground structures between (**a**) horizontal twin-tunnel configuration and (**b**) vertical twin-tunnel configuration.

Crossovers, which are track arrangements allowing trains to switch from one track to another, are essential for operational flexibility, enabling trains to be rerouted during emergencies, peak hours, or maintenance activities. From an operations perspective, well-placed crossovers allow for better train frequency management and facilitate smoother transitions during service disruptions. For operations and maintenance, these crossovers are crucial as they provide access points for maintenance crews to conduct necessary repairs and inspections without major service interruptions. Crossovers require additional mining operations for constructing large caverns, which must align with the tunneling strategy. Thus, good coordination between the tunneling and operations and maintenance teams is crucial for establishing the tunneling strategy.

An important strategic decision that influences the procurement strategy is the number of TBMs to employ, i.e., how to divide the tunnels between contractors. Figure 4 shows a simple illustration of two tunneling strategy options: in the first option, two TBMs are employed for tunneling from point A to point B, whereas, in the second option, the same length is divided for three TBMs. While both options are viable, the pros and cons of each should be carefully weighed. Using fewer TBMs reduces the project's immediate costs, as fewer machines need to be procured. However, this approach can prolong the schedule, as three TBMs would operate simultaneously, potentially completing the work faster. Additionally, using fewer TBMs introduces greater risk into the project, as delays due to technical failures have a larger impact on the overall schedule. The principles of this simple example are relevant to longer lines, where multiple tunneling options can be considered to optimize cost, time, and risk management. Selecting the optimal tunneling strategy requires the procurement team to be involved from the outset, as these issues are inherently linked. The availability and lead times of TBMs, as well as the expertise of operators, can significantly influence project timelines and costs. By involving the procurement team early, projects can better align their strategic decisions with market realities, ensuring a more efficient and feasible execution plan.

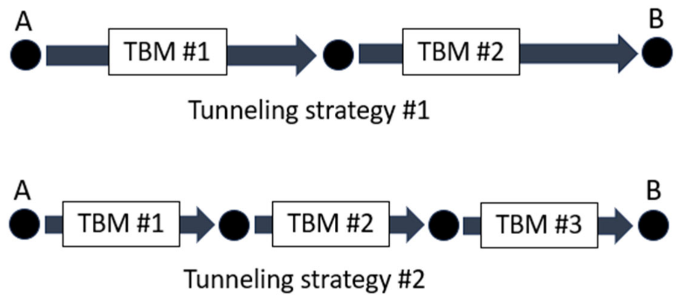


Figure 4. Comparison of 2 tunneling strategy options: Tunneling strategy #1, where 2 TBMs are employed for tunneling from point A to point B, and Tunneling strategy #2, where the same length is divided for 3 TBMs.

For the TBM to begin its operation, a launching shaft (LS) is regularly needed. The LS is a vertical structure connecting the surface level to the track alignment level. Note that in Figure 3 the circles represent shafts, where point A is an LS, the final circle at point B indicates the retrieval shaft, which must allow for the removal of the TBM upon its completion of the tunneling portion, and the intermediate shafts serve both functions, i.e., launching and retrieval. The number of TBMs used influences the location and design of the LSs. LSs are usually constructed adjacent to the metro stations. Alternatively, the LSs can be integrated later in the project into the train stations. Particularly for the latter option, LS design requires coordination with the station typology teams, so that stations are planned accordingly.

Additionally, the procurement team must address the allocation of responsibility to ensure that the interface between the LS and future station is well-managed. The LSs require a continuous supply of concrete segments and muck removal throughout the operation of the TBMs. Consequently, it is crucial to address traffic management and establish logistic facilities near the LSs. The procurement team must carefully consider the timing of LS construction: starting too early can cause unnecessary disruption to urban life, while starting too late can lead to project delays and potential claims.

In this context, a distinction can be made between two types of design components that must be addressed early in the design process. First are the design components that are highly interdependent, such as station typology. Establishing a tunneling strategy without coordination with the station typology team would result in wasted design resources and potential delays in the design schedule. The second type is design components that must be executed early in the construction sequence, with LSs being a primary example. In the case where an LS is designed without proper coordination, the consequences would be costly construction reworking of the LS and potential delays in the construction schedule.

As will be discussed in Section 7, compared to the more traditional disciplines, for environmental aspects, there are several related emerging trends and innovations. Hence, it is important that the tunnel strategy is established while allowing for relevant technologies to be incorporated. To summarize, the general tunnel strategy must be established early on with close coordination with other key factors.

4. Station Typology

In the design and construction of underground metro lines, the typology of stations is a critical consideration. Train stations typically consist of three primary components: (1) a concourse area, which serves to separate the station into unpaid and paid zones; (2) train platforms, where passengers board and alight from trains; and (3) technical rooms housing essential systems, including mechanical, electrical, plumbing (MEP), and systems equipment. Each of these components must be carefully designed to ensure efficient passenger flow, safety, and operational functionality. The concourse area is particularly important for managing the movement of passengers, providing access to ticketing services, and offering various amenities.

There are two main options for the construction of underground stations: (1) cut and cover (CC) and (2) mined stations (see Figure 2). The construction method has significant implications for the project, including impacts on traffic management, costs, schedule, and statutory requirements.

The CC method involves excavating a large trench from the surface, constructing the station within the trench, and then covering it up. CC stations are typically preferred for their straightforward construction process and relatively lower costs. However, this method requires extensive surface disruption, leading to considerable traffic management challenges. Prolonged road closures and detours may be necessary, which can significantly affect local communities and businesses. Therefore, detailed traffic management plans and community engagement strategies must be developed and implemented. Additionally, extensive statutory approvals may be required to permit the necessary surface disruptions and temporary land-use changes.

In contrast, mined stations are constructed entirely underground, with minimal surface disruption. This method is generally less preferable, as it is more complex and expensive due to the technical challenges associated with underground construction. The construction of mined stations requires advanced engineering techniques and careful planning to ensure structural stability and safety. Note that these stations are often referred to as NATM (New Austrian Tunneling Method), as this is the common method for mining such stations. However, other methods are available, e.g., pipe jacking. Mined stations are considered in densely populated urban areas where maintaining surface activities is crucial.

The selection between CC and mined stations impacts on the dimensions of the stations, which in turn require different typologies for fitting all the necessary components. Mined stations are more limited in their width, as their stability largely depends on the ground strength, whereas CC stations rely to a greater extent on concrete diaphragm walls (D-walls, see the blue-colored walls shown in Figure 2a,b). In addition, mined stations typically have arched roofs, for better distribution of vertical earth loads. The construction method also affects other project aspects, such as ventilation, emergency access, and integration with existing infrastructure. CC stations can be more easily integrated with surface-level amenities and infrastructure, while mined stations might require additional underground connections and access points. Both station typologies necessitate thorough consideration of logistical support throughout construction and statutory measures. For CC stations, securing temporary land-use permissions and managing environmental impacts are crucial. For mined stations, predicting surface impact and ensuring compliance is essential, and, in some instances, may require pre-reinforcement of the ground, using methods such as jet grouting. In some cases, constraints may dictate that unique geometrical configurations are required. For example, in the Melbourne metro project in Australia, station caverns were built in trinocular form [13].

Another important aspect of station typology relates to the selection of entrances and exits for each station. The design and placement of station entrances and exits are critical components of station typology. For both CC and mined stations, entrances and exits must be strategically located to ensure convenient access for passengers while minimizing disruption to surface activities. Entrances and exits must also comply with accessibility standards, providing safe and efficient routes for all passengers, including those with disabilities. The placement of these access points can affect pedestrian traffic flow, integration with other transport modes, and the overall urban landscape. In densely populated areas, entrances and exits might need to be placed in existing buildings or integrated with public spaces to optimize land use and enhance connectivity. Advanced tools have been developed to simulate and evaluate such different options [14].

Another crucial consideration in this regard is the choice between lifts and escalators for passenger transport within the station, with the latter being the preferred option. This decision impacts passenger convenience. Lifts are essential for ensuring accessibility for all passengers, particularly those with disabilities, parents with strollers, and passengers with heavy luggage. Escalators, on the other hand, can handle a higher volume of passengers and maintain a continuous flow, reducing congestion during peak hours. This choice is also influenced by the station's depth, with lifts being the faster method for transporting passengers in deep stations. The procurement team must work closely with experts that oversee that reliable lifts and escalators are installed, considering factors such as maintenance requirements, energy efficiency, and lifecycle costs.

Decisions regarding station typology are highly linked to the tunneling strategy, as well as procurement considerations. Stations are regularly constructed prior to TBM arrival. This option requires pulling or retrieving the TBMs upon their arrival at the station. For the option of TBM passage prior to station construction, some portion of the stations should be constructed prior to the arrival of TBMs. The minimum would be the construction of the D-walls perpendicular to the tunnel drive. Otherwise, construction of these walls would become a difficult operation, where the wall drilling is carried out through existing tunnel support elements, and concrete can be filled only after the necessary formwork has been completed from within the tunnels. The decision of whether to allocate the civil works of the stations to the tunneling contractor or to arrange for another division between contractors requires balancing between different pros and cons. For example, unifying stations and tunnels to a single large contractor reduces the potential for conflicts and 'blame games', whereas allocating the work to smaller and skilled contractors may potentially allow for lower prices at the tender phase. This alternative requires facilitating construction interfaces with proper means, such as developing and implementing a detailed construction scheme and clearly allocating responsibilities in the tender documents.

The choice of station typology must balance construction costs, project schedule, traffic management, and statutory requirements. A comprehensive evaluation of these factors, along with stakeholder engagement and detailed planning, is essential to ensure the successful implementation of the chosen station typology. In addition, the choice of station typology serves as a bottleneck for the design process. Station dimensions and ground level cannot be determined without first deciding upon the construction method. Hence, it is crucial that this decision is made as early as possible.

5. Operations and Maintenance

During the early design phase, operations and maintenance (OM) teams are responsible for several issues, such as determining train frequency and speed, ensuring track layout, developing safety protocols, and more. The OM team must oversee that stations and tunnels are planned in a manner that would allow for all future maintenance operations to be carried out with minimal interruption to train and station operation. Accordingly, OM must work closely with other architectural and engineering teams. For instance, maintenance operations may require the transportation of large, heavy equipment into these spaces, thereby necessitating sufficiently large entrance dimensions. Another example is the selection of a communication-based train control (CBTC) system. CBTC is an advanced signaling system that uses real-time communication between trains and track equipment to improve safety and optimize train intervals. This requires a discussion with system engineers to plan for integration with the overall infrastructure and technology framework.

The interplay between OM and procurement strategy development is crucial for ensuring the metro system's long-term reliability and efficiency. OM teams' decisions regarding maintenance strategies, technology integration, and resource allocation directly influence procurement needs, requiring close coordination to secure the necessary equipment, spare parts, and services. Early involvement of OM teams in the procurement process helps in selecting technologies and suppliers that align with operational requirements and maintenance goals, ultimately enhancing system performance and reducing lifecycle costs. OM considerations are tied with track alignment and stations, as mentioned in the previous sections. Furthermore, OM decisions influence energy efficiency, waste management, and other environmental aspects, thus requiring coordination with the relevant teams.

6. Procurement Strategy

The procurement team plays a critical role in metro projects, ensuring that the project works are properly divided into manageable packages that align with available contractors and technologies. There are numerous contractors and subcontractors in metro projects. Khosravi and Kähkönen [3] found that, for the Shiraz metro project in Iran, as well as the Espoo metro extension in Finland, the number of subcontractors was greater than 500. This scale requires that the procurement team adopts a systematic and strategic approach to manage the tendering process. The high costs and risks of metro projects require that tenders ensure contractors' compliance with terms and conditions and handle any disputes that may arise. Particularly, the geotechnical risks, inherent to any underground construction, must be accounted for by appropriate mechanisms, such as geological baselines and risk sharing [15].

Statutory considerations are another critical element in the procurement strategy for metro projects, as they influence design decisions and timelines. These constraints encompass land-use regulations and other regulatory approvals, which often require extensive processing times and carry significant risks. Collaboration with local experts—such as lawyers, architects, and government officials—is crucial for navigating these statutory requirements, especially when international teams are the lead designers. These experts provide essential insights into the regional regulatory landscape and cultural context, facilitating smoother procurement processes and ensuring compliance with local standards. While managing a multicultural working environment can present challenges, particularly in terms of communication and differing expectations, it can be highly beneficial if handled properly. Indeed, case studies have shown that a working environment that fosters multicultural collaboration contributes to the overall success of large-scale projects [16].

Data management is another integral consideration that intersects with procurement strategy. Modern metro projects generate and rely on vast amounts of information, from site surveys and regulatory requirements to design plans and technical specifications. The integration of Building Information Modeling (BIM) technologies into the design and management processes can significantly enhance the accuracy and accessibility of project data. By utilizing BIM as a central repository for project information, the procurement team can ensure that all stakeholders have access to up-to-date and accurate data, thereby improving coordination and reducing the risk of errors. Additionally, the growing role of artificial intelligence (AI) in data management offers opportunities to optimize procurement decisions through real-time analysis and predictive modeling. Integrating AI with BIM can further enhance decision-making and efficient resource allocation [17]. Data management may be the responsibility of an independent team dedicated to this matter. Nevertheless, the procurement strategy must ensure that the data that are gathered are efficiently transferred to the relevant contractors. By transferring data in the most ideal format, many construction mistakes can be prevented. Additionally, procurement documents should clearly outline how contractors and operators are to manage their own data, ensuring transparency and allowing for easy supervision by designers throughout the project lifecycle.

Selection of the TBMs is crucial for project success. The procurement team should be involved with the tunneling strategy early on to guide decisions that are influenced by contractor and machine availability, as discussed in the Tunneling Strategy section. Moreover, the procurement team should consider involving TBM contractors in the design process. TBM contractors have hands-on experience and are often more updated regarding technological innovations. Contractors can help identify potential risks related to equipment performance, ground conditions, and construction logistics. However, early contractor involvement raises concerns about compromising the fairness of the subsequent bidding process. To mitigate this risk, the procurement team must establish transparent and fair procedures, such as engaging multiple contractors in a non-binding manner, ensuring independent oversight, and sharing all relevant information equally with all potential bidders.

One of the key decisions is the procurement strategy is the type of tender, such as traditional design–bid–build, design–build, private–public partnerships, or other special tendering methods. Obviously, such decisions have an immense impact on the design process and deliverables. The procurement strategy must be closely linked to the project schedule to ensure timely delivery of construction works and other services. For example, the launching of a TBM requires coordination with several other activities, such as utility diversions, traffic arrangements, launching shaft construction, power supply, surface monitoring, and more. Statutory considerations, such as obtaining necessary permits, can influence procurement timelines and requirements. Given that essentially all aspects of the design must be procured, their interdependency with procurement is inherent.

7. Environmental Aspects

In contrast to the other key factors that have been discussed, which are part of traditional engineering, environmental aspects can sometimes be treated as secondary issues. However, this approach is increasingly outdated in the context of modern urban development, where sustainability must be a guiding principle. A metro system, by its very nature, is intended to be a sustainable alternative to other forms of transportation, particularly in reducing carbon emissions. For this reason, it is imperative that environmental aspects are not just included but prioritized from the very inception of the design process.

The construction of tunnels and stations requires a vast amount of concrete. Plans and procurement documents should be adjusted to prioritize environmentally friendly materials which reduce the carbon footprint. For example, geopolymer composites produce significantly lower carbon emissions compared to traditional Portland cement [18]. Recycled materials such as reclaimed steel and recycled concrete aggregates can be employed in the construction of tunnels and stations. In a case study from the Sydney Metro project, the use of recycled steel reduced the project's greenhouse gas emissions by approximately 20% [19]. High-performance concrete mixtures that include industrial by-products like fly ash and slag can enhance the longevity and structural integrity of the metro infrastructure while reducing the consumption of virgin raw materials. In order for such materials to be integrated into plans, the environmental specialists must collaborate early on with tunneling and station typology teams. Additionally, the environmental specialists must ensure that the tender documents set mechanisms that ensure the implementation of eco-friendly materials and practices by the contractor.

Environmental considerations apply to OM issues as well. By working with the OM team, maintenance practices that lower energy consumptions and repairs should be prioritized, as they both save costs and reduce emissions. The environmental aspects include the impact on local ecosystems, such as air quality and noise levels. It is important to actively search for innovative methods, particularly those that have been implemented and proven successful in real-world settings. For example, noise-absorbing materials and strategically placed barriers contributed both to noise reduction and air quality by blocking pollutants [20].

A focus on environmental sustainability should try to ensure that the metro system contributes positively to the urban ecosystem, beyond just reducing environmental damage. A simple example is including green spaces within metro stations. Implementing creative and innovative solutions could also be considered, such as utilizing heat generated in metro tunnels for heating buildings that are connected to the metro system [21].

Finally, procurement documents should facilitate a streamlined process for design improvements proposed by the winning contractor. Often, strict checks and balances are imposed alongside tight deadlines, discouraging contractors from making modifications that could enhance efficiency. For instance, if the station typology team has specified overly thick D-walls as a conservative measure, it would be beneficial, both in terms of cost savings and environmental impact, to allow the contractor to propose reducing the thickness, provided the revision is backed by sound engineering. However, without a clear process in the procurement documents for evaluating and accepting such proposals, overly conservative and wasteful designs are likely to be implemented.

8. Alignment Depth

One of the fundamental decisions in the reference design of an underground metro line is the elevation of the track alignment, i.e., shallow vs. deep alignment. Obviously, shallow and deep cannot be defined objectively, but, based on experience, a top-of-rail depth of 20 m can serve as a threshold between a shallow and deep alignment. This decision serves as an excellent example of the nature of metro lines, as it requires considering different constraints:

- Tunneling strategy—as geotechnical conditions and risks likely vary with depth, selection of a shallow or deep metro line can influence the selection of the TBM type, its advance rate, as well as other tunnel related considerations.
- Station typology—in general, shallow alignments would lead to CC stations, and deeper alignments to mined stations. While both may be considered for a given alignment depth, at a very shallow depth it may be geotechnically infeasible to construct a mine station, as some minimal overburden depth is needed for ground arching. In turn, at greater depths, it may become an expensive and lengthy operation, while the difference in costs and schedule may not be insignificant compared with the overall project budget. Nevertheless, lengthy disruption to urban life is a highly important consideration. In addition, alignment depth influences station entrances and safety escapes routes.
- Statutory considerations—the choice of alignment depth would likely have statutory impacts. For example, a shallow alignment may create conflicts with existing foundations or basements, which in turn require different approvals. A shallow alignment also increases tunneling-induced surface settlements, and this could require special approvals and monitoring operations.

Other considerations that influence the choice of alignment depth are site-specific considerations that must be studied in order that their impact is understood, such as geotechnical risk. For example, in the case where the groundwater level is high, this may serve as a downwards-driving factor. In cases where the soil strength and stiffness increase with depth, this would have the opposite effect. If the ground is highly contaminated in certain layers, this negatively impacts the recycling of the mucked soil. Ultimately, geotechnical risks must be studied in order to determine whether they pressure the alignment to be shallow or deep.

Figure 5 summarizes the key influencing factors. Perhaps the most important consideration is passenger experience, which is an upwards-driving factor. This is because a lengthy trip to reach a deep level could add substantial time, specifically when many of the passengers are anticipated to ride the train for only a few stations. In some cases, reduction of alignment depth for a limited portion of the metro line could be considered, based on site-specific considerations and constraints. However, this could have a detrimental impact on train passenger experience due to portions where steep vertical gradients would be required for these alterations.

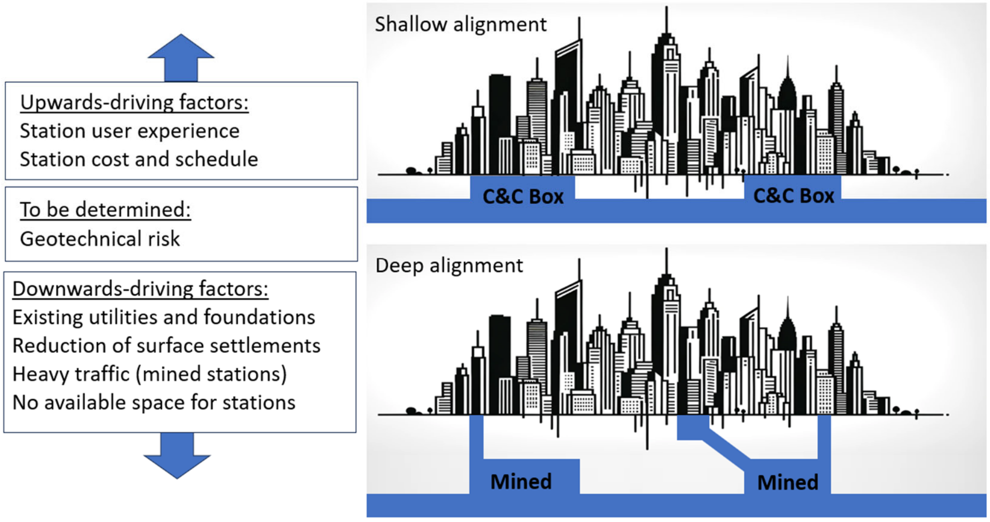


Figure 5. Upwards- and downwards-driving factors that influence the selection of shallow vs. deep track alignment.

Proper evaluation of multiple considerations requires effective communication between design teams, stakeholders, and decision-makers. The latter must acknowledge that there is likely no choice that is ideal, but, rather, the decision should aim to weigh the trade-offs between the options. Trade-offs involve weighing subjective factors, such as passenger experience, as well as more concrete influences, such as estimated costs. For such complex decisions, methods such as evaluation matrices can be particularly helpful [22]. In an evaluation matrix, weights for key factors and decision criteria are established, facilitating a structured comparison of different options. This method assists in conducting systematic discussions and analyses, thereby enhancing the transparency and accountability of the decision-making process. Utilizing evaluation matrices can ensure that all relevant factors are considered and balanced appropriately, leading to more informed decisions. Such tools are especially helpful in overcoming biases imposed by social dynamics, such as dominant individuals that may steer decisions according to their personal preferences rather than objective criteria.

9. Summary and Conclusions

This study has explored the intricate challenges associated with the initial reference design of underground metro lines in dense urban environments, focusing on the key aspects that drive optimal design decisions. The analysis of six critical factors—track alignment, tunneling strategy, station typology, operations and maintenance, procurement strategy, and environmental aspects—highlights the big decisions and interdependencies that influence the overall success of metro projects. Among these factors, track alignment is argued to be the primary driving force, significantly impacting the other design elements, as it directly dictates the tunneling strategy and station typology. The decision between shallow and deep alignment fundamentally alters station typology and determines the ground conditions for the tunneling works. In the process of deciding upon track alignment, numerous considerations and constraints must be assessed.

In contrast, environmental aspects can be neglected from traditional design workflows, but this would inevitably compromise the long-term sustainability and social utility of the project. Detrimental effects of overlooking environmental aspects include an increase in carbon emissions and greater disruption to local ecosystems. As this field consists of many emerging innovations, it is important to proactively search for opportunities for integrating these into design.

OM and procurement strategy have an intermediate impact. Early involvement of the OM team ensures that stations and tunnels are designed in a matter that allows for ideal maintenance and long-term operation. Involving the procurement team is essential for aligning big design decisions with procurement considerations, such as TBM availability, budget constraints, and the division of works and responsibilities.

Understanding these aspects and their interplay is essential for all members of the design team, not just senior management. This high-level perspective ensures that team members remain aware of the broader project objectives and avoid becoming overly focused on isolated technical details.

Another important implication of identifying interdependencies is understanding where there are no such constraints. This has a practical consequence, as it allows for promoting these topics, while interdependent issues are delayed and waiting for decisions. For example, where a train depot facility is planned to be placed at the end of the line, with no influence on alignment and stations, this design can be efficiently promoted. Recognizing these opportunities can help maintain project momentum and ensure efficient resource allocation.

The implications of this discussion extend to government agencies responsible for the tendering of reference design teams. Given the interdependent nature of metro projects and the large number of stakeholders involved, the tender must be strategically designed to reflect and facilitate these complexities. This requires addressing the principal–agent problem, where the interests of different teams may not align with the overall project goals [23]. Effective tendering should aim to foster collaboration, align incentives, and ensure that all stakeholders are working towards a common objective [24]. Often, public agency tenders focus primarily on deliverables and deadlines, which, if structured correctly, can effectively guide the design process. However, given the interdependencies and key factors discussed, it would be highly beneficial to define milestones that actively promote the necessary discussions and collaborations between different teams. For example, establishing checkpoints where teams are required to demonstrate that key factors have been thoroughly evaluated across relevant disciplines can ensure that no critical aspect is overlooked. Additionally, introducing evaluation matrices that explicitly measure how well these factors have been considered and integrated across teams would further enforce transparency and balance.

In conclusion, the success of metro design requires building teams and workflows that are reflective of the key aspects and their interdependencies. Fostering an environment of open communication and collaboration increases the likelihood of delivering efficient, cost-effective, and sustainable metro systems. It is imperative that researchers share observations from case studies to promote better practices. As innovative technologies that have the capability of revolutionizing transportation systems, such as hyperloop [25] and magnetic levitation systems [26], continue to emerge, design management strategies must evolve and adapt accordingly.

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