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Enhancing Construction Safety And Efficiency In Brownfield Petroleum Refinery Expansions: A Feasibility Study Of Modular Construction In India

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ABSTRACT
The petroleum industry in India is undergoing significant expansion, particularly in brownfield refinery projects, which involve expanding existing facilities and / or integrating newly installed facilities with existing ones. Cost overruns and delays in completion are often faced challenges in Indian Projects when being executed in a conventional stick-built approach, coupled with operational disruptions wherever projects involve brownfield expansion. Construction safety is a significant challenge in brownfield refinery expansion projects due to the concurrent execution of multiple activities near operational units that handle hydrocarbon materials at high pressures and temperatures above their ignition points. To address these challenges, modular construction can be adopted as against the conventional stick-built approach. Modular construction is a method where modules are fabricated away from the project site, mainly in the contractor's yard, and assembled at the site. This study explores the feasibility and effectiveness of modular construction in brownfield petroleum refinery expansion projects in India. It assesses the benefits, challenges, and potential for modular construction to improve project timelines, reduce costs, enhance safety, and improve environmental sustainability. Through a case study analysis, site visits and interviews, and a related literature review, the study identifies key barriers to adoption, such as logistical issues, Engineering errors and modifications, and high initial costs. Additionally, the research compares modular construction with traditional methods regarding time, cost, and construction safety specific to execution in operating petroleum refineries. The study concludes by proposing recommendations for adopting modular construction into future refinery expansion projects in India to the extent possible. The findings target informing industry stakeholders on how modular construction can be leveraged to optimize project performance and contribute to the petroleum sector's growth by addressing specific challenges concerning construction safety in operating refineries.

Keywords: *Brownfield Petroleum Refinery Expansion, Modular Construction, Construction Safety, Project Management, Industrial Environmental Management.*

INTRODUCTION

India is emerging as one of the largest and fastest-growing economies in the world. India's energy demand is rapidly increasing due to population growth, industrialization, and urbanization. The petroleum sector is the backbone for meeting the country's energy needs, which makes petroleum refineries a cornerstone of India's economic development. Petroleum refining typically involves processing crude oil into various value-added products such as bitumen, fuel oil, lubricants, diesel, kerosene, gasoline (petrol), aviation fuel, LPG, and petrochemicals, which are essential for domestic consumption and export markets. Fig. 1 indicates a typical product slate of petroleum refinery.

India is Asia's second-largest crude oil refiner and fourth-largest globally, equipped with 22 operational refineries and a cumulative refining capacity of 256.8 MMTPA as of April 2024. (Petroleum Planning and Analysis Cell, 2024-2025). Petroleum refineries are crucial in converting crude oil into multiple value-added products to ensure energy security and support multiple industries, including manufacturing, transportation and agriculture. Petrochemicals, which are essential inputs for several industries, including automobile, plastics, textiles, and pharmaceuticals, are also produced from Refineries & Petrochemical complexes.

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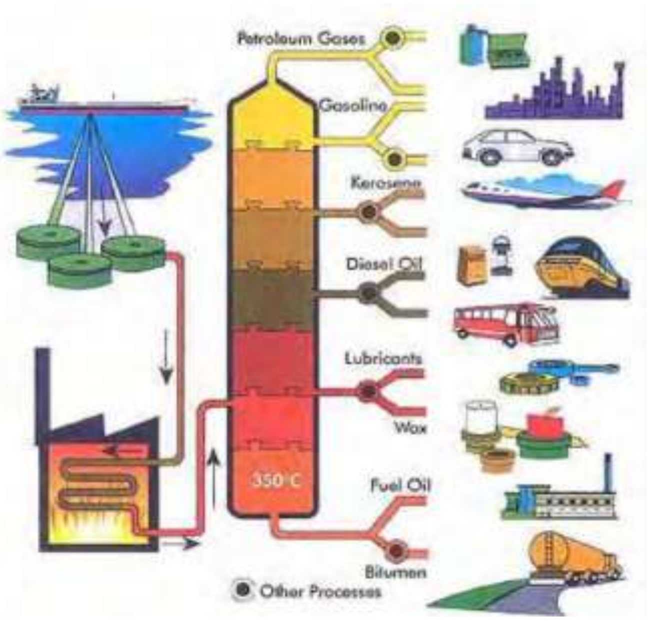

Fig 1. Typical product slate of petroleum refinery
Source: https://doe.gov.ph/sites/default/files/pdf/announcements/epower_06_03_energy_safety_ practices. pdf

India's petroleum refining sector will expand to 310 MMTPA by 2028. (Press Information Bureau, MoPNG, 2024). Both the options, viz. Greenfield and brownfield expansion are being explored by Indian Refineries to achieve this ambitious target. Greenfield projects mean constructing entirely new facilities at a completely new location without requiring any integration with any of the existing facilities at that particular location. Here, the owner has the freedom to create and develop a refinery with the latest global technologies and optimized efficiency. These projects provide more flexibility regarding layout, technology, and scalability. However, they also require significant efforts and investments in land acquisition as well as warrant completely new infrastructure development, including entire utilities and off-site facilities, along with the requirement of environmental clearances for the new location. Brownfield projects, on contrary, involve modifying, expanding, or upgrading existing facilities. Such projects are executed within existing facilities and alongside ongoing operations. This may involve revamp of older units, increasing capacity, or upgrading existing facilities by integrating new technologies (Visser & Brouwer, 2014).
Brownfield redevelopment also offers a unique advantage in transition to alternate energy sources from fossil fuels. Instead of building new facilities from scratch (greenfield development) which involves substantial capital investment including utility and off sites facilities, revamping existing facilities including those previously used for fossil fuel-related activities, can expedite the deployment of renewable energy and related technologies like petrochemical production with significant saving in investment. This approach fast-tracks the shift to renewable energy and optimizes the use of existing resources, leading to a more sustainable future for the petroleum sector. Basic infrastructure (e.g., access roads, power grid connections, water connections, and other utilities) is already available at existing site where brownfield projects are taken up. This can significantly shorten the time needed to establish petrochemical facilities or to deploy renewable energy projects within or adjacent to the premises. This faster deployment, on account of existing infrastructure of brownfield sites, is crucial for quickly scaling renewable energy generation and meeting climate goals (Adelaja et al., 2010). It also highlights that brownfield projects with their existing infrastructure, can benefit renewable energy development, especially in areas where availability of land and opposition from local communities substantially hinder new projects.
Indian Oil Corporation Limited, which is the flagship refiner in India's growing market, is undertaking massive capacity augmentation in its crude processing capacity. By 2030, with the ongoing expansions, Indian Oil's refining capacity is set to increase by a third- taking it from 80.8 MMTPA at present to 107.4 MMTPA (including its subsidiary CPCL). Fig. 2 (Indian Oil, Annual Report 2023-2024). Four out of five projects under implementation at IOCL involve brownfield refinery expansions—Fig. 3.

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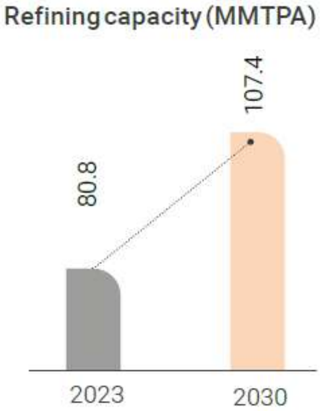

Fig 2. – Planned Expansion **Fig 3. – IOCL's Refinery expansion projects**

Source: Integrated Annual Report 2023-24 of Indian Oil Corporation Limited

Similarly, the majority of projects recently completed, such as Hindustan Petroleum Corporation Limited's Visakh Refinery Modernization Project (VRMP), which was dedicated to the Nation by the Honourable Prime Minister of India in March 2024 (Hindustan Petroleum, Annual Report 2023-2024) and all the three major ongoing projects by Bharat Petroleum Corporation Limited viz. Bina Petchem and Refinery Expansion Project (BPREP), Polypropylene Unit at Kochi Refinery, and De-Aromatized Solvents (DAS) Unit at Mumbai Refinery (Bharat Petroleum, Annual Report 2023-2024) involve substantial brownfield expansion in their existing facilities, focusing on integrating existing facilities with new units.

Executing brownfield projects, which involve expanding or revamping existing infrastructure, can be particularly complex. The careful and strategic management of project completion timelines, unplanned production downtime, and extended facility outages is essential to minimize disruptions to ongoing operations. This emphasizes the requirement of careful planning and precise execution in brownfield projects. Brownfield projects often involve the integration of new facilities with existing infrastructure, which presents unique challenges. (Visser & Brouwer, 2014) Highlights the difficulties in defining the scope and integrating changes driven by new facility standards in brownfield projects. (Visser & Brouwer, 2014) Further emphasizes the influence of poorly defined scope, limited accessibility to the project site, and work permit issues during the execution phase of brownfield projects. Multiple times, brownfield projects face challenges in terms of safety, as construction activities are conducted near operational units handling hydrocarbon materials under high pressure and temperature. In spite of so many challenges, brownfield projects also result in to substantial cost savings and provide options for integrating existing facilities for energy optimization and hence are considered more attractive as compared to green field developments.

Modular construction is one promising approach, which has gained traction recently (Shukla & Karki, 2015). Modularization is not a new concept. It has been widely used across various construction projects in the history. Over time, this topic is discussed and analysd, leading to its definition and interpretation in multiple ways to suit different situations and applications (O'Connor et al., 2014). Modular construction offers significant advantages in project efficiency, cost control, and schedule adherence. Modularization is the pre-construction of a complete facility away from the job site that is transported to the site in smaller parts called modules. Sometimes these modules are large in size and possibly may need to be further divided into multiple smaller pieces for transport" (Haas et al., 2000). Modular construction minimizes on-site work, reduces construction time, and improves quality control by fabricating large sections or entire processing units in a controlled factory environment. This approach is well-suited for remote locations or areas with limited accessibility, where conventional stick built construction methods can be challenging and expensive. (Worley, 1973) emphasizes modular construction's cost and time savings for offshore and remote locations, highlighting the benefits of pre-assembly and factory testing. Modular construction substantially reduces risks associated with conventional construction activities within operating refineries, streamlines project execution, and ultimately contribute to a more cost-effective and timely completion of refinery revamp projects.

In addition to operational and economic advantages, modular construction in brownfield refinery projects offers significant environmental benefits. By reducing the volume and duration of on-site activities, modular construction minimizes local air and noise pollution, lowers the generation of construction waste, and reduces traffic congestion around sensitive industrial sites. These improvements contribute to better environmental health outcomes for workers and surrounding communities. Furthermore, off-site fabrication allows for more efficient use of materials and energy, supporting sustainable construction practices in line with circular economy principles. In an era where industrial environmental management and climate-conscious development are national priorities, integrating modular construction methods into refinery expansions aligns with India's broader goals for reducing industrial emissions and enhancing environmental compliance in hazardous zones.

OBJECTIVES

This study targets to discover the major challenges encountered during brownfield refinery expansions in India, including difficulties in conventional construction practices such as extended timelines, cost overruns, and safety hazards. The research further aims to assess the feasibility of modular construction as an alternative approach, focusing on its potential applicability within the Indian petroleum refining industry. Additionally, it seeks to analyse the advantages of modular construction and identify the challenges in adopting it. Finally, the study aims to propose actionable recommendations for successfully integrating modular construction into future refinery expansion projects aligning with the growth objectives of the petroleum sector in India.

METHODS

This research adopts a mixed-methods approach mainly focusing on case study analysis in order to assess the effectiveness of modular construction in brownfield refinery expansion projects in India. The study begins with a selection of case and its analysis along with comprehensive literature review to find the difficulties associated with conventional stick-built construction methods and the potential benefits and barriers to adopting modular construction. Experts including industry professionals, including site engineers, project managers, and safety supervisors, were interviewed to gather insights into practical experiences and opinions on modular construction. A case study analysis is carried out to compare modular and traditional construction methods in terms of time, cost, and safety outcomes. Based on these insights, recommendations are developed for successfully implementing modular construction in the Indian petroleum industry.

The brownfield project selected for case study involved the construction of new solvent production facilities closely integrated with existing refinery units located in the heart of the Metro city.

The project involves installing hydrocarbon processing equipment like a Reactor, Compressor, Pumps, coolers, etc., interconnected with multiple pipelines, electrical power cables, and instruments. Since the new facility was to be integrated with existing refinery units, it had to be constructed very close to an operating hydrocarbon processing plant handling hydrocarbons at high pressures and temperatures exceeding its ignition temperature. The scope of work for this brownfield project included deep excavation up to 5 meters, laying civil foundations, lifting and installing heavy equipment using cranes, and—most critically—welding structural components and pipelines, which generates sparks and poses significant risks due to the nearby presence of pressurized flammable materials. What added to the challenge was that all of this had to be executed without shutting down the ongoing operations. This demanded meticulous planning and flawless execution to maintain the highest safety standards. Considering the operational hazards and complexity of the environment, modular construction was identified as the most practical and safe method to move forward efficiently. As a result, modular construction was mandated as the optimal solution for executing this critical project. Fig. 4. shows the Google Earth image of the Project Site surrounded by operating units.

Fig. 4. – Google Earth image of the Project Site surrounded by operating units

RESULTS

This chapter presents the key challenges identified during the execution of brownfield refinery expansion projects, as revealed through the research. Major issues such as extended timelines, cost overruns, and elevated safety risks were observed to be intrinsic to working within constrained and operational refinery environments. A comparative assessment of on-site versus off-site work conditions highlights the efficiency gaps, with modular construction emerging as a viable strategy to mitigate these challenges.

Challenges envisaged in the brownfield refinery expansion projects

Extended Timelines

The expansion of brownfield refinery projects presents a unique set of challenges, and one of the most significant hurdles is the issue of extended timelines. Brownfield projects, by their very nature, involve working within the constraints of existing facilities and ongoing operations, which can significantly complicate the project execution process (Visser et al., 2015)

Petroleum refinery operating areas are designated as prohibited zones due to hazardous materials, critical processes, and potential of catastrophic incidents. These areas are subject to strict regulatory controls, with access highly restricted and governed by stringent security protocols. Comprehensive checks are required for personnel and materials before entry is permitted, ensuring compliance with safety and security standards. As a result, moving manpower and equipment into these installations is time-intensive, often causing delays in daily operations. The restricted nature of these locations, coupled with the need to coordinate activities around ongoing operations, significantly limits the number of working hours available for construction tasks within operating refineries. This limitation reduces the pace of on-site work and impacts overall project efficiency, often leading to extended timelines for completion. In contrast, contractor-operated fabrication yards located off-site are free from such restrictions, allowing for extended and uninterrupted work schedules, thereby enabling greater productivity and efficiency in preparatory activities.

A comparative analysis of actually available net working hours within an operating petroleum refinery out of 12 Hr shift, as against contractor-operated fabrication yards located off-site indicates an improvement of more than 40% in the production efficiency of the skilled workforce.

Table 1

SR No	Activity	Operating Refinery	Fabrication Yard
A)	Entry gate to Project site[a]	1 Hr	15 Minutes
B)	Issue of Work Permit at start of work[b]	1 Hr	15 Minutes
C)	Lunch break[c]	1.5 Hr	45 Minutes
D)	Renewal of work permit at shift change[d]	1 Hr	NIL
E)	Cumulative working hours lost (A to D)	4.5 Hr	1.25 Hr
	Available working hours (12 - E)	7.5 Hr	10.75 Hr

a. Due to the potential for sabotage or terrorist attacks, petroleum refineries require robust security measures and restricted access which requires thorough scanning of all individuals at the entry point. Further, the project sites within refineries are far away from entry point where outside vehicles do not have a free access leading to delay.

b. Refineries handle highly flammable and explosive substances and hence required to follow stringent work permit protocols which requires thorough scanning of site parameters including tests to check presence of hydrocarbon / poisonous gas vapours before starting of work leading to delay which is not necessary for fabrication yards.

c. Project sites being in close vicinity of operating areas, workmen rest rooms are often located far away from the site in safe area owing to which additional time is spent in commuting from project site to rest area and back during lunch breaks.

d. Permit issuing authorities in operating refineries generally issue work permits for standard 08 Hr shifts, which need to be renewed at the end of the shift leading to stoppage of work and loss of productivity.

Fig. 5 depicts how modularization can help reduce the effective timelines for construction within operating units by almost 75% (3 against 12) with modularization for a small-scale project with overall time efficiency.

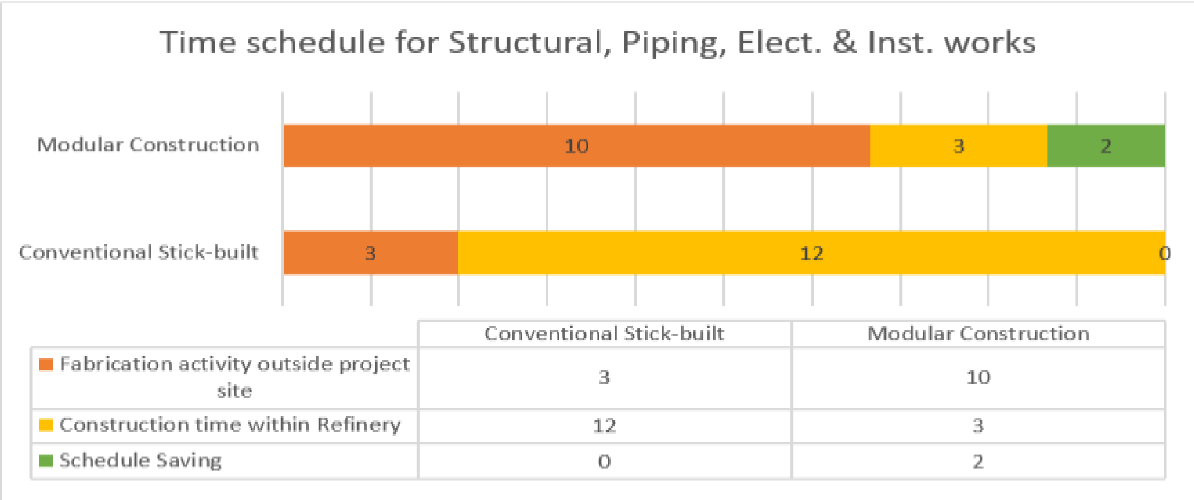

Fig. 5 – Comparison of timelines for Modular vs Stick-built construction

Hence, modularization emerges as a highly effective solution to address the challenges of limited working hours in operating refineries.

Cost Overruns

Brownfield projects involving existing refinery expansions / integration are naturally complex undertakings that often face the persistent challenge of cost overruns. This issue is frequently associated with extended timelines, as the project execution must face the constraints and complexities posed by the presence of existing facilities and ongoing operations. (Visser & Brouwer, 2014)
Accurately defining the project scope in the beginning is a significant challenge in these types of projects, as the project team must deal with a range of factors, including the current condition of the facilities, the process constraints, and the restrictions on executing the planned work, all of which can be difficult to anticipate fully. (Visser & Brouwer, 2014) As a result, estimates and schedules may be based on incomplete information or unreliable analogs, leading to unexpected increases in costs and delays during the execution phase. (Visser et al., 2015)
The restriction on working hours, as detailed above, not only slows the pace of on-site work, leading to extended project timelines, but also result in increased cost of labor on account of retaining workforce over longer durations. The constrained schedule also necessitates prolonged hiring of machinery and equipment, which inflates rental and operational expenses. Additionally, extended timelines result in cost escalation due to inflation, increased material prices, and other time-related expenses, further exacerbating the financial impact. Together, these factors significantly escalate the overall project cost.
Early engineering and establishing a clear modular philosophy enable accurate cost estimation. Furthermore, since most fabrication activities are conducted away from operational sites, the uncertainties associated with working hours and potential delays in execution can be minimized, thereby helping to prevent cost overruns. Hence, embracing modular construction can significantly mitigate the risk of cost overruns.

Safety Risks
Safety risks pose a significant challenge in the execution of brownfield refinery expansion projects, as the introduction of new equipment, processes, and personnel into an existing operational environment can introduce a complex array of potential hazards. One of the primary safety concerns in such projects is the potential for equipment failure or process disruptions, which can lead to the release of hazardous materials, explosions, or other catastrophic events. (Cigolini & Rossi, 2010). Petroleum refineries typically handle a range of flammable oil and gas at high pressures, and the intricate nature of their operations means that any untoward incident can have serious, unpredictable consequences. (Cigolini & Rossi, 2010).
Minimizing site work is one of the most effective strategies for mitigating safety risks during the execution of such projects. Transferring as much fabrication and assembly work as possible to off-site locations minimizes the risk of accidents associated with simultaneous operations (SIMOPS). This not only protects workers from exposure to high-risk conditions but also reduces the likelihood of unplanned releases of hydrocarbons or other pollutants into the environment, which can have long-lasting ecological and public health impacts. Therefore, modular construction enhances both occupational safety and environmental protection, making it a responsible and sustainable approach for brownfield refinery expansions.

Challenges in Adoption of Modular Construction
Logistics
The success of modular construction in refinery projects mainly depends on logistics. How well the transportation, storage, and handling of modules are managed can have a major impact on both the project schedule and overall cost. One of the main logistical challenges involves transporting large, heavy modules from fabrication facilities to construction sites, often located in remote or sometimes in heavily populated areas. This requires meticulous planning considering the dimensions and weight of the modules, as well as to meet regulatory requirements for road restrictions, permits, and escort vehicles (Müller et al., 2020). The delivery process also demands careful scheduling to minimize disruptions at the site, as well as overcrowding at both locations, shop and site due to space constraints. It also need to take into consideration the complex construction schedules with stringent deadlines. Coordinating multiple deliveries necessitates clear communication between transport companies and site managers to ensure that the right modules arrive on time, thus preventing delays that could affect the entire project timeline (El-Wardany et al., 2018).

Fig 6. – Google map snap of the Project site and Module assembly area

Storage and handling logistics present difficulties, as limited on-site space can restrict the ability to store several modules simultaneously. Ensuring that modules are not damaged during transport or storage is critical, necessitating appropriate rigging, loading, and unloading techniques and carefully selecting transportation routes to minimize risks (Zheng et al., 2019).

The present project site was situated in the heart of the metro city. Hence, transportation of modules became more challenging. The route survey was carried out from the nearest port, and the maximum size of the module that could have been transported was restricted to 5 Meters X 5 Meters X 24 Meters. Considering this challenge, it was decided to fabricate structural members and pipe spools outside in the contractor's fabrication yard and assemble them in modules within the refinery at around 1000 meters from the actual project site. Fig. 6.

Engineering Errors and Modifications

Modular construction is often associated with unique engineering challenges. Advanced engineering expertise is required for designing transportable and easily assembled modular systems while maintaining structural integrity both during transportation as well as construction (Pakkanen et al., 2018). This is further complicated by potential modifications or changes during the construction process, which can be more challenging in a modular framework. (Pakkanen et al., 2018). To address this issue, a detailed 3D model was developed during the engineering stage of the project including defining modules. 3D modeling in modular construction is critical in ensuring precision and minimizing errors. By creating detailed and accurate virtual representations of the project, 3D modeling allows for comprehensive visualization of all components, enabling concerned stakeholders to identify and address potential issues early in the design phase. This collaborative review process facilitates better communication among clients, consulting engineers, and contractors, ensuring alignment on design intent and technical requirements. By resolving conflicts and refining designs before construction begins, 3D modeling significantly reduces the risk of costly engineering errors and on-site modifications, streamlining the construction process through well-defined modules and enhancing overall project efficiency. Fig. 7 shows the snapshot of the 3D model prepared for the project.

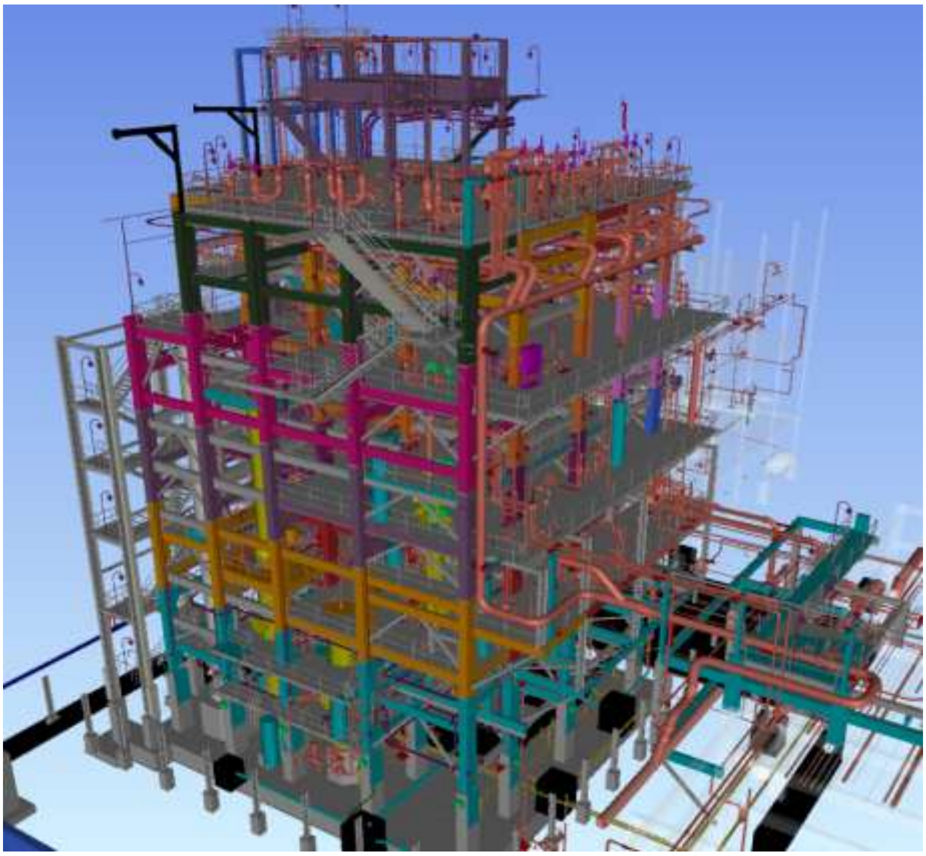

Fig. 7 - The snapshot of the 3D model

High Initial Cost

Significant challenge in adopting modular construction for petroleum refinery projects is the escalation of costs associated with fabrication and erection, driven by increased structural quantities and the complexities involved in transporting and installing heavy modules. With the increase in size and scale of modular components, during the fabrication itself additional materials and labor are required, resulting in higher upfront expenses (Hwang & Ng, 2013). The transportation of these large modules also brings logistical challenges that further increase costs, as specialized transportation equipment are often necessary to navigate the roads safely (Müller et al., 2020). Meticulous scheduling and coordination are essential to ensure that modules arrive on site in the manner that, they can be installed immediately, which helps minimize downtime and avoids costly delays (El-Wardany et al., 2018). Furthermore, the erection of these larger modules also requires adopting advanced lifting and handling equipment, leading to increased costs and additional safety considerations (Zheng et al., 2019). These factors emphasize the importance of conducting thorough cost analyses and logistical planning to effectively mitigate the financial implications of modular construction in refinery projects.

However, the primary benefit of adopting modular construction techniques in the context of refinery projects is the enhanced cost-effectiveness that this approach can deliver. Modularization allows for prefabricating key components off-site, significantly saving material costs and on-site labor expenses. (Naqvi et al., 2014) By fabricating modules in a controlled environment within contractor's fabrication shops, companies can leverage economies of scale, streamline the procurement process, and minimize the need for specialized on-site workers, all of which contribute to overall cost reductions. (Silva & Campos, 2019)

Additionally, the reduced on-site construction time associated with modular construction can lead to substantial cost savings by minimizing the duration of facility shutdowns and downtime. This is particularly relevant in the refinery industry, where unplanned disruptions can have significant financial consequences. Furthermore, the improved quality control and standardization inherent in modular construction can help to avoid costly rework and defects, further enhancing the cost-effectiveness of this approach. (Silva & Campos, 2019).

RECOMMENDATIONS

1. Prioritize modular construction as the preferred strategy for refinery expansions to overcome challenges associated with traditional construction methods. Prefabricating units off-site not only reduces on-site work and mitigates risks from restricted working hours but also minimizes air and noise pollution, construction waste, and safety hazards near sensitive operating units.
2. Develop comprehensive project scopes and detailed engineering designs using advanced tools like 3D modeling. This approach minimizes engineering errors, ensures precision, and facilitates flawless integration with existing facilities.
3. Conduct detailed route surveys and logistics planning to ensure smooth transportation of modules. Establish local module assembly areas, as demonstrated in the case study, to mitigate logistical challenges and accommodate site-specific constraints.

CONCLUSION

The significant and fast-paced expansion of India's petroleum refining sector presents both opportunities and challenges. While conventional stick-built construction methods continue to face hurdles such as extended timelines, cost overruns, and safety risks, especially near operational units, modular construction emerges as a transformative approach. By relocating fabrication and assembly to controlled off-site environments, modularization addresses key limitations of brownfield projects—including restricted working hours, complex site conditions, and safety hazards.

Beyond these operational advantages, modular construction also contributes to environmental sustainability by reducing on-site emissions, minimizing construction waste, and lowering the ecological footprint of infrastructure expansion.

The successful implementation of modular construction depends on detailed early-stage planning, digital integration, robust logistics, and a strong commitment to safety, quality, and environmental performance. Although initial capital costs may be higher, the long-term benefits—accelerated timelines, improved safety, reduced environmental impact, and enhanced project efficiency—make it a forward-looking and responsible strategy for modern refinery expansions.

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