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Exploration of Identification at Each Phase to Advance Productivity Towards Sustainable Practices

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Abstract. This study analyzes the productivity of tower cranes in high-rise building construction projects in Indonesia, focusing on sustainable practices and advanced techniques. The rapid growth of infrastructure has heightened competition in the construction sector, making efficiency essential. Tower cranes are key to accelerating project timelines and reducing costs, but their productivity can differ between theoretical specifications and actual field conditions. Using a quantitative descriptive method, this study compares theoretical productivity based on equipment specifications with direct field observations of the Potain MCT 205 tower crane at a high-rise site. Data on cycle time and lifting volume for work such as column reinforcement and concrete pouring were collected. Results show that theoretical productivity is higher than field observations, with a 40% increase for works and up to a 92% increase per phase. The findings stress the importance of incorporating advanced planning and sustainable practices to optimize productivity, minimize delays, and reduce costs in construction projects.

Keywords: sustainable practices, tower crane, cycle time, advance productivity

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1. Introduction

Infrastructure development in Indonesia is becoming more advanced each day [1]. This growth is driven by the expansion of new projects in the construction sector, which includes housing, roads, bridges, and public facilities. This, in turn, stimulates other sectors' development and intensifies competition among companies[2]. One critical aspect of enhancing project efficiency is the optimization of execution time [3]. Project implementation often faces challenges that lead to delays, increasing both project duration and associated costs [4]. Therefore, planning that includes the proper allocation of funds and resources within the specified timeline is crucial. [5].

Heavy equipment is a crucial component in big projects [6]. It plays an essential role in construction because it speeds up the construction process and efficiently supports the achievement of time targets beyond human capabilities [7, 8]. The tower crane is crucial heavy equipment for high-rise buildings [9, 10]. In building construction, the work comprises interconnected phases that form a unified cycle [11]. With tower cranes, construction projects can be completed using effective methods in a shorter period [12]. Tower cranes are designed to be adjustable in vertical and horizontal directions, making them suitable for handling tasks at varying heights and distances [13, 14]. Choosing the appropriate type of tower crane requires careful consideration, particularly regarding its productivity [15]. A common problem in using tower cranes is a decrease in productivity that is not comparable to operational costs, which can cause project delays and budget overruns. The higher the productivity, the shorter the duration required, so the costs incurred are also reduced. Conversely, decreased productivity will extend the duration and increase costs [1].

This study is based on some previous studies on the productivity of tower crane heavy equipment, including research entitled "Tower Crane Heavy Equipment Productivity for Casting in Building Construction (Case Study of XYZ Building Construction Project on Jl. Pemuda)" with the result indicating that the specification productivity is higher than in the field, because weather factors, field conditions, heavy equipment, and operators influence it. Tower cranes 1 and 2 obtained higher specification productivity, 64.41% of field productivity [17]. In addition, another study entitled "Effectiveness of Tower Crane Use with Comparison Method in Public Building Construction in Malang City" shows the Potain MD-559 type Tower Crane has a productivity of 1,962.97 kg/hour in the field. Its operational costs are Rp 663,780.72 per hour. External factors must be considered, such as equipment capacity, material transfer rate, load movement during transfer, and machine stop system[5].

This study analyzes tower crane productivity in high-rise building projects to support sustainable innovation in the construction sector. The analysis involves calculating theoretical productivity based on specifications and observing field productivity for each work phase. Phase-by-phase productivity research is limited, with most studies focusing on overall productivity. This research aims to fill that gap by providing data for more efficient and innovative high-rise construction planning and execution.

2. Methods

The research method employed is quantitative descriptive analysis, which aims to describe, evaluate, and explain the object of study based on existing realities, as well as draw conclusions from observable phenomena using quantitative data. This research does not cover operational costs, equipment efficiency, or productivity factors but focuses on work cycle times, such as column reinforcement installation, formwork lifting, beam reinforcement, and concrete pouring using a concrete bucket. This study uses primary data obtained through direct observations at the research site, focusing on structural work lifted using a Potain MCT 205 tower crane. The required data includes primary data in the form of the lifting volume using the tower crane and cycle time observations recorded directly in the field over seven days. Field observations were conducted using a stopwatch, pen, and observation sheets. Meanwhile, the secondary data required consists of the tower crane layout and the specifications of the tower crane. The collected data is then analyzed using Microsoft Excel before being presented as relevant information. The cycle time for each phase is calculated and averaged for each work. The calculations derived from cycle time and volume measurements are used to determine productivity for each phase. Productivity from direct observation is calculated based on the time from loading to return. Meanwhile, theoretical productivity is calculated based on equipment specifications and the work trajectory distance. The productivity results for the work and phases are then averaged and compared.

2.1 Tower Crane

A Tower crane is heavy equipment designed to transport materials or equipment vertically and horizontally to a certain height, especially in areas with limited space for movement [18]. Tower cranes are permanently placed at a predetermined location during the construction process. Therefore, the use of tower cranes must be well-planned. Tower cranes must cover transportation needs and mobilize materials and equipment within a radius that can be used according to tower crane specifications [19]. Four types of Tower cranes exist: Self-Supporting Static, Supported Static, Travelling, and Climbing Tower cranes [20]. In this project, a Self-Supporting Static type tower crane was used. Tower crane parts include a base, base section, mast section, climbing frame, support seat, slewing ring, slewing mast, cat head, jib, counter jib, counterweight, cabin set, access ladder, trolley, and hook [21].

2.2 Tower Crane Travel Distance

In Tower Crane Operations, the distance is divided into three segments[22-24], that is:

1. Vertical refers to the total vertical distance the hoist travels from the material pickup point to the delivery point.
2. Rotation is the distance referring to the angle generated between the starting point, the location of the tower crane, and its ending point.
3. Horizontal is the distance referring to the total distance that is calculated by the trolley in a horizontal direction. The calculation of the horizontal distance is carried out using the following steps[25]:
   - Distance between Demand Point and Tower Crane

$$d_1 = \sqrt{(y_{tc} - y_p)^2 + (x_{tc} - x_p)^2} \quad (1)$$

Where:
d_1 = Distance between Demand Point and Tower Crane
x_{tc}, y_{tc} = Tower Crane x and y Coordinate Points
x_p, y_p = Demand Point x and y Coordinates

   - Distance between Supply Point and Tower Crane

$$d_2 = \sqrt{(y_{tc} - y_s)^2 + (x_{tc} - x_s)^2} \quad (2)$$

Where:
d_2 = Distance between Supply Point and Tower Crane
x_{tc}, y_{tc} = Tower Crane x and y Coordinate Points
x_s, y_s = Supply Point x and y Coordinates

   - Distance between Supply Point and Demand Point

$$d_3 = \sqrt{(y_s - y_p)^2 + (x_s - x_p)^2} \quad (3)$$

Where:
d_3 = Distance between Supply Point and Demand Point
x_s, y_s = Supply Point x and y Coordinates
x_p, y_p = Demand Point x and y Coordinates

2.3 Cycle time

Cycle time refers to how long it takes for a tower crane to complete one lift, including vertical (Hoist), horizontal (Trolley), and rotating (Slewing) movements. In this cycle, there will be several stages, including material binding, lifting, material rotation, lowering, releasing, and returning to the initial position of the material [24]. Cycle time calculations are divided into:

1. Vertical Travel Duration (Tv)

   Vertical Travel Duration is the travel time in lifting material vertically [22-24]. Calculated using the formula:

$$T_V = \frac{D_V}{V_V} \quad (4)$$

Where :
Tv = Duration(min)
Dv = Height (m)
Vv = Speed (m/min)

2. Rotation Travel Duration (Tr)

Rotational travel duration is the duration required to move material in a rotating manner [22-24]. Calculated using the formula:

$$T_r = \frac{D_r}{Vr} \tag{5}$$

Where :
Tr = Duration (min)
Dr = Slewing angle (°)
Vr = Speed(°/min)

3. Horizontal Travel Duration (Th)

The tower crane's horizontal travel duration in moving materials horizontally [22-24]. Calculated using the formula:

$$T_h = \frac{Dh}{Vh} \tag{6}$$

Where:
Th = Duration (min)
Dh = Distance (m)
Vh = Speed (m/min)

4. Total Cycle Time

Total cycle time is the total duration required to complete the work of each batch. [26], can be calculated based on the formula [27]:

Cycle Time = Installation Time + Hoisting + Demolish + Return Time (7)

2.4 Productivity

Productivity refers to the ratio of volume output and resource input [28]. Output is the amount of material required to be mobilized by the tower crane, while input is the duration needed for the transfer[29]**.** By knowing the input and output data used, the productivity calculation of a tower crane can be done. This productivity is usually expressed in kilograms per hour (kg/hour) [30, 31]. According to Rostiyanti [21], equipment productivity is influenced by its capacity and cycle time; she also stated that the basic formula for finding equipment productivity is as follows:

$$Productivity = \frac{Capacity}{Cycle\ Time} \tag{8}$$

3. Results and Discussion

3.1Project Overview

This high-rise construction project is located in the city of Surabaya. It is designed to provide modern lecture rooms, canteens, seminar rooms, and other facilities supporting optimal learning continuity. The building has 13 floors + 1.

3.2Tower Crane Specifications

The tower crane used in this project is the Potain MCT 205 type, with specification data from the catalog [32]. The specifications are obtained in Table 1 below.

Table 1. Tower Crane Specifications

Merk	:	Potain
Type	:	MCT 205
Capacity	:	Maximum 10 T and at the end of the jib 1.8 T
Hoist speed	:	0-44-88 m/minute
Slewing speed	:	0.96 rpm (345,6°/min)
Trolley speed	:	0-69,6 m/min

Source: Manitowoc Catalog, 2024

Table 1 presents the data on the tower crane heavy equipment specifications used in the research project location.

3.3 Volume of Work

In structural work, tower cranes transport several materials, including formwork, hollow iron, reinforcement sets, concrete, and cast buckets. In casting work, the weight per kg is obtained from the capacity of m^3 multiplied by the weight of 2.200 kg/m^3[33]. The volume of work obtained through direct observation in the field is in Table 2 below.

Table 2. Volume Recapitulation

No	Work	Volume (Kg)
1	Formwork Type 1	2000
2	Formwork Type 2	3000
7	Column	1005.702
8	Beam Reinforcement	962.985
9	Slab Reinforcement	740
10	Multiplex Formwork	900
11	Shear wall Formwork	150
12	Hollow Iron	724
13	Bucket + Concrete	1940

3.4 Cycle Time

3.4.1 Direct Observation

Field observations, which were then processed, obtained a direct observation cycle time from loading to return time. An example of cycle time for 1 set of column reinforcements was taken from direct field observations. The cycle time from Installation to Return Time is 7.34 min.

3.4.2 Theoretical Calculation

In the theoretical Cycle Time Calculation, the coordinates of the tower crane, Fabrication, MPS Formwork, and Supply Point are needed. An example of Cycle Time Calculation for 1 set of Column reinforcement work is taken. So, the following data is obtained.

Tower Crane Coordinates :(0; 0)
Supply Point Coordinates :(22.43;8.19)
Demand Point Coordinates :(22.642;38.391)

- Distance between Demand Point and Tower Crane

  $d_1 = \sqrt{(y_{tc-}y_p)^2 + (x_{tc-}x_p)^2}$

  $= \sqrt{(0-38.391)^2 + (0-22.642)^2}$

  $= 44.57$ m
- Distance between Supply Point and Tower Crane

  $d_2 = \sqrt{(y_{tc-}y_s)^2 + (x_{tc-}x_s)^2}$

  $= \sqrt{(0-8.19)^2 + (0-22.43)^2}$

  $= 23.88$ m
- Distance between Supply Point and Demand Point

  $d_3 = \sqrt{(y_{s-}y_p)^2 + (x_{s-}x_p)^2}$

  $= \sqrt{(8.19-38.391)^2 + (22.43-22.642)^2}$

  $= 30.205$ m
- Trolley Distance

  D $= d_1 - d_2$

  $= 20.690$ m
- Slewing Angle

  Cos x $= \frac{d_1^2 + d_2^2 - d_3^2}{2\ x\ d_1 x d_2}$

  $= 0.773$

  X $= 39.419°$

Transport Time Calculation

- Hoist

  Vv = 44 m/min

  Dv = 39 m

  Tv $= \frac{39}{44}$

  = 0.886 min
- Slewing

  Vr = 345,6°/min

  Dr = 39.419°

  Tr $= \frac{39.419}{345,6}$

  = 0.114 min
- Trolley

  Vh = 69.6 m/min

  Dh = 20.690 m

  Th $= \frac{20.690}{69.6}$

  = 0.297 min
- Landing

  Vv = 44 m/min

  Dv = 6 m

  Tv $= \frac{6}{44}$

  = 0.136 min

Obtained for total transport time = 0.886 + 0.114 +0.297 + 0.136 = 1.434 min

Payback Time Calculation

- Hoist

Vv	= 88 m/min
Dv	= 6 m
Tv	$= \frac{6}{88}$
	= 0.068 min

- Slewing

Vr	= 345,6°/min
Dr	= 39.419°
Tr	$= \frac{39.419}{345,6}$
	= 0.114 min

- Trolley

Vh	= 69.6 m/min
Dh	= 20.690 m
Th	$= \frac{20.690}{69.6}$
	= 0.297 min

- Landing

Vv	= 88 m/min
Dv	= 39 m
Th	$= \frac{39}{88}$
	= 0.443 min

Obtained for total transport time = 0.068 + 0.114 + 0.297 + 0.443 = 0.923 min

From the theoretical calculations above, the total tower crane cycle time for transporting 1 set of column fabrication is obtained as follows:

Cycle Time = 1.367 + 1.434 + 0.923 + 1.372
= 5.096 min

The results of the cycle time calculations for each work are then averaged for each phase, and the summary is presented as shown in Table 3.

Table 3. Recapitulation of the Average Cycle Time of Direct Observation and Theoretical Calculation Cycle Time in Each Phase.

No	Work	Cycle Time of Direct Observation (Minute)								Cycle Time of Theoretical Calculation (Minute)							
		Installation	Hoisting	slewing	Trolley	Landing	Demolish	Return Time	Total	Installation	Hoisting	slewing	Trolley	Landing	Demolish	Return Time	Total
1	Formwork Type 1	1.271	0.659	0.471	0.314	1.125	1.232	1.576	6.647	1.271	0.878	0.153	0.185	0.204	1.232	0.882	4.804
2	Formwork Type 2	1.138	0.647	0.529	0.357	1.113	1.044	1.524	6.352	1.138	0.886	0.124	0.172	0.136	1.044	0.807	4.307
3	Multiplex Formwork	1.167	0.752	0.507	0.360	0.636	0.961	1.458	5.841	1.167	0.866	0.098	0.157	0.107	0.961	0.741	4.097
4	Shear wall formwork	1.082	0.717	0.624	0.375	0.882	1.144	1.617	6.440	1.082	0.886	0.190	0.033	0.136	1.144	0.735	4.206
5	Column	0.945	0.741	0.604	0.333	1.304	1.160	1.547	6.634	0.945	0.977	0.170	0.215	0.136	1.160	0.942	4.545
6	Beam Reinforcement	1.215	0.688	0.565	0.419	0.524	0.729	1.471	5.611	1.215	0.932	0.140	0.195	0.114	0.729	0.857	4.181
7	Slab Reinforcement	0.889	0.738	0.488	0.428	0.405	0.672	1.367	4.987	0.889	0.932	0.140	0.195	0.136	0.672	0.869	3.832
8	Hollow iron	1.060	0.745	0.492	0.371	0.673	0.952	1.504	5.798	1.060	0.857	0.098	0.157	0.103	0.952	0.735	3.962
9	Bucket + Concrete	1.382	0.644	0.489	0.476	0.481	2.844	1.529	7.844	1.382	0.874	0.158	0.214	0.102	2.844	0.860	6.432
	Average	1.128	0.704	0.530	0.381	0.794	1.193	1.510	6.239	1.128	0.899	0.141	0.169	0.131	1.193	0.825	4.485

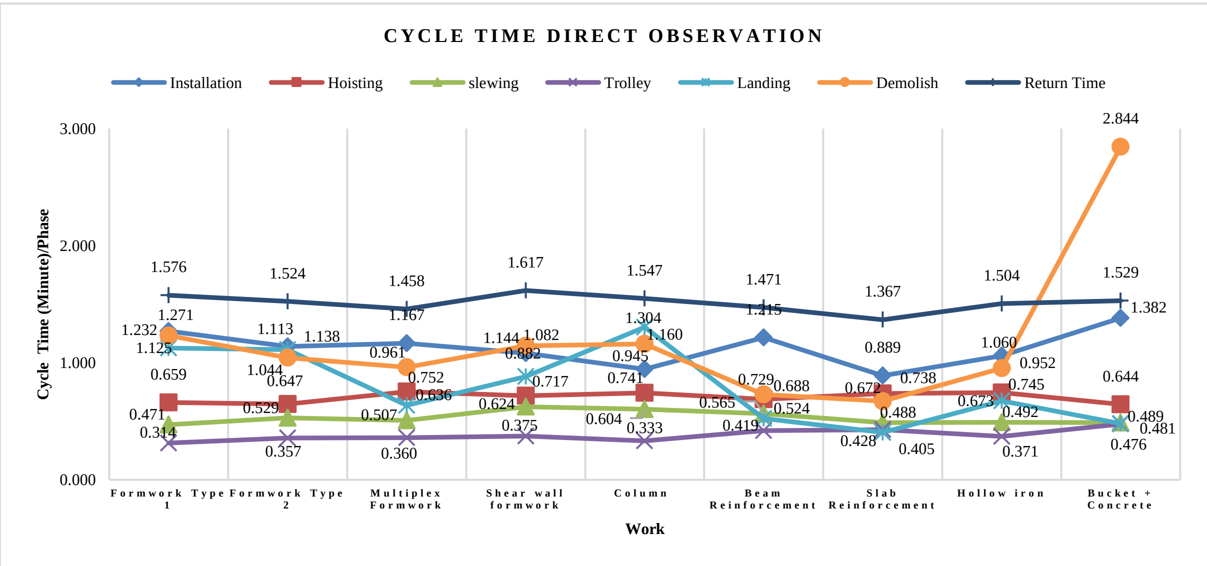

Figure 1. Cycle time of direct observation for each phase

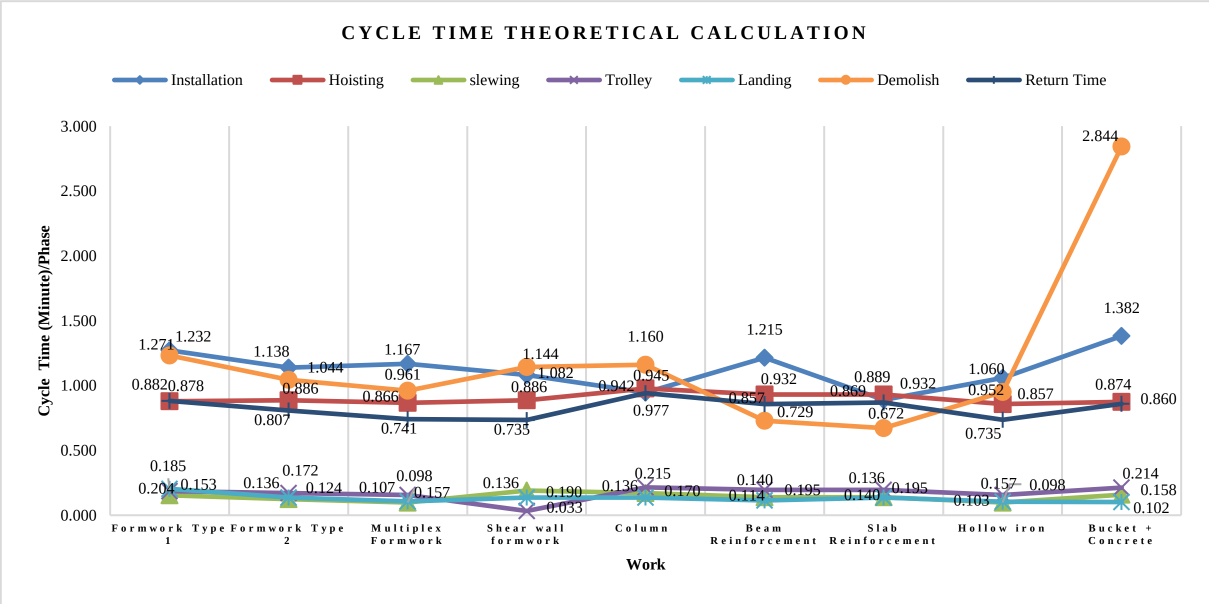

Figure 2. Cycle time of Theoretical Calculation for each phase

Table 3 is clarified using graphs that can be seen in Figures 1 and 2 above, the graph recapitulation of the average cycle time of the tower crane in each phase and activity is presented. In each phase, the three phases with the longest average cycle time based on direct observation were Installation (1.128 minutes), Return Time (1.510 minutes), and Demolish (1.193 minutes). Meanwhile, in the theoretical cycle time calculations, the three phases with the longest average cycle time were Demolish (1.193 minutes), Installation (1.128 minutes), and Hoisting (0.889 minutes). Regarding work activities, it was found that the longest average cycle time for both methods in each phase occurred in the Bucket + Concrete operation, with a direct observation cycle time of 7.844 minutes and a theoretical cycle time of 6.432 minutes.

3.5 Productivity

3.5.1 Direct Observation

During seven days of direct field observation, productivity for each task was recorded. For example, in the column work, with a volume of 1,005.702 kg, productivity was calculated using the formula where volume is divided by the cycle time of each phase, resulting in productivity for each phase. For instance, in the column work during the Landing phase, 1,005.702 kg divided by 1.034 minutes resulted in a 771.326 kg/minute productivity.

3.5.2 Theoretical Calculation Productivity

The productivity calculation is the same for both; the difference lies in the cycle time used. For example, in the column work during the Landing phase, 1,005.702 kg divided by 0.136 minutes resulted in a 7,375.148 kg/minute productivity. The results of the productivity calculations for each work are summarized and then averaged for each phase, as shown in Table 4.

Table 4. Recapitulation of the Productivity of Direct Observation and Theoretical Calculation Productivity in Each Phase.

No	Work	Productivity of Direct Observation (Kg/Minute)								Productivity of Theoretical Calculation (Kg/Minute)							
		Installation	**Hoisting**	**slewing**	**Trolley**	**Landing**	**Demolish**	**Return Time**	**Total**	**Installation**	**Hoisting**	**slewing**	**Trolley**	**Landing**	**Demolish**	**Return Time**	**Total**
1	Formwork Type 1	1574	3034	4249	6368	1778	1623	1269	301	1574	2278	13049	10833	9824	1623	2268	416
2	Formwork Type 2	2637	4634	5667	8402	2696	2874	1969	472	2637	3385	24212	17456	22000	2874	3717	696
3	Multiplex Formwork	771	1197	1775	2500	1415	936	617	154	771	1040	9178	5748	8377	936	1214	219
4	Shear wall formwork	139	209	240	400	170	131	93	23	139	169	788	4567	1100	131	204	35
5	Column	1064	1357	1665	3018	771	867	650	152	1064	1029	5917	4680	7375	867	1068	221
6	Beam Reinforce ment	792	1399	1703	2298	1839	1321	655	172	792	1033	6902	4941	8474	1321	1123	230
7	Slab Reinforce ment	832	1003	1515	1730	1829	1102	541	148	832	794	5304	3797	5427	1102	852	193
8	Hollow iron	683	971	1471	1950	1075	761	481	125	683	844	7384	4624	7008	761	985	182
9	Bucket + Concrete	1404	3011	3966	4076	4037	682	1269	247	1404	2220	12269	9081	19064	682	2257	301
	Average	1100	1868	2473	3416	1734	1144	838	199	1100	1421	9445	7303	9850	1144	1521	277

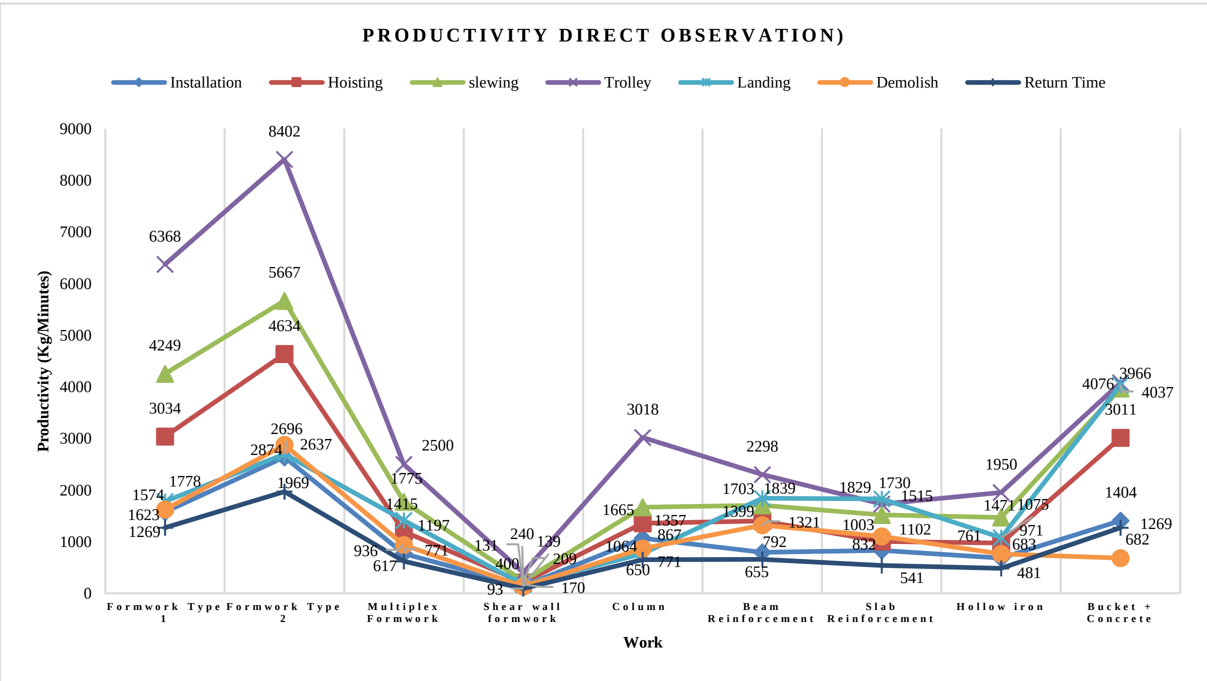

Figure 3. Productivity of direct observation for each phase

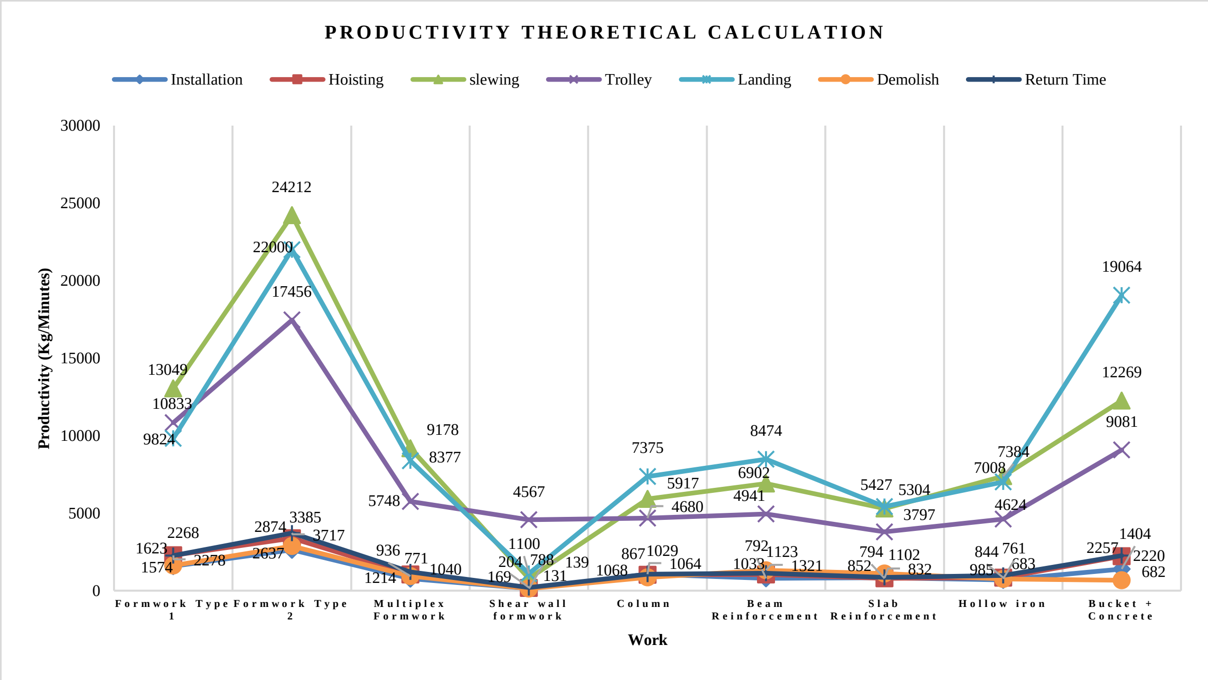

Figure 4. Productivity of Theoretical Calculation for each phase

Table 4 is clarified using graphs that can be seen in Figures 3 and 4 above, presenting the graph summarizing the average productivity of the tower crane in each phase and activity. In each phase, the three phases with the highest average productivity based on direct observation were Trolley (3416 kg/minute), Slewing (2473 kg/minute), and Hoisting (1868 kg/minute). Meanwhile, in the theoretical productivity calculations, the three phases with the highest average productivity were Landing (9850 kg/minute), Slewing (9445 kg/minute), and Trolley (7303 kg/minute). Regarding work activities, it was found that the longest average productivity for both methods in each phase occurred during Formwork Type 2 operations, with a direct observation productivity of 472 kg/minute and a theoretical productivity of 696 kg/minute.

3.8 Comparative Analysis of Productivity

The productivity of the tower crane is obtained by calculating the average work productivity and the average productivity per phase, followed by a comparative analysis between the productivity obtained from direct field observations and the theoretical productivity calculated based on the specifications of the tower crane, resulting in a comparison as shown in Tables 5 and 6.

Table 5. Comparison of Average Productivity for the Work

No	Work	Productivity (kg/Minute)		Productivity (kg/Hour)		Comparison Percentage (%)
		Direct Observation	Theoretical Calculation	Direct Observation	Theoretical Calculation	
1	Formwork Type 1	301	416	18053	24981	38%
2	Formwork Type 2	472	697	28338	41791	47%
3	Multiplex Formwork	154	220	9245	13181	43%
4	Shear wall formwork	23	36	1397	2140	53%
5	Column	152	221	9096	13277	46%
6	Beam Reinforcement	172	230	10297	13820	34%
7	Slab Reinforcement	148	193	8904	11586	30%
8	Hollow iron	125	183	7492	10964	46%
9	Bucket + Concrete	247	302	14839	18096	22%
	Average					40%

Table 5 above shows that the average productivity comparison for each task is 40%, meaning that productivity during the theoretical cycle time calculation is 40% higher than productivity from direct field observations.

Table 6. Comparison of the Average Productivity for Each Phase

No	Phase	Productivity (kg/Minute)		Productivity (kg/Hour)		Comparison Percentage (%)
		Direct Observation	Theoretical Calculation	Direct Observation	Theoretical Calculation	
1	Installation	1100	1100	65978	65978	0%
2	Hoisting	1868	1421	112099	85286	24%
3	slewing	2473	9445	148355	566678	282%
4	Trolley	3416	7303	204951	438177	114%
5	Landing	4037	9850	242199	590996	144%
6	Demolish	1144	1144	68655	68655	0%
7	Return Time	838	1521	50296	91260	81%
		Average				92%

Table 6 above shows a significant comparison, with the average productivity for each phase being 92%, meaning that productivity during the theoretical cycle time calculation is 92% higher than productivity from direct field observations.

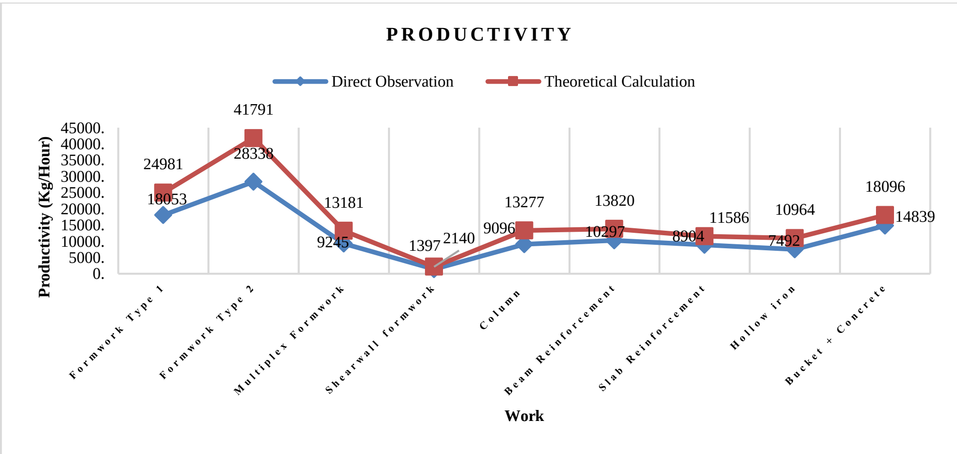

Figure 5. Comparison of the Average Productivity for Each Work

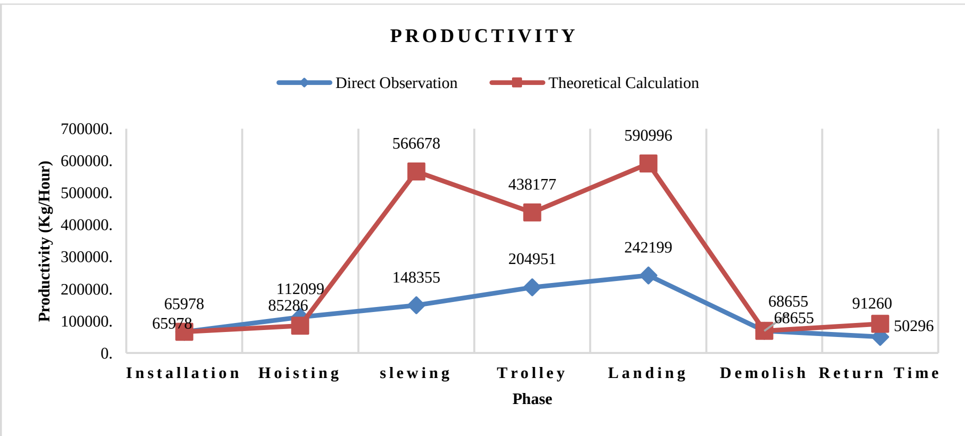

Figure 6. Comparison of the Average Productivity for Each Phase

Figure 5, which compares the average productivity for each phase of every work, shows that theoretical calculation productivity is higher than direct observation productivity. The highest productivity for both methods was found in the Formwork Type 2 task, with a direct observation value of 28,338 kg/hour and a theoretical calculation value of 41,791 kg/hour. Figure 6, which compares the average productivity for each work in every phase, found that theoretical calculation productivity is higher than direct observation productivity. The highest productivity for both methods was observed in the Landing phase, with a direct observation value of 242,199 kg/hour and a theoretical calculation value of 590,996 kg/hour.

This study demonstrates a significant comparison, emphasizing that in planning the productivity values of tower cranes, careful attention must be given to the productivity of each phase to avoid impacting the productivity of each lifting work. This ensures that the planned productivity of the tower crane does not experience delays that could affect project duration and lead to cost overruns. This study is consistent with previous research in the journal "Tower Crane Heavy Equipment Productivity for Casting in Building Construction," where the productivity of theoretical calculations with higher specifications compared to the productivity of direct field observations.

4. Conclusion

Observations of cycle time and productivity revealed significant differences between direct field observations and theoretical calculations. The phases with the longest cycle time included installation, return time, and demolition, while the highest productivity was noted in the landing, slewing, and trolley phases. Work on formwork type 2 demonstrated the highest productivity, with a direct observation value of 28,338 kg/hour and a theoretical value of 41,791 kg/hour. On average, theoretical productivity values were 40% higher for tasks and 92% higher per phase compared to direct observations. The results underscore the need for meticulous planning of tower crane productivity for each phase to minimize delays and prevent project cost overruns. This comparison can be used to plan the operational cost budget of the tower crane so that there is no overrun of the allocation of funds during the implementation of the project's construction. In an interview with a tower crane operator, there are several external factors, that influence productivity differences. These factors include the theoretical calculations based on equipment specifications that have not been updated annually. Additionally, from the results of the interview with the tower crane operator, several external factors affect the stability of tower crane productivity on site, such as weather conditions like wind direction, the placement of the tower crane, the capacity of each lifting cycle, and the operator's skills in operating the tower crane. These external factors can be used as an analysis for future research.

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