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# DYNAMIC MATERIAL MANAGEMENT FOR IMPROVED MULTI-CRANE OPERATIONS

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***SUMMARY***: *Inefficient multi-tower crane operations are a persistent source of delay, cost overruns, and safety risks in complex projects. These inefficiencies are influenced by many interacting factors. While building on prior research in crane motion path flexibility and dynamic supply selection, this research advances crane operations by integrating dynamic material management planning with the established agent-based modeling (ABM) methods. It introduces Agent-Based Dynamic Material Planning (ABDMP), a heterogeneous material management framework that dynamically reallocates materials in various supply points for crane operations within overlapping areas. Through scenario generation and simulation analyses, ABDMP identifies optimal material supply setups and reallocation strategies that improve crane utilization, reduce idle time, and shorten project durations compared to traditional methods. A detailed case study provides analytical evidence of its benefit: reductions in total schedule time and improvements in crane efficiency as material flexibility increases. By tackling a previously unaddressed gap related to how to systematically and flexibly manage material flows in multi-crane environments, this research advances construction operations planning, especially with crane operations. While acknowledging implementation challenges in practices, as a pilot research study, the framework offers a scalable and practical tool for enhancing safety, efficiency, and reliability in complex, high-risk construction environments.*

***KEYWORDS***: *material management, agent-based modelling, case study, multi-crane planning.*

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# 1. INTRODUCTION

Effective crane utilization can significantly enhance construction project performance, particularly when employing various types of cranes (Karmakar et al., 2022; Marzouk & Abubakr, 2016; Wang et al., 2021), such as tower cranes, which are commonly used in high-rise projects (Wang et al., 2021; Moussavi Nadoushani et al., 2016). Tower cranes play a crucial role in transporting heavy materials, including steel beams, ready-mixed concrete, formwork, and preassembled modules, both horizontally and vertically (Tam & Tong, 2003; Irizarry & Karan, 2012; Kluck & Choi, 2023). By efficiently moving materials from supply points to designated work areas, tower cranes facilitate scheduled labor activities, ensuring project timelines are maintained without disruptions (Al Hattab et al., 2017).

The prominence of tower cranes in construction projects, especially for high-rise and large-scale structures, cannot be overstated due to their essential role in material transportation and their impact on project success metrics (Marzouk & Abubakr, 2016; Wang et al., 2021; Al Hattab et al., 2017; Kaveh & Vazirinia, 2018). Rider Levett Bucknall (RLB) reports the use of tower cranes has gained increased attention, which document rising crane counts across major cities in North America and globally, with the exception of certain years affected by external factors like COVID-19 (Rider Bucknall, 2019 a; Rider Bucknall, 2020; Rider Bucknall,2019 b; Kwan, 2022; Sewell, 2021; Schiafone, 2021). This growth highlights the industry's reliance on tower cranes to meet demands in urban construction, where managing complex logistical and operational challenges is paramount. However, tower cranes are also among the riskiest equipment on construction sites, as shown by numerous incidents and fatalities associated with crane accidents (Sadeghi et al., 2021; Hegeman, 2020; U.S. Bureau of Labor Statistics, 2017; Kone Cranes Training Institute, 2022). These statistics underscore the critical need for a carefully structured crane management plan that prioritizes both productivity and safety standards.

Efficient tower crane planning involves detailed considerations, including the number, type, and positioning of cranes, as well as factors related to material flow and storage logistics (Hu et al., 2021; Al Hattab et al., 2017; Younes & Marzouk, 2021). In large-scale projects, the deployment of multiple cranes is a practical approach to managing activities, though it introduces potential conflicts, especially when cranes operate in overlapping areas (Al Hattab et al., 2017; Sadeghi et al., 2021; Khodabandelu & Park, 2021; Younes & Marzouk, 2018). Most previous research on multi-crane planning either oversimplified overlapping zones or handled crane clashes inefficiently (Marzouk & Abubakr, 2016; Irizarry & Karen; 2012; Kaveh & Vazirinia, 2018; Abdelmegid et al., 2015; Zhang et al., 1999; Alkriz & Mangin, 2005; Tam & Tong, 2003; Lien & Cheng, 2014; Huang et al., 2011; Wang et al., 2015). We term the developed approach Agent-Based Dynamic Material Planning (ABDMP). ABDMP operationalizes dynamic, heterogeneous material allocation across overlapping crane zones via rule-based, iterative re-planning within an ABM environment.

With insights from the literature review and limitations identified in prior studies, it is clear that there is a need for a dynamic material management model that optimizes both crane utilization and material distribution in multi-crane environments. Building on earlier work while extending it to incorporate heterogeneous supply points, material inflow/outflow strategies, and explicit scheduling, this study frames its investigation around the following research questions:

1. Design and Implementation: How can a heterogeneous, dynamically managed supply system be designed to integrate material inflow/outflow with multi-tower crane operations, and what decision rules enable its effective implementation within an ABM framework?

2. Performance Impact: To what extent does dynamic material allocation across multiple supply points improve crane utilization rates and reduce project durations compared to static material management approaches?

3. Trade-offs and Evaluation: What trade-offs arise between increased flexibility at supply points and the added complexity of implementation, and how can scenario-based simulations reveal optimal balances for practical construction projects?

# 2. LITERATURE REVIEW ON MATERIAL MANAGEMENT

Research on material management in construction has traditionally focused on procurement and delivery logistics. For instance, Said and El-Rayes (2011) examined how optimizing material order timing can reduce waste and cost, while Ajayi et al. (2017) explored procurement strategies that align deliveries with project sequencing.

Hadikusumo et al. (2005) introduced an Internet-based agent system for procurement and demonstrated early interest in digital solutions. However, these studies largely focus on pre-site logistics by considering materials before they reach the construction site.

Technological solutions for material visibility have also been explored. El Ghazali et al. (2012) studied RFID applications for tracking material deliveries, and Kwon et al. (2017) evaluated barcode systems for monitoring on-site flow. While these tools improve delivery accuracy, they rarely address how materials are stored, redistributed or reallocated after they arrive on site.

Inventory and storage practices have received attention as well. Donyavi and Flanagan (2009) linked poor material handling to productivity losses in small and medium enterprises. Thomas and Ellis (2017) studied structured inventory controls, and Patil and Pataskar (2013) assessed FIFO (first in first out) and LIFO (last in first out) handling strategies. Kumar (2018) further identified mismanaged inventory as a cause of resource conflicts. Although these studies advanced storage and handling methods, they remain yet disconnected from crane operations.

*Table 1: A summary of past literature.*

| References | Optimization variables | Objective function |
|---|---|---|
| Abdelmegid et al. (2015) | Tower crane locations | Minimize total crane travel distance |
| Huang et al. (2011) | Tower crane and supply point locations | Minimize travel time/distance |
| Zhang et al. (1999) | Tower crane locations | Minimize overall operational cost |
| Tam et al. (2001) | Supply locations | Minimize hook travel time |
| Tam & Tong (2003) | Crane and supply point locations | Minimize operation time |
| Irizarry & Karan (2012) | Tower crane locations | Improve placement efficiency |
| Kaveh & Vazirinia (2018) | Crane and supply point locations | Reduce cost/time |
| Li et al. (2018) | Attached tower crane and supply point locations | Minimize transport distance |
| Marzouk & Abubakr (2016) | Tower crane selection | Minimize cost & improve efficiency |
| Lien & Cheng (2014) | Supply/demand optimization | Balance material flows |
| Moussavi Nadoushani et al. (2016) | Crane location and supply allocation | Minimize operating & rental costs |
| Said & El-Rayes (2011) | Procurement timing & storage planning | Minimize cost and congestion |
| Ajayi et al. (2017) | Procurement strategy | Minimize waste, align with sequencing |
| Hadikusumo et al. (2005) | Internet-based procurement agent system | Minimize procurement delays |
| El Ghazali et al. (2012) | RFID tracking | Improve delivery visibility, reduce delays |
| Kwon et al. (2017) | Barcode systems | Improve accuracy of material flow |
| Donyavi & Flanagan (2009) | On-site material management | Minimize productivity losses |
| Thomas & Ellis (2017) | Inventory/storage strategies | Improve site-level material efficiency |
| Patil & Pataskar (2013) | FIFO/LIFO storage systems | Optimize on-site handling |
| Kumar (2018) | On-site material management | Minimize conflicts, improve utilization |

Research that directly connects crane to material logistics is available but limited. Tam and Tong (2003) used genetic algorithms to optimize crane and supply point placement, while Huang et al. (2011) applied mixed-integer programming to minimize crane travel distances. Moussavi Nadoushani et al. (2016) factored in cost components (operational and rental costs) for supply point selection. These studies advanced location optimization but assumed fixed supply locations and static material allocations, limiting adaptability to evolving site conditions, especially for multi-crane operating condition within crane overlapping zones.

More recent research attempted to integrate crane operations with layout planning. Younes and Marzouk (2018) used agent-based simulation to consider activity conflicts, and Khodabandelu et al. (2023) introduced flexibility in crane motion paths. Yet, even these contributions continued to treat supply points as static buffers rather than dynamic resources. Table 1 summarizes past research with respect to considered variables and objective context. This summary empathizes the needs of more research to address the inadequacy of past research in this interplay among crane operation, overlapping areas, materials, and supply points in the view of dynamic planning.

Therefore, an unresolved research gap exists as prior studies rarely link material inflow and outflow at supply points with evolving crane schedules in overlapping operational zones. To address this, our study introduces a heterogeneous supply system governed by agent-based rules, allowing supply points to adapt dynamically to crane demands. By coupling material management with crane task planning, we offer a framework that improves operational flexibility, reduces idle time, and enhances efficiency in multi-crane environments.

## 3. OBJECTIVE AND SCOPE

This research aims to develop a material management plan for a multi-tower crane deployment. As acknowledged, past studies assumed types of materials and their sufficiency in supply points, thereby overlooking the potential benefits of dynamic material providence from multiple supply points in a holistic view. This research, therefore, further enhances the performance of multi-tower crane operation boosted by past work in crane planning and layout planning, with a specific focus on overlapping areas for maximized benefit. Consequently, this research develops ABDMP for multi-tower crane deployments, linking material inflow/outflow with crane operations under overlapping coverage.

In this study, a heterogeneous supply system refers to the allocation of multiple material types across supply points within a construction site, enabling cranes to dynamically access a variety of materials. This contrasts with traditional homogeneous systems, where each supply point is restricted to a single material type. A single case study is used to test various scenarios, providing insights into the impact of this approach on overall project efficiency. Although designed for tower cranes, the methodology can be adapted with minimal modifications to other fixed-base cranes, making it suitable for large-scale construction projects requiring multi-crane deployment.

The approach is applicable to large scale construction projects where multi-tower cranes are to be deployed. With a focus on dynamic material management at supply points, the research adopts state-of-the-art approaches of the past in crane operations (Khodabandelu et al., 2020) and layout planning (Khodabandelu et al., 2023) as verified methodology for executing crane motions. ABDMP is used for effective integration of algorithms and procedures. While this approach is developed for a tower crane, other cranes that share the characteristics of operation at a fixed base should be able to adopt, with a few necessary modifications, the developed approach for potential performance enhancement.

## 4. METHODOLOGY

This section outlines the methodology, as shown in Figure 1, for developing an operational plan centered on material management in multi-tower crane construction projects where overlapping areas are allowed when safety is not compromised. Utilizing an ABDMP approach, the methodology begins by defining the agents, including their attributes, behaviors, and interactions. Next, considering system input (e.g., construction and site information, tasks, and crane specifications) all possible interaction scenarios are designed to ensure the completion of tasks from start to finish. Building on prior research in operational and layout planning, this study focuses on material management planning, incorporating flexibility in material placement across available supply points within the construction site.

The methodology facilitates multi-crane operations by allowing movement in overlapping areas, leveraging ABDMP's adaptability in agent behaviors to optimize efficiency. This process is iterated across all scenarios to identify the optimal strategy for effective material management in multi-tower crane operations.

It assumes that tower crane locations and the specifications of supply and demand points are predetermined, as discussed in previous sections and investigated in past studies. The primary aim of this section is to strategize material availability and usage during construction to facilitate smooth crane operations in accordance with the operational plan. The subsequent subsections introduce the material management planning model developed in this research and demonstrate its significance through a case study on effective material planning in construction projects.

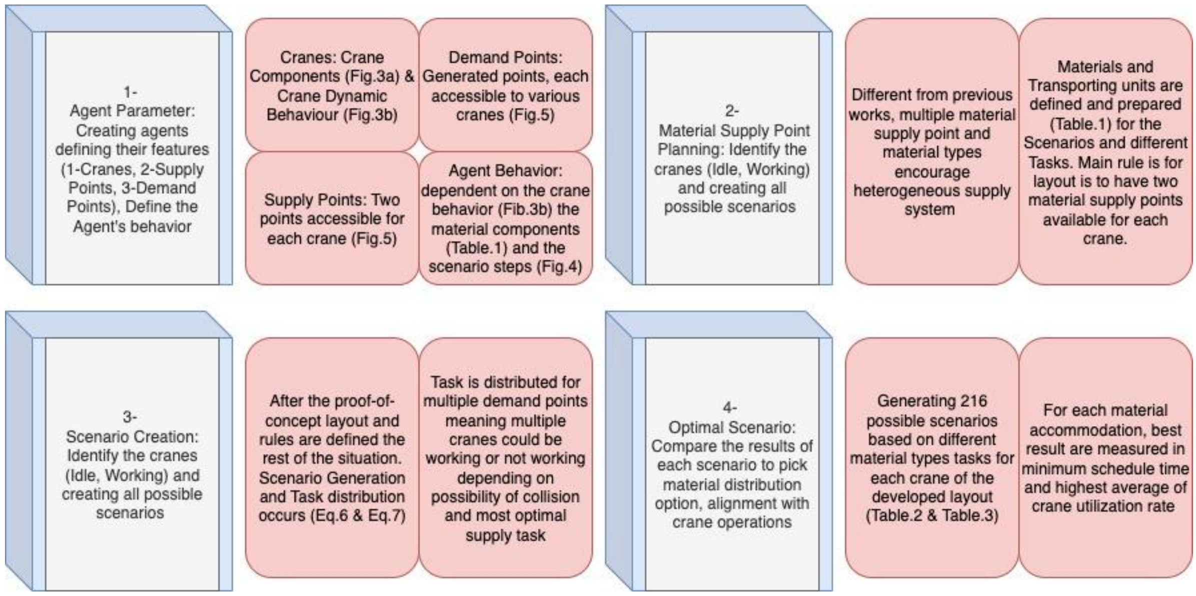



*Figure 1: ABDMP workflow: (1) Agent definition, (2) Scenario generation & task distribution, (3) Dynamic material allocation & scheduling, (4) Scenario evaluation & selection, with iterative re-planning.*

## 4.1 ABM model components

This study employs ABM to simulate interactions among tower cranes, supply points, and demand points on construction sites, focusing on material storage planning while respecting operational, and layout planning from the most relevant past ABDMP research. Figure 2 illustrates the types of agents, their networks, and the key features incorporated in this study. These agents and rules implement ABDMP by enabling state-dependent reallocation decisions.

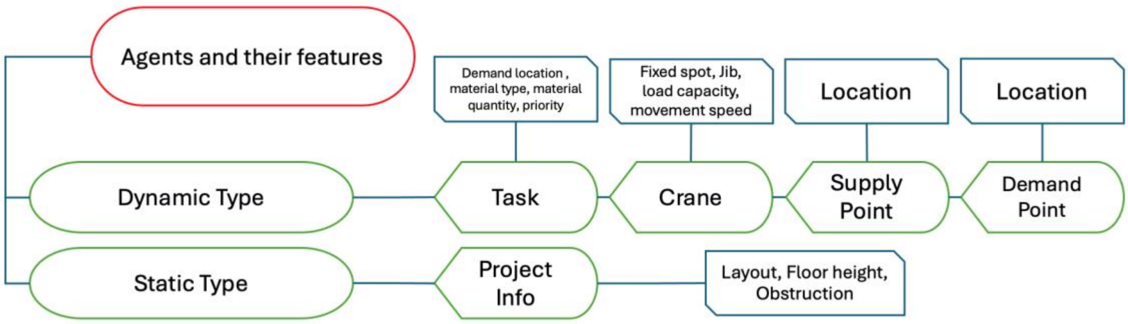



*Figure 2: Agent types and their features.*

Developed on a Java-based platform, the framework models key agents such as materials, supply points, demand points, tasks, and tower cranes, each with distinct attributes such as location, capacity, or task lists. By simulating various scenarios, the framework identifies optimal configurations to enhance planning and operational efficiency. The model provides a comprehensive approach to addressing construction challenges by leveraging agent characteristics to improve task coordination and material flow.

The model comprises three fundamental elements:

- A simulation environment visualizing the construction site;
- Agents with distinct characteristics and behaviors;
- Rules governing agent interactions and environmental constraints.

The model incorporates five primary agents, each with static (fixed) and dynamic (changing) characteristics:

- Materials: Materials are characterized by their type (e.g., ready-mix concrete, prefabricated panels), minimum transportable batch load, and loading/unloading pace based on crew efficiency;
- Material type: The specific category of construction materials, such as wood panels, ready-mix concrete, steel beams, and others;
- Material minimum batch: The smallest transportable component of a material type; for example, a steel beam cannot be cut into half, so one full-size beam is considered as the minimum batch for steel beams;
- Supply Points: Supply points are defined by their cartesian coordinates, permitted material types, and storage capacity limitations;
- Position: The geometric position of the center of a storage area;
- Permitted Material Type: The types of materials that can be stored in a storage area; due to capacity and spatial constraints, some storage areas cannot store specific material types or a certain combination of material types;
- Capacity: Maximum storage size of a storage area based on its spatial dimensions;
- Demand Points: Demand points are identified by their cartesian coordinates, representing delivery locations for required materials;
- Tasks: Each crane lifting task is defined by four main parameters. They are 1) target demand point location, 2) material specifications (type and quantity), 3) priority level (scale of 1-5, with 1 being highest), and 4) status (outstanding, initiated, or completed).
- Tower Cranes: Tower cranes exhibit several unique characteristics critical in this research. They are 1) fixed jib length determining coverage area, 2) load capacity specifications, 3) operational velocities for different movements, 4) base location coordinates, 5) operational status (idle/operating), 6) task list capabilities and 7) outstanding task inventory.

The model utilizes these agents and their characteristics to simulate various scenarios, enabling the identification of optimal configurations based on predetermined criteria.

## 4.2 Operational and layout planning

It is important to note that the focus of this research is to examine material placement strategies for multi-crane operations for large construction projects, using ABDMP. In this examination, it is imperative to use operational and layout planning methods available within ABDMP environments. Adopted by the past ABM work of crane operations (Khodabandelu et al., 2020) and layout planning (Khodabandelu et al., 2023), this study uses models the ABM key agents and their parameters.

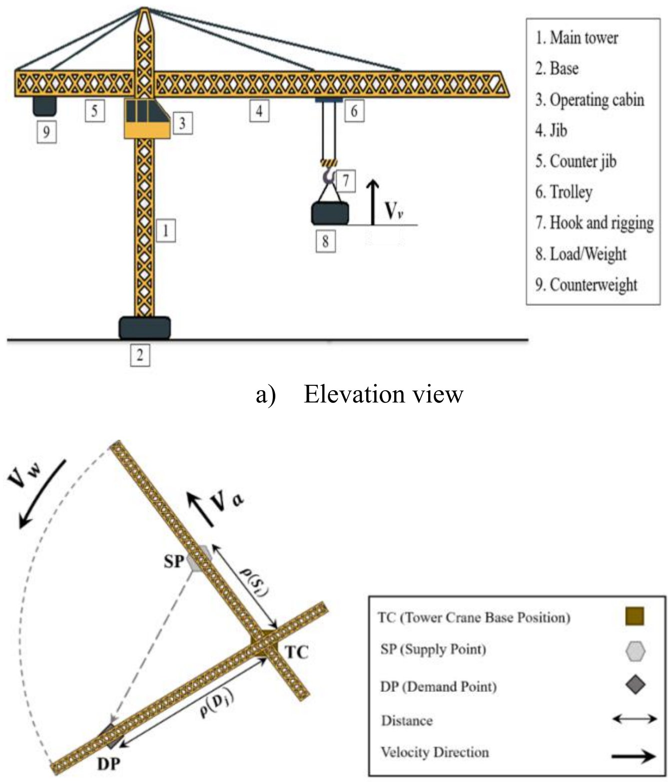
Figure 3 presents a pictorial description of key parameters defined above in both elevation and top-down views.

The following describes each parameter's information within ABM modeling.

- Crane location: denoted as $(X, Y, Z)$ for the coordinates of the crane
- Supply location: denoted as $\left(X_{S_i}, Y_{S_i}, Z_{S_i}\right)$ for the coordinates of supply location $i$
- Demand location: denoted as $\left(X_{D_j}, Y_{D_j}, Z_{D_j}\right)$ for the coordinates of demand location $j$
- Horizontal distance between supply location and crane: noted as $\rho(S_i)$, which varies over time
- Horizontal distance between demand location and crane: noted as $\rho(D_i)$, which varies over time
- $V_v$: Hoisting vertical velocity of hook
- $V_a$: Radial velocity of trolley
- $V_w$: Slewing velocity of jib

The other parameters associated with various calculations are as follows:

- $T$: Total time of hook travel from supply location $i$ to demand location $j$
- $T_h$: Time of hook horizontal movement
- $T_v$: Time of hook vertical hoisting movement
- $T_a$: Time of trolley radial movement
- $T_w$: Time of jib slewing movement
- $L_{ij}$: Distance between supply location and demand location
- $\alpha$: Degree of simultaneous horizontal movements between the trolley and the jib
- $\beta$: Degree of simultaneous vertical and horizontal movements among the hook, trolley and jib.




a) Elevation view

b) Top-down view

*Figure 3: Crane views with key parameters in modeling.*

The following equations (EQ 1 - 5) are used to compute various time parameters shown above.

$$T_a = \frac{|\rho(D_j) - \rho(S_i)|}{V_a} \tag{1}$$

$$T_w = \frac{1}{V_w} \times Arc\cos\left(\frac{-L_{ij}^2 + \rho(D_j)^2 + \rho(S_i)^2}{2\rho(S_i).\rho(D_j)}\right) \qquad (0 \leq Arc\cos(\Theta) \leq \pi) \tag{2}$$

$$T_h = \max(T_a, T_w) + \alpha \times \min(T_a, T_w) \tag{3}$$

$$T_v = V_v \times |(Z_{S_i} - Z_{D_j})| \tag{4}$$

$$T = \max(T_h, T_v) + \beta \times \min(T_h, T_v) \tag{5}$$

With these operational and layout planning model details, this study further integrates material management aspects to fill the gap resulting from an oversight of material management in a holistic approach. We claim that this aspect is critical because crane operation, crane layout and material management for supply and demand points for cranes heavily depend on each other, impacting the overall project performance.

The integrated model maximizes the benefits of dynamic agents' interactions and their behaviors to optimize crane operations in overlapping areas. The methodology begins with defining agents, such as cranes, tasks, supply points, and demand points, and incorporates their interactions into a dynamic simulation environment. This simulation accounts for factors such as task priorities, crane capacities, potential collisions, and material types. The ABDMP uses a dynamic supply selection system that identifies the most efficient supply point for each task, optimizing crane utilization and minimizing total project time. The model repeatedly evaluates various scenarios to ensure safe and efficient crane operations, leveraging a non-homogeneous supply system for increased flexibility in material placement.

Key features of the model include its ability to dynamically link tasks to cranes and supply points while addressing safety through collision detection mechanisms. The process involves scenario generation to explore all possible crane-task-supply combinations, evaluating factors such as operating times and potential conflicts. By iterating through these scenarios, the model identifies the optimal operational plan, balancing efficiency, and safety. These models provide motion and feasibility checks that ABDMP uses when generating and updating allocations.

## 4.3 Material management planning model

This study introduces ABDMP, which employs a heterogeneous supply system and rule-based, iterative reallocation of materials to supply points in response to evolving crane demands and task states. After each task, ABDMP updates stocks, crane availability, and outstanding tasks, then reselects the supply point with required material and shortest safe travel, and assigns the nearest feasible crane—repeating until completion. Unlike previous methods that assigned materials to fixed supply points, the approach dynamically distributes materials across supply points in response to crane demands. This adaptive strategy allows our simulation model to test the flow of materials and thus optimize the material flow throughout the project's progression, aligning supply with operational needs.

In managing material services, the approach defines protocols in relation to ABDMP agents in the simulation model to follow strict and well-defined rules for systematic evaluation. Table 2 presents the agent features of material services requests and material transporting units included in the developed ABDMP approach.

Using various agents' unique characteristics, the study develops a heterogeneous supply system. This then allows multiple types of materials to be stored at each supply point, enhancing flexibility and resource allocation. This approach not only creates a broader range of potential scenarios but also offers opportunities to improve crane operations and overall project efficiency. The dynamic adjustment of material distribution to meet crane demands is a key advancement over traditional methods, potentially reducing project duration and optimizing resource utilization.

Ensuring uninterrupted material availability at supply points throughout the project is essential for project success. The effectiveness of a crane operational plan hinges on the timely availability of materials at these supply points. This necessitates a strategic material distribution process aligned with crane activities. This entire process requires meticulous planning to address challenges related to the finite nature of materials and the restricted capacities of supply points. This model emphasizes coordinating material availability with crane operations throughout project execution.

The material management process is depicted in the flowchart in Figure 4, which outlines the steps of the model developed in this research. The flowchart is designed to ensure materials are available at supply points according to the crane operations planned for each task distribution scenario. As shown in Figure 4, after establishing a crane-task pair in Step 6, Step 7 identifies supply points within the crane's operational reach that are designated to store the specific material type required for the task. In the subsequent steps (Step 8 to Step 13), the assessment is refined to supply points capable of storing the material needed. Step 12 involves planning material availability, detailing the type and quantity needed for each task. This planning builds on the crane-task-supply point link established in previous steps (up to Step 11). Finally, the last step records and presents the simulation results, including the types and quantities of materials allocated to each supply point.

*Table 2: Features of material service requests, transporting units and their explanations.*

| Feature | Explanation |
|---|---|
| Material type | The type of to-be-delivered material for execution of a service request |
| Material quantity | The amount of to-be-delivered material for execution of a service request |
| Material destination | The location to which the materials should be delivered for execution of a service request |
| Service request priority | The level of criticality of a service request based on precedence diagram and contractor's schedule |
| Completion status | This is a varying feature which is checked by the model frequently over the simulation run; the status of a material service request can be either "completed" or "ongoing" or "not initiated yet" |
| Potential transporting units | A material service request can be completed by either one or multiple material transporting equipment which forms the corresponding list of potential transporting units |
| Operation time | The operation time of a material service request is calculated in relation to the material transporting unit and the material storage area involved in executing the service request |
| Spatial operation range | The spatial operation range of a material service request is defined in relation to the material transporting unit and the material storage area involved in executing the service request; the spatial operation range is useful for ensuring safe operations |
| Operation status | This is a varying feature and could be either active or idle at any moment during the simulation run |
| Material load capacity | The maximum weight and volume of material loads a transporting unit can carry; This feature is defined in relation to material type |
| Mobility status | A transporting unit could be either fixed-base or mobile; for example, tower cranes are fixed while mobile cranes are not |
| Position | The geometric position of the center of a transporting unit which is a varying feature for mobile transporting units and a stable feature for fixed-base transporting units |

The material management flowchart is versatile and adaptable to various timeframes, such as daily, weekly, bi-weekly, or other intervals preferred by contractors and crane/material management personnel. This is critical because it allows the construction manager onsite to be able to plan ahead of actual material delivery based on their material delivery schedules. Upon completing each scenario simulation, including the top-selected scenario, the required material types and quantities for each supply point within a given timeframe are determined within a given timeframe. These quantities, combined with the existing material levels at each supply point, serve as the basis for planning material orders and their accommodation at supply points. The quantity to be ordered for each material type at each supply point is derived by subtracting the current quantity from the required amount. Once materials are procured, contractors can distribute them across supply points according to the chosen material management plan.

Unlike traditional methods that assign one material type to a fixed supply point for the entire project, ABDMP implements heterogeneous, time-phased, and reconfigurable supply points. In practice, this means supply point assignments are defined for a specific planning window—such as a day or week—during which they remain static for operational stability. However, between windows, ABDMP updates the assignments based on upcoming task demands, crane availability, and material levels.

Reallocation is also event driven. The model recalculates supply assignments when stock at a point drop below a threshold, when crane idle times are predicted to exceed acceptable limits, when new workfaces open, or when delivery schedules shift. These reconfigurations preserve capacity constraints while prioritizing the shortest safe crane travel paths and avoiding collisions. For example, in a weekly baseline plan, a supply point may hold Material A and B on Monday–Tuesday, but by Wednesday evening the model reallocates it to Material C as tasks shift southward. Within each daily shift, the allocation is "static" to crews, but over the project timeline it evolves dynamically to reflect changing operational needs. This balance between stability within windows and adaptability across them distinguishes ABDMP from static storage approaches.

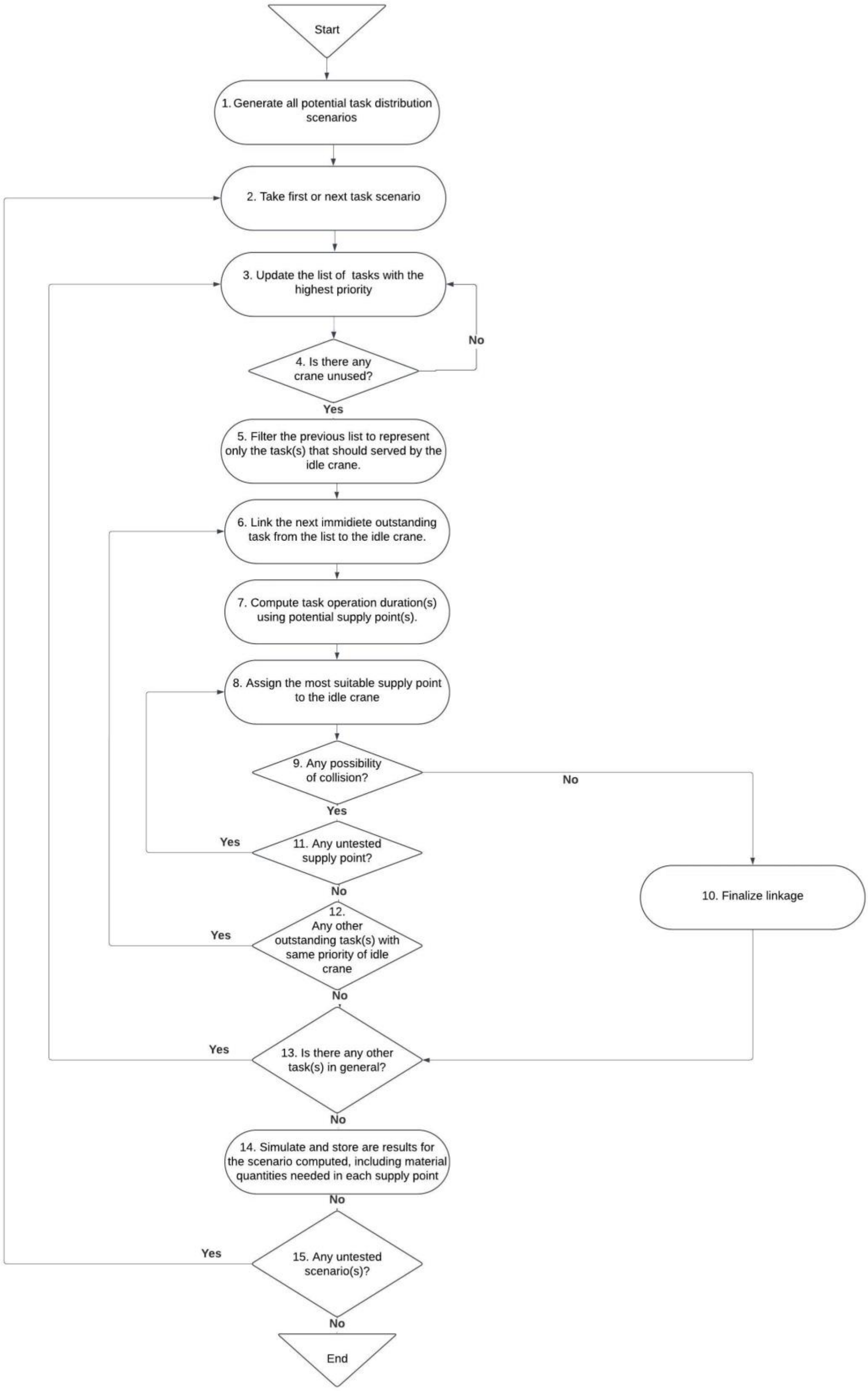



*Figure 4: Material management planning flowchart for multi-tower crane operations.*

## 4.4 Scenario generation and task distribution

Within ABDMP, scenario generation enumerates feasible task–crane–supply triples, while pruning unsafe or stock-infeasible options. The process begins by generating potential task distribution scenarios across tower cranes. The total number of scenarios (NS) is calculated using the following two equations, Equation 6 and Equation 7.

$$N_S = \prod_{i}^{k} N_{s_i} \tag{6}$$

$$N_{s_i} = {Nc_i}^{Nt_i} \tag{7}$$

Where:

- $N_S$: Total potential task distribution scenarios
- $Ns_i$: Scenarios in overlapping area i
- $Nt_i$:: Overlapping tasks in area i
- $Nc_i$: Tower cranes accessing area i
- i: Overlapping area index (1 to k)

### 4.4.1 Systematic evaluation process

The model evaluates each scenario through the following key steps:

1. Task Prioritization: Identifies outstanding tasks by priority level
2. Crane Availability: Monitors crane status to identify available equipment
3. Task-Crane Pairing: Matches highest-priority tasks with available cranes
4. Supply Point Optimization:
   - Calculates operation times for potential supply points
   - Selects the most efficient supply point based on operation time
5. Collision Prevention:
   - Analyzes potential collisions between active cranes
   - Redirects to alternative supply points if collision risk exists
6. Completion Verification:
   - Monitors outstanding tasks
   - Advances to outcome calculation upon task completion

For performance evaluation, the model computes three key metrics: total schedule time, tower crane operation durations, and crane utilization rates. The evaluation approach is anticipated to outperform previous studies due to its incorporation of three key flexibilities in crane operations. These include task distribution across multiple cranes, flexible sequencing of tasks within priority levels, and dynamic selection of supply points. This comprehensive methodology—especially the integration of alternative supply points—effectively addresses limitations in earlier research and contributes to reduced total schedule time through optimized, concurrent crane operations.

The ABDMP framework does not rely on a single static allocation of materials and tasks. Instead, it dynamically updates system states, crane availability, and task status throughout the simulation. After each task execution, the model recalculates material levels at supply points, crane utilization, and outstanding tasks. Based on these updated conditions, the framework adaptively reassigns supply points and cranes using priority rules and collision-avoidance checks. This continuous feedback look process enables real-time re-planning across the workflow, ensuring crane operations remain responsive to changing material and task demands.

## 5. ANALYSIS AND RESULTS

This section applies ABDMP in a proof-of-concept case study to demonstrate the impact of dynamic, heterogeneous material allocation on multi-crane performance. The case study is based on a construction project featuring multiple tower cranes, supply points, and demand points. Specifically, the project features three tower cranes, six supply points, seven demand points, and three types of materials during the period of work considered. Each crane is assigned access to two supply points within its coverage area. Figure 5 shows the approximate positions of the cranes, supply points, and demand locations, with coordinates for the central points of the cranes, supply points, and demand locations corresponding to data in Table 3.

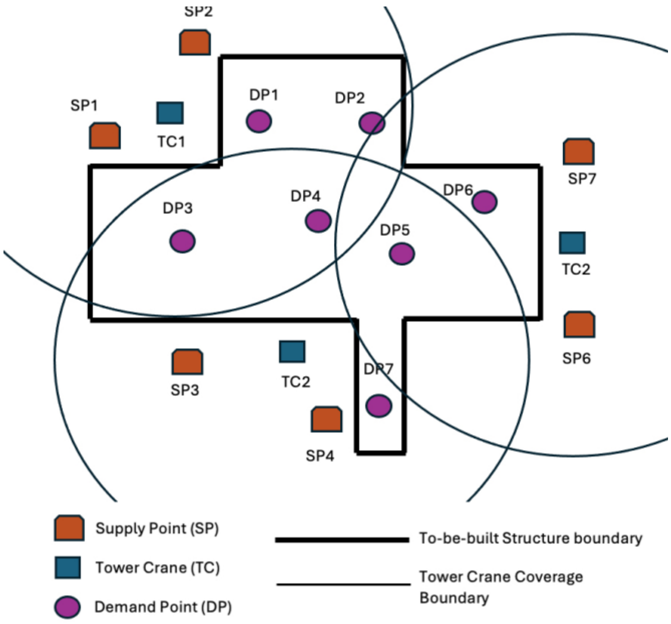



*Figure 5: Plan view of the case study project.*

*Table 3: Coordinates of the base center of tower cranes, supply points, and demand points.*

| Agent | ID | X (ft) | Y (ft) | Z (ft) |
|---|---|---|---|---|
| Crane | 1 | 137 | 433 | 0 |
| Crane | 2 | 220 | 167 | 0 |
| Crane | 3 | 518 | 298 | 0 |
| Supply Point | 1 | 20 | 436 | 0 |
| Supply Point | 2 | 144 | 515 | 0 |
| Supply Point | 3 | 102 | 183 | 0 |
| Supply Point | 4 | 272 | 105 | 0 |
| Supply Point | 5 | 521 | 436 | 0 |
| Supply Point | 6 | 521 | 174 | 0 |
| Demand Point | 1 | 137 | 466 | 20 |
| Demand Point | 2 | 220 | 466 | 20 |
| Demand Point | 3 | 118 | 285 | 20 |
| Demand Point | 4 | 272 | 315 | 20 |
| Demand Point | 5 | 341 | 242 | 20 |
| Demand Point | 6 | 436 | 331 | 20 |
| Demand Point | 7 | 328 | 102 | 20 |

## 5.1 Scenario sets

This study evaluates various material accommodation scenarios with the rule that all three material types are accessible to each crane through two supply points within its coverage area. These scenarios are categorized into four distinct sets, each exploring different strategies for material placement at supply points and following crane operation from supply points to demand points. These configurations are referred to as "material accommodation scenarios."

Table 4 shows the arrangement configurations for the first three scenarios of the four sets as an example of the supply point assignment for one specific crane (Crane #1). In the first scenario set, two material types are assigned to one supply point, while the third material type is allocated to the other within the crane's coverage area. This arrangement generates 216 potential scenarios, derived from six possible configurations of material placement for each supply point within each crane's coverage. Figure 6 provides detailed representation for one such scenario. The same is applied to all 216 potential scenarios along with subsequent simulations to assess them systematically.

*Table 4: Possible arrangements of materials in Crane 1's supply points for the first three scenarios.*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Scenario Set 1** | Possible material arrangement method No. | 1 | 2 | 3 | 4 | 5 | 6 |
| | Materials to store at Supply Point 1 | A, B | A, C | B, C | A | B | C |
| | Materials to store at Supply Point 2 | C | B | A | B,C | A,C | A,B |
| **Scenario Set 2** | Possible material arrangement method No. | 1 | 2 | 3 | 4 | 5 | 6 |
| | Materials to store at Supply Point 1 | A, B | A, B | A, C | A, C | B, C | B, C |
| | Materials to store at Supply Point 2 | A, C | B, C | A, B | B, C | A, B | A, C |
| **Scenario Set 3** | Possible material arrangement method No. | 1 | 2 | 3 | 4 | 5 | 6 |
| | Materials to store at Supply Point 1 | A, B | A, C | B, C | A, B, C | A, B, C | A, B, C |
| | Materials to store at Supply Point 2 | A, B, C | A, B, C | A, B, C | A, B | A, C | B, C |

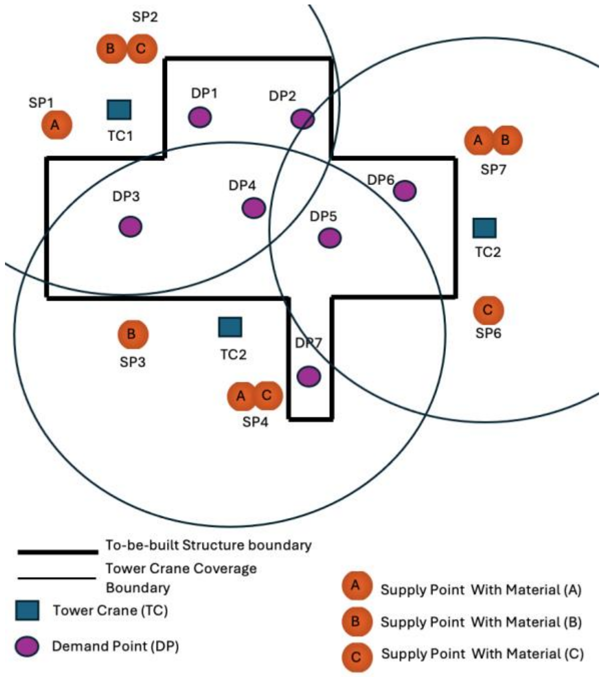



*Figure 6: An example of a material accommodation scenario in Set 1.*

The second scenario set adopts a different approach, where two material types are accommodated at each supply point within the crane's operational range. Similar to the first set, this configuration also generates 216 scenarios, based on six possible arrangements of materials within the supply points. Figure 7 shows an example of these arrangement cases. For the third scenario set, three material types are placed in one supply point, while two are assigned to the other within the crane's coverage area. This arrangement leads to 216 possible scenarios, each representing different material distributions across supply points. Figure 8 presents these configurations. Finally, the fourth scenario set is the most constrained, requiring all three material types to be available at both supply points within each crane's coverage area. Unlike the other sets, this configuration results in only one feasible scenario, as shown in Figure 9.

By evaluating these scenario sets, the research simulates all possible cases per given configurations and identifies the optimal material accommodation strategy that aligns with crane operations, maximizing efficiency and ensuring smooth material flow throughout the construction process.

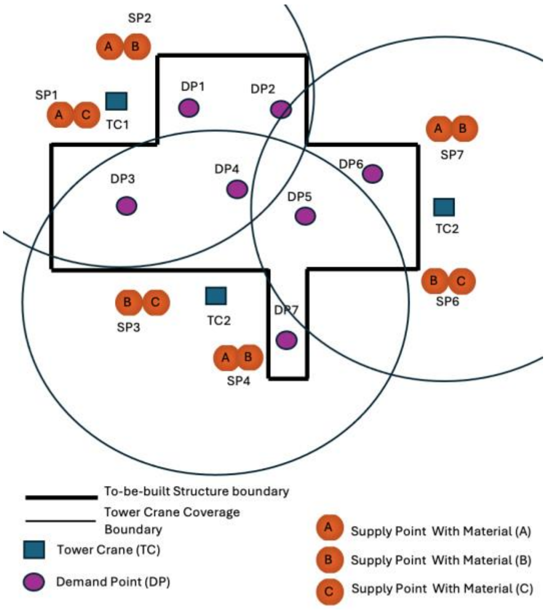



*Figure 7: An example of a material accommodation scenario in Set 2.*

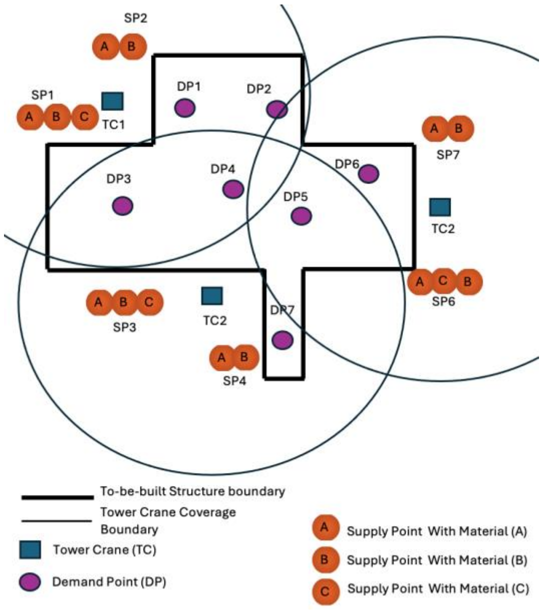



*Figure 8: An example of a material accommodation scenario in Set 3.*

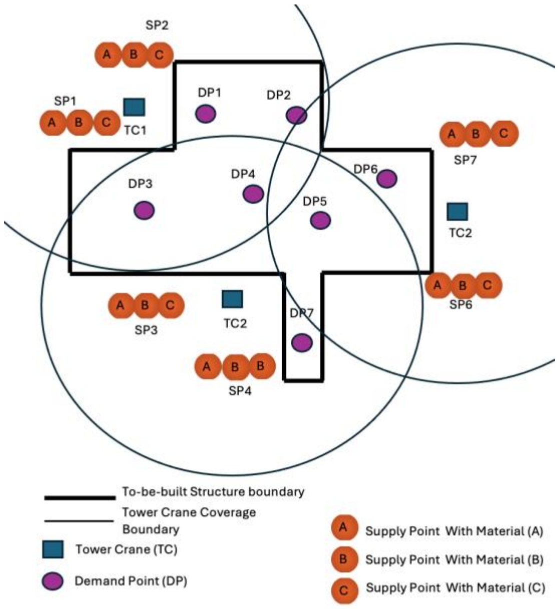



*Figure 9: An example of a material accommodation scenario in Set 4.*

After defining the material accommodation scenarios, relevant data for each scenario was imported into the material management planning model. Additionally, task data covering a one-week period (five working days) from the project schedule was integrated into the model. A total of 649 scenarios were simulated across all sets for the specified week.

Following the simulations, total schedule time and average crane utilization rates were calculated for each material accommodation scenario in order to eventually identify the most effective task distribution scenario. Average values for each scenario set were also determined. Table 5 presents the simulation results for each scenario set and the outcomes for the most effective scenario within each set. The most effective material accommodation scenario is identified as the case with the shortest total schedule time for its optimal task distribution. This entire process was simulated for all 649 scenarios, encompassing all possible configurations for the given set up with cranes, supply and demand points and their respective locations. It is important to note that this process evaluates all possible conditions within a given setup. For other studies or applications, users must define the specific setup for their cases to explore potential scenarios and identify the most effective one.

*Table 5: Average and best simulation results per material accommodation scenario set.*

| **Result type** | **Scenario set No.** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|---|
| Average results | Total schedule time (min) | 2,723 | 2,584 | 2,323 | 2,069 |
| | Average crane utilization rate (%) | 47.3 | 52.6 | 59.4 | 66.1 |
| | Total number of material types in two supply points | 3 | 4 | 5 | 6 |
| Best results | Total schedule time (min) | 2,401 | 2,295 | 2,166 | 2,069 |
| | Average crane utilization rate (%) | 53.8 | 59.7 | 64.0 | 66.1 |
| | Total number of material types in two supply points | 3 | 4 | 5 | 6 |

Scrutinizing the chart along with the tables reveals several interesting findings about the relationship between material flexibility, crane utilization, and overall project efficiency. Improvement across scenarios sets is clearly observed. The results show a progressive improvement in total schedule time and average crane utilization rates as the supply points are more dynamically utilized. For example, Scenario Set 1 (the least flexible configuration) has the longest average schedule time (2,723 minutes) and the lowest average crane utilization rate (47.3%), while Scenario Set 4 (the most flexible) achieves the shortest schedule time (2,069 minutes) and the highest utilization rate (66.1%). The results underscore the importance of material flexibility in optimizing crane operations, particularly in scenarios involving overlapping operational zones or high task density.

In each iteration, once a task is executed, the model immediately updates the state of the system—crane availability, material levels at supply points, and the list of outstanding tasks. Based on these updates, the next allocation is determined by reapplying decision rules: selecting the highest-priority task, assigning the nearest available crane within capacity, and choosing a supply point with the required material, shortest safe travel path, and collision possibilities with simultaneously operating cranes. This entire cycle continues until all tasks are completed, enabling the plan to evolve dynamically rather than being fixed from the outset.

While presenting significant improvement in a general view, the improvement in crane utilization rates becomes less pronounced between Scenario Sets 3 and 4, increasing only from 59.4% to 66.1%. Similarly, the reduction in schedule time between these sets is smaller compared to earlier transitions. While broader material storage at supply points improves results under this model, practical constraints, such as project specifications and supply point capacity, may limit this approach. However, when minimal storage restrictions are present, including a greater variety of material types can significantly enhance project outcomes. The added complexity of implementing this model in material planning is justified by the considerable improvements in project efficiency and crane operations. In a practical perspective, the practitioners should be able to justify various factors between the added complexity in management from adding more dynamicity in supply point and anticipated improvement in efficiency and utilization rate.

The model identifies effective solutions by pruning infeasible scenarios early, such as those involving empty supply points or unsafe crane overlaps, and ranking the remaining options based on schedule time and crane utilization. This rule-based filtering avoids exhaustive computation while preserving realistic simulation tasks and thus scenarios.

## 6. CONCLUSIONS

ABDMP improves efficiency of multi-tower crane operations by coordinating dynamic, heterogeneous material allocation with crane layout and operations. This research emphasizes the critical role of material management in enhancing the efficiency of multi-tower crane operations. The material management planning model developed in this study addresses the often-overlooked constraints of limited supply point capacities and storage conditions. By designing a detailed strategy to manage materials within these restrictions, the model diverges from traditional approaches that assume unlimited material availability. Instead, it facilitates better coordination with crane operations and task sequencing, resulting in significant time savings and operational efficiency, as evidenced by the case studies.

The model's ability to accommodate diverse material types at supply points proved instrumental in improving crane layout efficiency, reducing delays, and optimizing material flow. The interconnected relationship between material management and crane layout planning became evident, as well-coordinated material availability enabled adaptable layouts and streamlined task execution. This adaptability is particularly valuable in complex construction projects, such as urban high-rises with overlapping crane zones, where efficient material flow directly influences project timelines.

Despite its advantages, implementing the model in real-world projects introduces notable complexity. The intricate strategies require meticulous planning and careful attention to detail. While theoretically feasible, strict adherence to the plans during project execution could pose practical challenges, emphasizing the need for flexibility to accommodate on-site adjustments.

As a key finding of this paper, material flexibility is a key driver of efficiency as it can improves overall performance significantly. The findings demonstrate that increasing the variety of material types at supply points significantly enhances crane utilization and reduces project schedules. Projects with fewer storage constraints should prioritize flexible material accommodation strategies to maximize operational efficiency.

The study highlights the consistent outperformance of the most effective scenarios over average configurations, particularly in less flexible setups. Advanced simulation tools, such as ABM, are critical for identifying and implementing optimal scenarios, even in constrained environments. It is important to note that practical applications must consider balancing complexity and benefits. The findings noted diminishing returns in performance gains after certain point, suggesting the importance of balancing added complexity with achievable benefits. Practical constraints, such as supply point capacity and material handling limitations, should inform the selection of appropriate scenario sets.

The case study replicates a portion of a high-rise constitution scenario. The configuration of three tower cranes, six supply points, and seven demand points captures key challenges such as overlapping crane coverage, shared material resources, and task prioritization conflicts. These, together with other subsequent supplementary factors, are core drivers of inefficiency in real projects. While the scale is simplified for clarity and computational efficiency to be able to develop verifiable quantitative measures, the framework is scalable and adaptable to larger projects with more cranes and denser material networks. ABDMP provides a deployable material planning layer that can ingest BIM/RFID/IoT updates to enable field-level re-planning.

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