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Productivity Analysis Of A Tower Crane Based On Cycle Time At The New Satya Terra Bhinneka Building Project

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ABSTRACT

Tower cranes play a critical role in vertical material logistics on multi-storey construction projects, yet productivity losses associated with individual cycle-time components are seldom quantified. This study evaluates tower crane productivity through a time–motion analysis of 71 productive lifting cycles collected over 14 working days (09:00–17:00) at the New Satya Terra Bhinneka Building project. The analysis decomposed each lifting cycle into four measurable components: T1 (hooking/rigging), T2 (outbound travel), T3 (unloading/landing), and T4 (return), with particular emphasis on Travel Cycle Time (TCT = T2 + T4). Floors L3 and L4 were selected to represent the masonry stage of construction involving sand buckets and palletized concrete blocks, while L7 represented the structural stage involving reinforcing steel and concrete casting. Recorded times were converted from minute:second (m:ss) format to decimal minutes, non-productive cycles were excluded, and No-Return cases were completed using a hierarchical T4 imputation procedure. Actual productivity (Q_{act}) was compared with a theoretical benchmark (Q_{theor}) derived from crane geometry, rated hoisting, trolleying, and slewing speeds, and an operator factor of $F_a = 0.75$ adopted from Lampiran II Surat Edaran Direktur Jenderal Bina Konstruksi Nomor 182/SE/Dk/2025. Performance was evaluated using the Productivity Performance Index (PPI). The results showed that sand bucket transportation achieved the highest average PPI values of 1.03 on Floor L3 and 1.08 on Floor L4, while palletized concrete blocks achieved average PPI values of 0.97 on both floors. Concrete casting materials and reinforcing steel delivered to Floor L7 produced average PPI values of 0.98 and 0.95, respectively, indicating that additional handling and placement activities reduced productivity relative to the theoretical benchmark. Component-level analysis further demonstrated that travel time dominated bulk-material transportation, whereas handling time was the primary contributor to productivity losses for palletized and reinforcement materials. These findings provide practical guidance for optimizing tower crane scheduling, material logistics, and resource allocation, thereby supporting more reliable construction planning and public infrastructure management.

Keywords: *cycle time (T1–T4), productivity performance index (PPI), tower crane productivity*

1. Introduction

Vertical material logistics is a decisive driver of schedule reliability, equipment utilization, and cost performance on multi-storey building projects because lifting operations directly influence project scheduling and construction productivity [1,2]. Among the available lifting systems, the tower crane often functions as a central bottleneck resource because operational inefficiencies can propagate across multiple work activities, increase idle time, disrupt work sequencing, and reduce downstream labor productivity. The operating cycle of a tower crane consists of four principal components: loading time (T1), outbound travel time (T2), unloading

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time (T3), and return time (T4) [3]. While construction planning commonly assumes a single average handling rate, actual field productivity is governed by variations in these individual cycle-time components, which are influenced by lifting height, travel distance, swing angle, routing, operator performance, and material characteristics. Therefore, evaluating productivity at the component level provides more practical information for construction planning, material logistics management, and equipment utilization than considering total cycle time alone.

Various approaches have been developed to evaluate and improve tower crane productivity. Analytical models have been proposed to estimate tower crane cycle time based on crane geometry and material coordinates, enabling planners to predict lifting duration during project planning [4]. Tower crane productivity has also been shown to be strongly influenced by lifting height, travel distance, and construction activities during concrete casting operations [5]. Field-based productivity evaluations have demonstrated that comparing observed productivity with planned productivity provides an effective approach for monitoring construction performance and identifying operational inefficiencies [6]. Other studies have shown that optimizing tower crane placement can reduce lifting cycle time and improve material distribution efficiency [7,8], while equipment selection between tower cranes and concrete pumps affects the productivity of concrete casting operations [9]. Furthermore, operational management, lifting characteristics, and construction sequencing have been identified as important factors governing tower crane performance on multi-storey building projects [10,11,12].

Despite these advances, several research gaps remain. Most previous studies have focused on overall cycle-time estimation, tower crane placement optimization, equipment comparison, or automated productivity monitoring. Relatively few studies have distinguished Travel Cycle Time (TCT = T2 + T4) from Handling Time (T1 + T3) as independent productivity components under actual construction conditions. Consequently, limited information is available regarding whether productivity losses originate primarily from crane movement or from material-handling activities. Moreover, comparisons of productivity across different material types and construction stages using a theoretical productivity benchmark remain limited. Addressing these gaps is essential for developing operational strategies that improve crane utilization and support more reliable construction planning.

This study evaluates tower crane productivity through detailed time–motion observations integrated with theoretical productivity analysis. Each lifting cycle was decomposed into four measurable components: T1 (hooking/rigging), T2 (outbound travel), T3 (unloading/landing), and T4 (return). Particular emphasis was placed on Travel Cycle Time (TCT = T2 + T4), which represents crane movement, and Handling Time (T1 + T3), which represents rigging and landing operations. Separating these two productivity components enables the dominant sources of productivity loss to be identified and provides a basis for selecting appropriate operational improvements, including routing optimization, clearance management, rigging standardization, and crew coordination.

The empirical study was conducted at the New Satya Terra Bhinneka Building project using a structured time–motion observation over fourteen working days (09:00–17:00). Three destination floors (L3, L4, and L7) were intentionally selected because they represented different construction stages during the observation period. Floors L3 and L4 were undergoing masonry work, where tower crane operations primarily transported sand in buckets and palletized concrete blocks for wall construction. In contrast, Floor L7 was in the structural construction stage, requiring the transportation of reinforcing steel, shear reinforcement ties, and concrete casting materials. Comparing these representative construction stages enables the influence of material characteristics, lifting height, and handling requirements on tower crane productivity to be evaluated under actual site conditions. Each productive lifting cycle was recorded together with the material type, lifted mass, and the four cycle-time components. Recorded times in minute:second format were converted into decimal minutes, non-productive cycles were excluded, and No-Return (NR) observations were completed using a hierarchical T4 imputation procedure to preserve dataset consistency.

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Measured productivity was evaluated by comparing the actual productivity,

$$Q_{act} = \frac{\text{Mass}}{T_{total}}$$

with a theoretical productivity benchmark derived from crane geometry and the rated hoisting, trolleying, and slewing speeds. An operator factor of 0.75 was adopted in accordance with Appendix II of the Circular Letter of the Director General of Construction Development No. 182/SE/Dk/2025, which recommends an equipment efficiency factor of 0.75 for construction equipment operating under good operating and maintenance conditions. This factor represents practical operating conditions in which equipment cannot continuously achieve its rated capacity. The comparison between actual and theoretical productivity was expressed using the Productivity Performance Index (PPI), where values approaching 1.00 indicate close agreement with the planning benchmark, while lower or higher values indicate underperformance or overperformance, respectively.

This study contributes in three ways. First, it presents a practical and replicable field methodology for observing and processing tower crane cycle-time data, including a transparent procedure for treating No-Return observations. Second, it distinguishes travel-related productivity losses from handling-related productivity losses, enabling operational improvement strategies to be tailored to different construction materials and work stages. Third, it integrates field-based time–motion observations with a theoretical productivity benchmark through the Productivity Performance Index (PPI), providing a practical evaluation framework for tower crane scheduling, material logistics planning, equipment management, and decision-making in building and public infrastructure projects. The findings are expected to support construction planners and site managers in identifying the dominant sources of productivity loss and implementing more effective strategies for improving lifting performance under actual construction conditions

2. Research Methods

The study was conducted at the New Satya Terra Bhinneka Building Project, where a single tower crane was used to transport construction materials to multiple work areas on Floors L3, L4, and L7. A time–motion observational approach was carried out over 14 working days between 09:00 and 17:00 to evaluate tower crane productivity during material handling operations. Each crane cycle was defined as the interval from the moment the load was lifted at the supply point until the crane returned to a ready position for the subsequent lifting cycle. Four measurable time components were recorded for every cycle, namely T1 (hooking/rigging), T2 (outbound travel), T3 (unloading/landing), and T4 (return). The analysis emphasized Travel Cycle Time (TCT = T2 + T4) and Handling Time (T1 + T3) to distinguish productivity losses associated with crane movement from those related to rigging and landing activities.

A total of 71 valid lifting cycles were collected during the observation period. The dataset consisted of 15 sand bucket lifts and 13 palletized concrete block lifts to Floor L3, 8 sand bucket lifts and 18 palletized concrete block lifts to Floor L4, and 2 concrete casting bucket lifts together with 15 reinforcing steel and shear reinforcement tie lifts to Floor L7. The distribution of observations reflected the actual construction sequence rather than a predetermined sampling plan. During the observation period, masonry work on Floors L3 and L4 required frequent transportation of sand and concrete blocks, whereas structural reinforcement activities on Floor L7 were prioritized by the project team, resulting in a greater number of reinforcing steel lifting operations. The lifted mass for each cycle was obtained from site delivery records or standardized bundle weights.

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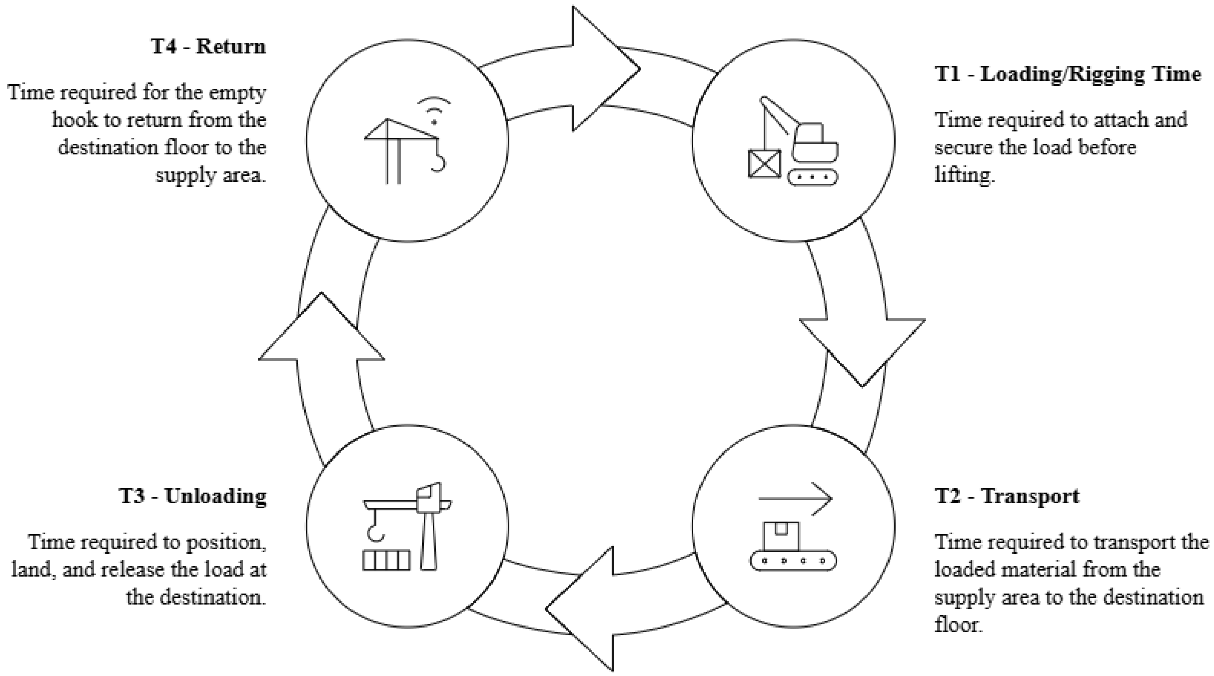

Figure 1. Observation Data Sample

Cycle times were measured using synchronized stopwatches and recorded in minute:second (m:ss) format together with the destination floor, material type, and lifted mass. Before analysis, all recorded times were converted into decimal minutes to ensure numerical consistency. Non-productive cycles, including test lifts, safety holds, and aborted operations, were excluded from productivity calculations but retained in an audit log. For cycles in which the crane did not immediately return to the supply point (No-Return, NR), the missing T4 values were completed using a hierarchical imputation procedure. The first priority was the corresponding same-day, same-floor, and same-material observation; if unavailable, the average value from the same day and route was used. When no matching observation existed on the same day, the campaign-wide average for the corresponding floor–material combination was adopted. All imputed records were identified to maintain transparency during subsequent analysis.

The actual productivity of each lifting cycle was calculated as

$$Q_{\text{act}} = \frac{\text{mass per trip}}{T_{\text{total}}} \ [\text{kg/min}] \tag{1}$$

where $Q_{act}$is the observed productivity (kg/min), mass per trip is the lifted material weight (kg), and $T_{total}$is the observed total cycle time (min), defined as

$$T_{\text{total}} = T_1 + T_2 + T_3 + T_4 \tag{2}$$

where:

- T_1= hooking/rigging time (min)
- T_2= outbound travel time (min)
- T_3= unloading/landing time (min)
- T_4= return travel time (min)

To establish a theoretical benchmark, the theoretical outbound travel time was estimated analytically using the crane geometry and the rated operating speeds of the three principal crane mechanisms: hoisting, trolleying, and slewing. The calculation assumes that each crane mechanism operates at a constant rated speed throughout the lifting cycle and that travel follows the shortest practical path between the supply and destination points. The model further assumes normal operating conditions without significant interruptions caused by wind,

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congestion, operator waiting time, or interference from other site activities. Consequently, the theoretical travel time represents an idealized reference for comparison rather than the exact field operating time. Under these assumptions, the theoretical outbound travel time was calculated as

$$T_{2,\text{theor}} = \frac{\frac{h}{V_{\text{hoist}}} + \frac{|S_{td} - S_{ts}|}{V_{\text{trolley}}} + \frac{\theta}{\omega}}{F_a} \tag{3}$$

where $T_{2,\text{theor}}$ is the theoretical outbound travel time (min), $h$is the vertical lifting distance (m), S_{td} and S_{ts} are the trolley positions at the destination and supply points (m), $V_{hoist}$is the rated hoisting speed (m/min), $V_{trolley}$is the rated trolley speed (m/min), $\theta$is the crane slewing angle (°), $\omega$is the rated slewing speed (°/min), and $F_a$is the operator factor. The rated mechanism speeds were obtained from the tower crane specification used on site, namely 40 m/min for hoisting, 58 m/min for trolleying, and 252°/min for slewing (equivalent to 0.7 rad/min). An operator factor of $F_a = 0.75$was adopted based on "Lampiran II Surat Edaran Direktur Jenderal Bina Konstruksi Nomor 182/SE/DK/2025", which recommends this value for equipment operating under good operational and maintenance conditions.

Table 1. Equipment Efficiency Factor (Fa)

Operating Condition	Very Good	Good	Fair	Poor	Very Poor
Very Good	0.83	0.81	0.76	0.7	0.63
Good	0.78	0.75	0.71	0.65	0.60
Fair	0.72	0.69	0.65	0.6	0.54
Poor	0.63	0.61	0.57	0.52	0.45
Very Poor	0.53	0.50	0.47	0.42	0.32

The theoretical return travel time was assumed to be proportional to the outbound travel time,

$$T_{4,\text{theor}} = kT_{2,\text{theor}},\ k = 0.75 \tag{4}$$

where $k$represents the average ratio between the observed return travel time and outbound travel time for the corresponding lifting route. Since the return movement is performed without payload, the return travel time is expected to be shorter than the outbound travel time.

The theoretical total cycle time was subsequently obtained by combining the calculated travel time with the observed handling time,

$$T_{\text{total,theor}} = T_1 + T_{2,\text{theor}} + T_3 + T_{4,\text{theor}}, \tag{5}$$

and the theoretical productivity was determined as

$$Q_{\text{theor}} = \frac{\text{mass per trip}}{T_{\text{total,theor}}}\ [\text{kg/min}] \tag{6}$$

The agreement between observed and theoretical productivity was evaluated using the Productivity Performance Index (PPI),

$$PPI = \frac{Q_{\text{act}}}{Q_{\text{theor}}} \tag{7}$$

where PPI ≈ 1.00 indicates agreement between observed and theoretical productivity, PPI < 1.00 indicates under-performance, and PPI > 1.00 indicates over-performance. Productivity, theoretical productivity, and PPI were summarized according to destination floor and material type using the mean as the measure of central tendency and the standard deviation as the measure of variation. The PPI values were interpreted together with Travel Cycle Time (TCT) and Handling Time (T1 + T3) to determine whether productivity deviations were primarily associated with crane travel or material-handling activities.

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To evaluate the robustness of the analytical model, a simple sensitivity analysis was performed on the two principal assumptions adopted in this study, namely the imputation of missing T4 values and the operator factor ($F_a = 0.75$). Alternative T4 donor values from comparable observations produced only minor variations in the calculated productivity and PPI values, while small changes in the operator factor proportionally affected the theoretical productivity without altering the relative productivity ranking among floors and material types. These findings indicate that the overall conclusions are not sensitive to the adopted assumptions.

All calculations and statistical summaries were performed using Microsoft Excel, while structural performance, weather effects, and broader site interactions were considered beyond the scope of this study.

3. Results and Discussion

The analysis begins with the raw cycle-time data collected during the time–motion study and continues with data processing, including time conversion and treatment of No-Return (NR) cases. Subsequently, actual productivity is evaluated and compared with the theoretical benchmark through analyses of Travel Cycle Time (TCT), Handling Time (T1 + T3), and the Productivity Performance Index (PPI). The results are discussed according to floor elevation and material type to identify the dominant factors affecting tower crane productivity and to establish practical recommendations for improving lifting operations.

3.1 Field Observation Data

A time–motion study was conducted over 14 working days to observe tower crane operations during material handling activities. After excluding non-productive operations, a total of 71 valid lifting cycles were analyzed. Each productive cycle was recorded by measuring the four cycle-time components T1 (hooking/rigging), T2 (outbound travel), T3 (unloading/landing), and T4 (return) together with the material type, lifted mass, and destination floor. The dataset comprised 15 bucket-of-sand deliveries to Floor 3, 13 palletized concrete-block deliveries to Floor 3, 8 bucket-of-sand deliveries to Floor 4, 18 palletized concrete-block deliveries to Floor 4, 2 concrete-casting bucket deliveries to Floor 7, and 15 reinforcing-steel deliveries to Floor 7. These observations represent the dominant lifting activities during the structural and masonry phases of the project and formed the basis for all subsequent productivity analyses.

Table 2 presents a representative sample of the raw field observations collected on 8 September 2025. The data indicate that the tower crane handled various construction materials, including reinforcing steel, concrete blocks, and sand, with lifted loads ranging from 330 kg to 1,200 kg. The lifting operations were distributed across several destination floors (L3, L4, and L7), resulting in varying cycle times depending on the material type and lifting height. A number of cycles were also recorded as No-Return (NR), indicating that the crane did not immediately return to the supply point after completing a lift. These records were retained and processed according to the data treatment procedure described in the methodology before further productivity analysis was performed.

Table 2. Observation Data Sample

08/09/2025							
CYCLE	T1	T2	T3	T4	MATERIAL	MATERIAL WEIGHT (KG)	DESTINATION
1	-	-	-	-	-	-	-
2	1.50	1.38	2.47	NR	REINFORCING STEEL & SHEAR REINFORCEMENT TIES	954,00	L.7
3	4.24	1.44	0.37	1.20	1 PALLET OF CONCRETE BLOCKS	1200,00	L.4
4	-	-	-	-	-	-	-
5	7.37	1.20	7.04	NR	REINFORCING STEEL & SHEAR REINFORCEMENT TIES	2088,00	L.7
6	-	-	-	-	-	-	-
7	1.33	2.23	1.51	2.06	1 BUCKET OF SAND	3300,00	L.3
8	4.02	1.38	0.35	NR	1 PALLET OF CONCRETE BLOCKS	1200,00	L.3
9	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-

A total of 71 lifting cycles were observed during the 14-day monitoring period, of which productive cycles

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were classified according to material type and destination floor. The dataset comprised bucket-of-sand deliveries to Floors L3 (14 cycles) and L4 (8 cycles), palletized concrete-block deliveries to Floors L3 (13 cycles) and L4 (17 valid cycles), concrete-casting bucket deliveries to Floor L7 (2 cycles), and reinforcing steel with shear reinforcement ties delivered to Floor L7 (15 cycles). The observed productivity exhibited measurable variation among the lifting activities. Bucket-of-sand transportation showed the highest productivity, ranging from 373.58–460.47 kg/min on Floor L3 and 427.65–502.54 kg/min on Floor L4, whereas palletized concrete blocks ranged from 156.52–198.35 kg/min on Floor L3 and 142.95–164.89 kg/min on Floor L4. Reinforcing-steel lifting displayed the widest productivity range (109.55–216.39 kg/min) because of differences in lifted mass and handling requirements, while concrete-casting operations ranged from 326.37–337.56 kg/min. These ranges demonstrate that productivity varied according to both material characteristics and operational conditions, thereby providing an adequate basis for the subsequent comparative analysis.

3.2 Data Processing and Time Conversion

The raw observation data were processed before productivity analysis to ensure numerical consistency. All cycle times originally recorded in minute:second (m:ss) format were converted into decimal minutes using:

$$t_{\min} = m + \frac{s}{60}$$

where $m$is the recorded minute value and $s$is the corresponding second value. For example, a recorded time of 1:50 was converted to 1.83 min, while 2:24 became 2.40 min. After conversion, the total cycle time for each lifting operation was calculated as:

$$T_{\text{total}} = T_1 + T_2 + T_3 + T_4$$

For lifting cycles identified as No-Return (NR) during field observations, the missing T4 values were completed using the hierarchical imputation procedure described in Section 2. The processed dataset was subsequently used to calculate actual productivity, theoretical productivity, and the Productivity Performance Index (PPI).

Table 3 presents a representative example of the processed data from 8 September 2025, showing the converted cycle-time components in decimal minutes together with the corresponding total cycle time.

Table 3. Conversion Result

08/09/2025			TIME CONVERSION (MNT)				T1+T2+T3+T4
MATERIAL	MATERIAL WEIGHT (KG)	DESTINATION	T1	T2	T3	T4	
-	-	-					0,00
REINFORCING STEEL & SHEAR REINFORCEMENT TIES	954,00	L.7	1,83	1,63	2,78	2,24	8,49
1 PALLET OF CONCRETE BLOCKS	1200,00	L.4	4,40	1,73	0,62	1,33	8,08
-	-	-					0,00
REINFORCING STEEL AND SHEAR REINFORCEMENT TIES	2088,00	L.7	7,62	1,33	7,07	2,24	18,26
-	-	-					0,00
1 BUCKET OF SAND	3300,00	L.3	1,55	2,38	1,85	2,10	7,88
1 PALLET OF CONCRETE BLOCKS	1200,00	L.3	4,03	1,63	0,58	0,90	7,15

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-	-	-	0,00
-	-	-	0,00

Table 3 presents the converted cycle-time data obtained from the field observations after transforming the recorded minute:second (m:ss) values into decimal minutes. The converted data reveal that total cycle times varied considerably among lifting operations, ranging from 7.15 minutes for palletized concrete blocks delivered to Floor 3 to 18.26 minutes for reinforcing steel delivered to Floor 7. The longest cycle times were generally associated with reinforcing steel because additional time was required for positioning and placement at the destination, whereas sand buckets and palletized concrete blocks exhibited shorter and more consistent cycle durations. These converted values formed the basis for calculating the actual productivity of each lifting cycle.

3.3 Actual Productivity Analysis

After the cycle times had been converted into decimal minutes, the actual productivity of each lifting cycle was calculated by dividing the lifted material weight by the corresponding total cycle time, as expressed in equation (1). The resulting productivity values, expressed in kg/min, provide a quantitative measure of the tower crane's material-handling performance for each lifting operation.

Table 4 presents a representative example of the productivity calculation based on the processed data collected on 8 September 2025. For each lifting cycle, the table reports the material type, lifted weight, destination floor, total cycle time, calculated productivity, and the average productivity for each material–floor combination.

The results indicate noticeable variations in productivity among different lifting operations. These variations are primarily influenced by differences in lifted material weight, destination floor, and total cycle time. In general, lifting cycles with heavier loads and shorter cycle times produced higher productivity values, whereas longer cycle times reduced the material-handling rate. The calculated productivity values presented in Table 4 form the basis for the subsequent comparison with theoretical productivity and the evaluation of operational performance using the Productivity Performance Index (PPI).

Table 4. Productivity Result

08/09/2025			CYCLE TIME (m)	PRODUCTIVITY (KG/Minutes)	AVERAGE PRODUCTIVITY (KG/MINUTES)
MATERIAL	MATERIAL WEIGHT (KG)	DESTINATION			
-	-	-	0,00	DATA EXCLUDED	FLOOR 3
REINFORCING STEEL & SHEAR REINFORCEMENT TIES	954,00	L.7	8,49	112,35	299,38
1 PALLET OF CONCRETE BLOCKS	1200,00	L.4	8,08	148,45	
-	-	-	0,00	DATA EXCLUDED	FLOOR 4
REINFORCING STEEL AND SHEAR REINFORCEMENT TIES	2088,00	L.7	18,26	114,36	148,45
-	-	-	0,00	DATA EXCLUDED	
1 BUCKET OF SAND	3300,00	L.3	7,88	418,60	FLOOR 7
1 PALLET OF CONCRETE BLOCKS	1200,00	L.3	7,15	167,89	
-	-	-	0,00	DATA EXCLUDED	113,72
-	-	-	0,00	DATA EXCLUDED	

Table 4 summarizes the productivity calculated from each valid lifting cycle in one day. The results indicate noticeable differences among material types and destination floors. Sand bucket transportation to Floor 3 achieved the highest productivity of 418.60 kg/min, while palletized concrete blocks delivered to the same floor produced 167.89 kg/min. Reinforcing steel delivered to Floor 7 recorded the lowest productivity of 112.35–114.36 kg/min, reflecting the longer handling time required for unloading and positioning the

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reinforcement. The average productivity also differed by destination floor, with Floor 3 recording approximately 299.38 kg/min, Floor 4 approximately 148.45 kg/min, and Floor 7 approximately 113.72 kg/min, indicating that productivity decreased as handling complexity increased.

3.4 Travel Cycle Time (TCT) and Handling Time (T1 + T3) Analysis

To identify the dominant contributors to each lifting cycle, the total cycle time was decomposed into Travel Cycle Time (TCT = T2 + T4) and Handling Time (T1 + T3). The average values of both components, together with their respective percentages of the total cycle time, were calculated for each material–destination combination. This comparison allows the productivity losses to be attributed either to crane travel or to material-handling activities.

Table 5 presents the average TCT and Handling Time for representative lifting operations to Floor L3. The results show that the relative contribution of each component varies considerably with the type of material being transported. For sand transported in buckets, the average TCT was 4.49 min, accounting for approximately 52–59% of the total cycle time, whereas the average Handling Time was 3.61 min, representing the remaining 41–48%. These results indicate that the lifting process for sand is predominantly travel-dominated, with most of the cycle duration consumed by crane movement between the supply point and the destination.

In contrast, the lifting of concrete blocks on pallets exhibited a different operational characteristic. The average TCT was only 2.05 min, contributing approximately 24–35% of the total cycle time, while the average Handling Time reached 4.63 min, accounting for around 65–76% of the total cycle duration. This indicates that palletized concrete blocks are handling-dominated, where the majority of the lifting cycle is spent on hooking, positioning, landing, and releasing the load rather than crane travel.

The contrasting characteristics demonstrate that productivity improvement strategies should be tailored to the material being handled. For travel-dominated operations, such as sand lifting, improvements should focus on optimizing crane routing, reducing travel distance, and minimizing clearance-related delays. Conversely, for handling-dominated operations, such as palletized concrete blocks, productivity gains are more likely to be achieved through standardized rigging procedures, improved landing-zone organization, and better coordination between the crane operator and rigging personnel.

Table 5. Travel Cycle Time (TCT) and Handling Time (T1 + T3) Results

MATERIAL	DEST.	T2+T4	TCT (T2+T4) AVERAGE (MINUTES)	T1+T3	AVERAGE T1 + T3 (MINUTES)	TCT PERCENTAGE	T1+T3 PERCENTAGE
1 BUCKET OF SAND	L.3	4,48	4,49	3,40	3,61	56,87%	43,13%
1 BUCKET OF SAND	L.3	4,78		4,05		54,15%	45,85%
1 BUCKET OF SAND	L.3	4,75		4,00		54,29%	45,71%
1 BUCKET OF SAND	L.3	4,33		2,97		59,36%	40,64%
1 BUCKET OF SAND	L.3	4,87		3,85		55,83%	44,17%
1 BUCKET OF SAND	L.3	4,25		3,17		57,30%	42,70%
1 BUCKET OF SAND	L.3	4,75		4,03		54,08%	45,92%
1 BUCKET OF SAND	L.3	4,52		3,80		54,31%	45,69%
1 BUCKET OF SAND	L.3	4,22		2,95		58,84%	41,16%
1 BUCKET OF SAND	L.3	4,35		4,02		51,99%	48,01%
1 BUCKET OF SAND	L.3	4,10		3,10		56,94%	43,06%
1 BUCKET OF SAND	L.3	4,65		3,92		54,28%	45,72%
1 BUCKET OF SAND	L.3	4,68		3,93		54,35%	45,65%
1 BUCKET OF SAND	L.3	4,27		2,90		59,53%	40,47%

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1 BUCKET OF SAND	L.3	4,35		4,02		51,99%	48,01%
1 PALLET OF CONCRETE BLOCKS	L.3	2,53		4,62		35,41%	64,59%
1 PALLET OF CONCRETE BLOCKS	L.3	1,73		4,32		28,65%	71,35%
1 PALLET OF CONCRETE BLOCKS	L.3	2,11		4,65		31,26%	68,74%
1 PALLET OF CONCRETE BLOCKS	L.3	2,03		4,37		31,77%	68,23%
1 PALLET OF CONCRETE BLOCKS	L.3	2,35		4,58		33,87%	66,13%
1 PALLET OF CONCRETE BLOCKS	L.3	2,03		4,38		31,66%	68,34%
1 PALLET OF CONCRETE BLOCKS	L.3	1,87	2,05	5,80	4,63	24,35%	75,65%
1 PALLET OF CONCRETE BLOCKS	L.3	2,50		4,45		35,97%	64,03%
1 PALLET OF CONCRETE BLOCKS	L.3	2,11		4,53		31,81%	68,19%
1 PALLET OF CONCRETE BLOCKS	L.3	2,00		4,45		31,01%	68,99%
1 PALLET OF CONCRETE BLOCKS	L.3	1,67		4,78		25,84%	74,16%
1 PALLET OF CONCRETE BLOCKS	L.3	1,85		4,75		28,03%	71,97%
1 PALLET OF CONCRETE BLOCKS	L.3	1,83		4,45		29,18%	70,82%

Table 5 compares the contribution of Travel Cycle Time (TCT = T2 + T4) and Handling Time (T1 + T3) for each lifting operation. For sand bucket transportation to Floor 3, travel activities accounted for approximately 52–59% of the total cycle time, indicating that crane movement constituted the dominant component of the lifting cycle. In contrast, palletized concrete block transportation exhibited substantially higher handling proportions, where T1 + T3 contributed approximately 64–76% of the total cycle time because additional rigging, positioning, and unloading were required. These findings suggest that productivity improvements for sand transportation should primarily focus on reducing crane travel time, whereas improvements for palletized concrete blocks should emphasize more efficient loading and unloading procedures.

3.5 Theoretical Productivity and Productivity Performance Index (PPI)

The theoretical productivity of each lifting cycle was calculated using the analytical model presented in Section 2. The model combines the calculated theoretical travel time with the observed handling time to obtain the theoretical total cycle time, from which the expected productivity of each lifting operation is determined. This theoretical productivity serves as the reference for evaluating the actual tower crane performance observed in the field.

Table 6. Theoretical Productivity

MATERIAL	DEST.	T2 THEORIZED	T4 THEORIZED	T1+T2+T3+T4 (THEORIZED)	THEORICAL PRODUCTIVITY (KG/MINUTE)
1 BUCKET OF SAND	L.3	2,53	2,15	8,09	407,97
1 BUCKET OF SAND	L.3	2,53	2,15	8,74	377,63
1 BUCKET OF SAND	L.3	2,53	2,15	8,69	379,80
1 BUCKET OF SAND	L.3	2,53	2,15	7,66	431,07
1 BUCKET OF SAND	L.3	2,53	2,15	8,54	386,47
1 BUCKET OF SAND	L.3	2,53	2,15	7,86	420,09
1 BUCKET OF SAND	L.3	2,53	2,15	8,72	378,35
1 BUCKET OF SAND	L.3	2,53	2,15	8,49	388,75
1 BUCKET OF SAND	L.3	2,53	2,15	7,64	432,01
1 BUCKET OF SAND	L.3	2,53	2,15	8,71	379,07
1 BUCKET OF SAND	L.3	2,53	2,15	7,79	423,69
1 BUCKET OF SAND	L.3	2,53	2,15	8,61	383,48
1 BUCKET OF SAND	L.3	2,53	2,15	8,62	382,74
1 BUCKET OF SAND	L.3	2,53	2,15	7,59	434,85

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1 BUCKET OF SAND	L.3	2,53	2,15	8,71	379,07

Table 6 presents the theoretical productivity calculated for each lifting operation using the analytical cycle-time model. The calculated productivity varied according to lifting geometry, travel distance, lifted mass, and observed handling time. For sand bucket transportation to Floor L3, theoretical productivity ranged from 377.63 to 434.85 kg/min, while the theoretical travel times remained constant because the lifting route and crane configuration did not change during the observation period. Consequently, variations in theoretical productivity were primarily influenced by differences in handling time (T1 + T3), indicating that loading and unloading activities remained an important determinant of overall productivity even under ideal crane operating conditions.

The theoretical productivity varies between approximately 377.63 kg/min and 434.85 kg/min, with most values concentrated between 380 and 420 kg/min. The relatively narrow range indicates that the analytical model provides a consistent estimate of the expected tower crane performance under normal operating conditions. Shorter handling durations produce higher theoretical productivity, whereas longer rigging and unloading activities increase the theoretical cycle time and reduce the expected output.

To evaluate the agreement between theoretical and observed performance, the Productivity Performance Index (PPI) was calculated for each lifting cycle as the ratio of actual productivity to theoretical productivity. A PPI value equal to 1.00 indicates perfect agreement with the theoretical benchmark, values greater than 1.00 indicate productivity exceeding the theoretical expectation, and values below 1.00 indicate lower-than-expected performance.

Table 7. Productivity Performance Index

MATERIAL	PRODUCTIVITY (KG/MINUTES)	THEORICAL PRODUCTIVITY (KG/MINUTES)	PPI	AVERAGE PPI
1 BUCKET OF SAND	418,60	407,97	1,03	
1 BUCKET OF SAND	373,58	377,63	0,99	
1 BUCKET OF SAND	377,14	379,80	0,99	
1 BUCKET OF SAND	452,05	431,07	1,05	
1 BUCKET OF SAND	378,59	386,47	0,98	
1 BUCKET OF SAND	444,94	420,09	1,06	
1 BUCKET OF SAND	375,71	378,35	0,99	
1 BUCKET OF SAND	396,79	388,75	1,02	1,03
1 BUCKET OF SAND	460,47	432,01	1,07	
1 BUCKET OF SAND	394,42	379,07	1,04	
1 BUCKET OF SAND	458,33	423,69	1,08	
1 BUCKET OF SAND	385,21	383,48	1,00	
1 BUCKET OF SAND	382,98	382,74	1,00	
1 BUCKET OF SAND	460,47	434,85	1,06	
1 BUCKET OF SAND	394,42	379,07	1,04	

Table 7 summarizes the Productivity Performance Index (PPI) obtained by comparing the observed productivity with the theoretical benchmark. Sand bucket transportation achieved the highest average PPI values (1.03 on Floor L3 and 1.08 on Floor L4), indicating that the observed productivity slightly exceeded the predicted performance. Palletized concrete blocks produced average PPI values of 0.97 on both Floors L3 and L4, while concrete casting and reinforcing steel transported to Floor L7 achieved average PPI values of 0.98 and 0.95, respectively. Overall, the results demonstrate that productivity was influenced not only by travel distance but also by the characteristics of the transported material and the complexity of handling operations

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Table 8. PPI Material-Floor Comparison

MATERIAL	DEST.	AVERAGE PRODUCTIVITY	AVERAGE THEORITICAL PRODUCTIVITY	AVERAGE PPI
BUCKET OF SAND	L.3	410,25	399,00	1,03
PALLET OF CONCRETE BLOCKS		180,46	185,53	0,97
BUCKET OF SAND	L.4	475,29	441,27	1,08
PALLET OF CONCRETE BLOCKS		152,93	157,27	0,97
BUCKET OF CONCRETE	L.7	280,54	286,48	0,98
REINFORCING STEEL & SHEAR REINFORCEMENT TIES		148,81	157,00	0,95

Table 8 summarizes the average observed productivity, average theoretical productivity, and average Productivity Performance Index (PPI) for each material–destination combination based on the 71 valid lifting cycles. Sand bucket transportation achieved the highest average PPI values, reaching 1.03 on Floor L3 and 1.08 on Floor L4, indicating that the observed productivity slightly exceeded the theoretical benchmark. Palletized concrete blocks yielded consistent average PPI values of 0.97 on both Floors L3 and L4, demonstrating close agreement between observed and theoretical productivity. Concrete casting operations on Floor L7 recorded an average PPI of 0.98, while reinforcing steel transportation produced the lowest average PPI (0.95), reflecting longer handling and placement activities required during unloading. Overall, the results indicate that tower crane productivity is governed not only by lifting distance and destination floor but also by the characteristics of the transported material and the complexity of handling operations. These findings suggest that productivity improvements should be material-specific, with travel-path optimization being more effective for bulk materials, whereas improvements in rigging, unloading, and crew coordination are more beneficial for palletized materials and reinforcing steel.

The close agreement between actual and theoretical productivity also confirms that the analytical travel model provides a reliable representation of the lifting operations. The small deviations observed among individual lifting cycles are considered normal field variations caused by differences in bucket filling, operator response, minor positioning adjustments, and coordination between the crane operator and ground personnel. When interpreted together with the component-time analysis presented in Section 3.4, the PPI results indicate that the remaining opportunities for productivity improvement are primarily associated with travel-related factors, such as crane routing, lift scheduling, and clearance management, rather than deficiencies in the theoretical model itself.

4. Conclusion

This study evaluated tower crane productivity through a time–motion analysis by decomposing each lifting cycle into hooking/rigging (T1), outbound travel (T2), unloading/landing (T3), and return (T4). Based on observations collected over fourteen working days at the New Satya Terra Bhinneka Building project, productivity was analyzed across three destination floors (L3, L4, and L7) and several representative construction materials. The results indicate that tower crane productivity decreases with increasing lifting elevation, primarily due to longer travel cycle times. Sand transported in buckets was found to be travel-dominated, with TCT accounting for more than half of the total cycle time, whereas palletized concrete blocks were handling-dominated, with most of the cycle consumed by rigging and landing activities. These findings demonstrate that productivity improvement strategies should differ according to material characteristics. The analytical productivity model developed in this study provided a theoretical benchmark that closely matched observed field performance. The calculated Productivity Performance Index (PPI) values generally ranged close to unity, with an average value of approximately 1.03 for sand transportation to Floor L3, indicating that observed productivity differed by only about 3% from the theoretical prediction.

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Overall, the proposed methodology provides a practical framework for evaluating tower crane productivity by combining field observations with analytical modelling. The results may assist planners and site managers in identifying whether productivity losses originate primarily from crane travel or material-handling operations, thereby enabling more targeted operational improvements. Future research should incorporate automated crane telemetry, environmental factors such as wind conditions, and multi-crane coordination to further improve productivity modelling and construction planning.

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