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Original Article

Technical Evaluation of Elevator Performance and Capacity Planning in High-Rise Apartment Towers: A Case Study in Jakarta

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ABSTRACT

Elevator systems are critical for ensuring efficient vertical mobility, safety, and occupant comfort in high-rise residential buildings. This study presents a comprehensive performance evaluation of the elevator system in a three-tower apartment complex in Jakarta, Indonesia. The analysis integrates both qualitative and quantitative methods to assess key performance indicators, including peak load demand, round-trip time, handling capacity, recommended number of elevator units, waiting time, and estimated daily energy consumption. The peak load during the initial five-minute interval was found to range from 23 to 48 persons per tower. Elevator speeds were set at 180 m/min for Tower 1 and 150 m/min for Towers 2 and 3, resulting in round-trip time values between 183 and 208 seconds. The estimated handling capacities varied from 54 to 69 persons per elevator. To ensure optimal service performance and redundancy, four elevator units are recommended for Tower 1, and three units each for Towers 2 and 3. The projected daily energy consumption, based on a five-hour operational window, ranges from 80.51 to 96.61 kWh. The findings offer practical insights for designing energy-efficient and service-optimized elevator systems in high-density urban residential developments.

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1. Introduction

Urban population growth has led to severe housing shortages in major metropolitan areas worldwide. Consequently, vertical residential expansion through high-rise apartments has become prevalent [1-4]. This verticalization introduces critical engineering challenges, chief among them being the provision of efficient, safe, and energy-conscious vertical transportation. Despite the essential role of elevators in supporting resident mobility and comfort, many high-rise buildings, particularly in rapidly urbanizing cities such as Jakarta, operate with under-optimized elevator systems. Similar challenges exist in other major global cities, as shown in Figure 1 [5]. Common problems include excessive waiting times, limited carrying capacity, and high energy consumption, which remain insufficiently analyzed in the literature. High energy usage by Elevators contribute significantly to the carbon footprint and operational costs of buildings [5, 6]. This underscores the need for comprehensive performance evaluations of elevator systems specifically tailored to the spatial and demographic characteristics of high-rise residential developments in urban Indonesia [6].

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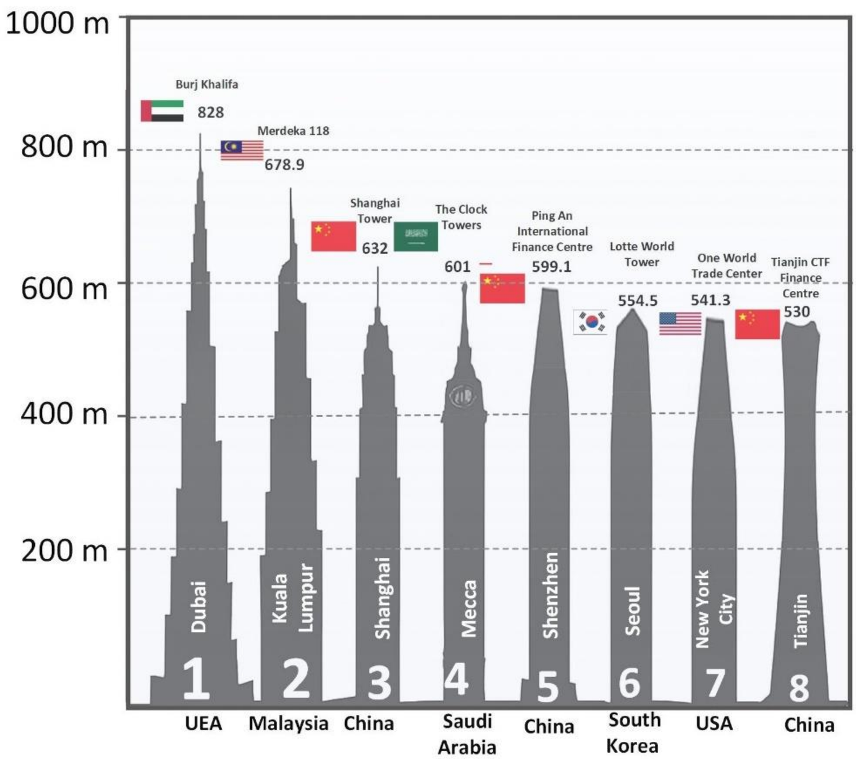

Figure 1. The Eight tallest buildings were completed in 2024.

Planning is a systematic process of formulating goals and determining the steps to achieve them, which are then evaluated through a systematic assessment of the results of the planning, aiming to achieve efficiency and security by meeting the planning needs [4, 7]. Elevators are vertical transportation systems that are crucial in multi-story buildings to support the activities of occupants [8]. Elevators are designed for vertical transportation to quickly and safely transport people, including residents and goods, between floors of buildings. Activities in high-rise buildings are disrupted without elevators, especially for elderly residents (elderly), people with disabilities, and workers who must always move to maintain high mobility. Therefore, the design and planning of an elevator system as a means of vertical transportation must consider several aspects, including functional needs, capacity, speed, energy efficiency, safety, and user comfort [9].

Professionals in the field of mechanical and electrical (ME) engineering face challenges in designing and planning elevator systems based on the needs and characteristics of high-rise buildings. For example, office buildings with high circulation of elevator users require elevator systems with greater speeds and capacities than high-rise buildings intended for residences and apartments [10, 11]. The Elevator circulation system considers the number of floors, number of occupants, and selection of the right elevator technology, which also affects the overall performance and efficiency of the multi-story building [12, 13]. Elevators are needed to facilitate the activities of residents or transport goods needed by building residents to make it easier to go up and down floors, so that the time needed is more efficient and saves energy compared with using manual stairs [14]. Although elevators have become a basic requirement in high-rise buildings, many buildings in Indonesia have not optimized the design and management of elevator systems [5, 15, 16]. Common problems encountered in the field include a mismatch between the elevator capacity and the number of occupants, lack of regular maintenance, and a system design that does not consider the overall flow of occupant traffic. These problems must be solved through careful planning and evaluation.

Therefore, several key aspects must be considered to achieve an efficient and optimal design. The number of building occupants must be accurately calculated to meet the needs of elevators that can support the vertical transportation system in the building [17]. The analysis and evaluation in this field align with the direction of sustainable development, which emphasizes energy efficiency, enhances the quality of life of the community, and optimizes resource utilization [18]. Calculating peak loads requires building data in the form of the net area of the building [19] as follows: ensuring that transportation capacity and waiting time are maintained within the required service level when there is a concentration of passengers during peak hours [20]. The round-trip time is the cycle time required for the elevator to pick up passengers from the main entrance, deliver them to the upper levels, and return to the main entrance [21-23]. Determining the optimal number of elevators is challenging, and selecting a number close to the actual need is best. Uneven user movement patterns cause uncertainty, for example, during peak hours of high and low demand [17, 24].It is essential to determine the energy consumption of an elevator, and studies on elevator traffic have demonstrated that elevator cycles significantly impact energy consumption [25]; therefore, they affect the lifting capacity of the elevator. It is important to determine the energy consumption of an elevator, and studies on elevator traffic have shown that elevator cycles significantly affect energy consumption [26].

This study examines the performance gap in vertical transportation systems through a comprehensive analysis of elevator operations in a three-tower residential complex in Jakarta, Indonesia. Utilizing a mixed-method approach, this study incorporates occupancy load estimation, peak demand analysis, round-trip time (RTT), elevator capacity assessment, unit adequacy, service interval calculation, total load and motor torque estimation, and energy consumption modeling. By benchmarking these indicators against established performance standards, this study identified critical inefficiencies during peak usage and highlighted discrepancies between design assumptions and actual operations. The novelty of this research lies in its context-specific analytical framework tailored to dense urban residential environments, providing diagnostic insights and practical recommendations for enhancing elevator efficiency, user comfort, and energy sustainability. These findings contribute to the optimization of high-rise residential building design and serve as valuable technical references for architects, MEP engineers, and vertical transportation planners. Furthermore, the outcomes of this study can inform the development of regulatory guidelines for vertical-transport planning in rapidly urbanizing regions. The proposed framework is adaptable to future studies involving smart elevator technologies and energy-efficient design strategies for high-density urban environments.

2. Methods and Data Collections

This study adopted a mixed-methods approach, integrating qualitative and quantitative techniques to evaluate the mechanical performance of elevators in high-rise residential buildings. The qualitative component provided a contextual understanding of elevator system planning, whereas the quantitative analysis offered measurable indicators of system efficiency. A descriptive framework was used to document elevator characteristics using both primary and secondary data sources [18]. An empirical case study was conducted on a high-rise residential complex in Jakarta, Indonesia [27, 28]. Primary data were collected through field surveys and direct observations of spatial configurations, including residential unit layouts, elevator lobbies, public circulation areas, and shared amenities. Secondary data were obtained from building management archives and included architectural drawings, mechanical-electrical (ME) documentation, elevator technical specifications, floor distribution, and occupancy profiles. The residential complex comprises three towers: Tower 1 (43 floors), Tower 2 (34 floors), and Tower 3 (30 floors), each supported by two basement levels. The complex includes 761 residential units and occupies a land area of 18,954.15 m², with a gross floor area (GFA) of 121,287.15 m². Table 1 summarizes the unit typologies and estimated occupancy levels, which were determined based on the design standards outlined in Indonesia's Ministry of Public Works Regulation No. 26/PRT/M/2008, concerning residential occupancy thresholds. Additional calculations were conducted to estimate the elevator demand, RTT, and peak traffic capacity using engineering formulas adapted from vertical transportation planning standards. These metrics serve as key performance indicators for evaluating elevator adequacy, service interval, motor sizing, and projected energy consumption.

Table 1. The unit type, area, and estimated number of occupants were considered [29].

	Information	Area (m²)	Unit Type	Occupancy Load		
				Regulation-based) †	Based on bedrooms‡	Take for Calculation
Tower 1	Unit Type A	64,58	2 Bedroom	3,5	4	4
	Unit Type B	76,31	2 Bedroom	4,1	4	4
	Unit Type C	111,08	3 Bedroom	5,97	6	6
	Unit Type D	52,14	2 Bedroom	2,8	4	4
	Unit Type E	73,25	2 Bedroom	3,9	4	4
	Total Unit			440 unit		
Tower 1	Unit Type 2A	113,33	3 Bedroom	6,1	6	6
	Unit Type 2B	129,63	3 Bedroom	6,96	6	6
	Unit Type 2D	98,10	2 Bedroom	5,3	4	4
	Total Unit			165 unit		
Tower 3	Unit Type 3A1	72	1 Bedroom	3,9	2	2
	Unit Type 3A2	72	1 Bedroom	3,9	2	2
	Unit Type 3A3	72	1 Bedroom	3,9	2	2
	Unit Type 3B	115,65	2 Bedroom	6,2	4	4
	Unit Type 3C	135	3 Bedroom	7,2	6	6
	Total Unit			156 unit		

† Based on Ministry of Public Works Regulation No. 26/PRT/M/2008 (18.6 m²/person). ‡ Standard assumption: one bedroom = two people

Detailed architectural and operational data for each tower, such as floor-by-floor layouts, unit distributions, and vertical circulation schemes, are presented in Table 2 (Tower 1), Table 3 (Tower 2), and Table 4 (Tower 3). These datasets form the basis for calculating the peak occupant loads, estimating the elevator RTT, analyzing the carrying capacity and adequacy, and modeling the energy consumption. This methodological framework ensures a comprehensive assessment of the efficiency, serviceability, and mechanical performance of elevator systems in buildings [6].

Table 2. Floor and unit distribution of Tower 1 (43 floors).

No	Floor	Area (m²)	Floor Height (mm)	Function / Allocation	Occupancy Load
1	Ground Floor	1,680.35	5000	R. Genset Room, Lobby, Gym/Fitness Area	114
2	2	1,122.02	3300	Apt. Units (Type 1A, 1B, 1C, 1D, 1E)	46
3	3	1,122.02	3300	Apt. Units (Type 1A, 1B, 1C, 1D, 1E)	46
4	4-19	17,952.32	† 3300	Apt. Units (Type 1A, 1B, 1C, 1D, 1E)	736
5	20	1,122.02	3300	Apt. Units (Type 1A–1E), Water Tank	42
6	21	1,122.02	3300	Apt. Units (Type 1A–1E), Refuge Floor	38
7	22-41	2,244.04	‡3300	Apt. Units (Type 1A–1E)	920
8	Roof	1,122.02	-	Lift Machine Room, Roof Tank, Mechanical & Electrical (M&E) Room	
	Total	47.683,17			1942

Noted: Apt. = Apartment, †16 floors, ‡ 20 floors

2.1. *Calculation of the number of building occupants*

Following the data collection phase, the next step involves a comprehensive set of engineering calculations to evaluate the performance, adequacy, and energy efficiency of the elevator system [5]. These calculations are essential to ensure that the vertical transportation system meets safety standards, fulfills user comfort expectations, and operates efficiently under normal and peak conditions. The analytical scope includes estimating the number of building occupants, determining the peak load, analyzing passenger waiting time, and calculating the elevator RTT. It further covers the evaluation of the carrying capacity and system adequacy, total elevator load calculation, motor power and torque requirements, and energy consumption modeling of elevators. Collectively, these components provide a structured basis for assessing the effectiveness and sustainability of elevator systems.

Table 3. Floor and unit distribution of Tower 2 (34 floors).

No	Floor	Area (m^2)	Floor Height (mm)	Function / Allocation	Occupancy Load
1	Ground Floor	858.81	5,000	S. Lobby, General Office, GM Office, Multi-Purpose Room	29
2	2	858.11	3,300	Apt. Unit Type 2A, 2B	30
3	3	858.11	3,300	Apt. Unit Type 2A, 2B	30
4	4-12	7,722.99	†3,300	Apt. Unit Type 2A, 2B	270
5	13	858.11	3,300	Apt. Unit Type 2A, 2B, Water Tank	28
6	14-34	11,220.20	‡3,300	Apt. Unit Type 2A, 2B	630
7	Roof	858.11	-	Lift Machine Room, Roof Tank, Mechanical & Electrical (M&E) Room	
	Total	30,005.37	-		1017

Noted: Apt. = Apartment, †9 floors, ‡ 21 floors

Table 4. Floor and unit distribution of Tower 3 (30 floors).

No	Floor	Area (m^2)	Floor Height (mm)	Function / Allocation	Occupancy Load
1	Ground Floor	873.66	5,000	Reception, Café & Bar, Meeting Room, Kitchen, Operational Office	150
2	2	742.93	3,300	Gym/Fitness, Playground, Office	83
3	3	742.93	3,300	Apt. Units (Type 3A1, 3A2, 3A3)	14
4	4-15	8,915.16	†3,300	Apt. Units (Type 3A1, 3A2, 3A3)	168
5	16	815.73	3,300	Apt. Units (Type 3B, 3C)	22
6	17-27	8,973.03	‡3,300	Apt. Units (Type 3B, 3C)	242
7	28	815.73	-	Apt. Units (Type 3B, 3C)	22
8	Roof	815.73	-	Machine Room, Roof Tank, M&E Room	
	Total				701

Noted: Apt. = Apartment, †12 floors, ‡ 11 floors

2.1.1. Calculation of the number of building occupants

The building occupant count is a fundamental parameter in elevator planning because it affects vertical transportation demand, capacity sizing, and system performance during peak periods. An accurate estimation of the maximum occupancy is essential to ensure that the elevator system efficiently accommodates user mobility in high-load scenarios. This estimation is based on the net usable floor area divided by the average area per person, as specified in the national building regulations. In Indonesia, this approach follows the Ministry of Public Works Regulation (Permen PU No. 26/PRT/M/2008), which outlines residential population density standards. Accordingly, the maximum number of occupants (N) was calculated using the following equation:

$$N = \frac{A}{a''} \tag{1}$$

where A represents the total usable building area (m²), and a" denotes the net floor area required per person (m² per person). For residential buildings, a" varies based on the unit type or occupancy, with values derived from zoning guidelines. This calculation was refined by considering residential units per floor and the average household size to estimate the total population. The final occupancy figures were validated against the national design criteria to ensure compliance and alignment with the usage patterns.

2.1.2. Calculating peak load

Peak load refers to the estimated number of building occupants requiring elevator service during the highest demand interval, typically within five minutes of peak periods, such as morning entry or evening exit. An accurate estimation of the peak load is essential for designing elevator systems that maintain efficiency and user comfort under maximum occupancy. This estimation was performed by applying an empirical percentage to the total number of building occupants. This percentage reflects user behavior patterns during peak periods based on the planning guidelines. In Indonesian elevator design standards, these empirical percentages vary according to the building type and use. Table 5 provides the recommended values for estimating the peak demand across occupancy categories, facilitating the realistic modeling of the elevator load during critical periods.

Table 5. Estimated arrival rates and up-peak intervals based on building type [20].

Building type	Arrival Rate (%)	Up-Peak Interval (s)
Hotel	10-15	30-50
Flats	5-7	40-90
Hospital	8-10	30-50
School	15-25	30-50
Office (multiple tenancy – regular)	11–15	25–30
Office (multiple tenancy – prestige)	17	20–25
Office (single tenancy – regular)	15	20–30
Office (single tenancy – prestige)	17–25	20–25
Residential	15	25–35

2.1.3. Calculating waiting time

Waiting time, defined as the time a passenger must wait before entering an elevator, is a key performance metric for evaluating vertical transportation systems, particularly in high-rise buildings. It directly affects user satisfaction, perceived service quality, and overall operational efficiency. Acceptable thresholds for waiting time vary based on building type, user density, and socio-cultural expectations. For instance, occupants of densely populated urban environments generally exhibit a lower tolerance for delays than those in suburban areas. From a design standpoint, the waiting time is influenced by several factors, including the elevator capacity, number of elevators in service, and round-trip (RT) time required for a car to complete a full operational cycle from the main floor to the uppermost level and back. Additionally, passenger boarding and alighting times, typically estimated at 1.5 s per person, contribute to the total service time at each stop. The average waiting time is commonly analyzed using three primary parameters: round-trip time (RT, in seconds), interval between elevator arrivals (I, in seconds), and number of elevators in operation (N). These variables are interrelated using the following equation [6].

$$I = \frac{RT}{N} \tag{2}$$

where RT is the round-trip time of the elevator (s), I is the interval or average time between elevator arrivals (s), and N is the number of elevators operating in the system.

2.1.4. Calculating round-trip time

The round-trip time (RT) refers to the total time required for an elevator to complete a full operational cycle. This includes the time from passenger entry at the lobby, elevator departure from the ground floor, stops at intermediate floors, arrival at the top floor, and return journey [21]. The round-trip time is essential for evaluating the elevator performance and system capacity and can be calculated as follows [6]:

$$T = \frac{(2h+4s)(n-1)+s(3M+4)}{s} \tag{3}$$

where T denotes the round-trip time in seconds, h is the floor-to-floor distance in meters, s is the average speed of the elevator in meters per second, n represents the number of floors served, and M indicates the elevator load capacity in kilograms.

These variables collectively enable the estimation of the time required for an elevator to complete a full operational cycle, transporting passengers from the ground floor to the upper floors and returning to the starting point of the cycle.

2.1.5. Estimating Carrying Capacity and Determining the Required Number of Elevators

The carrying capacity of an elevator system and the number of elevator units required are interdependent parameters essential for ensuring efficient vertical transportation, particularly during peak load periods. The carrying capacity refers to the total mass that a single elevator can transport within a specified time frame, commonly set at five minutes (300 s) to represent rush-hour conditions. This capacity is a function of the rated load of the elevator (in kg) and the round-trip time (in s), which defines the duration of a full operational cycle. The effective transport capacity per elevator unit during the peak interval was estimated using the following equation [30]:

$$C = \frac{5 \times 60 \times M}{W} = \frac{300 \times M}{T} \tag{4}$$

where C is the maximum load capacity of the elevator, M is the number of passengers per trip (15), and T is the round-trip time. This formulation assumes ideal utilization at full capacity over the designated period.

To ensure that the system accommodates the projected occupant traffic under peak demand, it is necessary to estimate the minimum number of elevator units required for the system. This calculation considers the gross floor area of the building, number of floors, elevator performance characteristics, occupant density, and proportion of occupants moving during peak hours. The number of elevators required (N) can be determined using the following equation [30].

$$N = \frac{2 \times a \times n \times T \times PHC}{3 \times M \times [(200 \times a") + (n \times T \times PHC)]} \tag{5}$$

In this equation, a represents the gross floor area (m²), n is the number of floors, T is the round-trip time (s), PHC is the peak-hour coefficient (fraction of total occupants active during peak), a'' is the net floor area per person (m²/person), and M is the elevator capacity (kg). This equation provides a balanced assessment of supply and demand, ensuring that the number of elevator units is sufficient to maintain acceptable service levels and minimize waiting times.

2.1.6. Total load calculation

Calculating the total load is critical to ensure that the elevator system is properly designed to accommodate the maximum mechanical load that it may experience during its operation. This total load includes the combined weight of the elevator cabin, maximum anticipated load of passengers and goods, and counterweight. The total force that must be lifted by the elevator, expressed in Newtons (N), was calculated using the following equation [31]:

$$W_{\text{total}} = W_{\text{cabin}} + W_{\text{load}} + W_{\text{cw}} \tag{6}$$

In this formulation, W_{total} represents the total lifting force acting on the elevator system, expressed in newtons (N). It is the sum of three primary components: W_{cabin}, which is the weight of the elevator cabin; W_{load}, which refers to the maximum expected weight of passengers and goods transported during peak conditions; and W_{cw}, which is the weight of the counterbalance installed to offset the system load and reduce the energy demand on the elevator motor. These components are expressed in newtons to maintain consistency in unit measurements and ensure accurate mechanical system calculations. Because the values of the cabin, load, and counterweight are typically obtained in units of mass (kg), they must be converted to weight (Newtons) using the standard gravitational formula:

$$W = m \times g \tag{7}$$

where W is the weight in Newtons (N), m is the mass in kilograms (kg), and g is the gravitational acceleration, which is taken as 9.81 m/s². This conversion ensured that all load components were represented in force units, which is essential for the accurate mechanical and structural analysis of the elevator system.

2.1.7. Calculation of required motor power and torque

Estimating the required motor power is a critical step in designing an elevator system capable of safely and efficiently lifting a full mechanical load. This load, denoted as W_{total}, consists of the combined mass of the elevator cabin and its rated payload, expressed in kilograms. The motor power requirement depends on three primary factors: gravitational acceleration g (typically taken as 9.81 m/s²), vertical travel speed of the elevator v (in meters per second), and mechanical efficiency of the traction system η, which is commonly assumed to be 0.8 (or 80%) to account for frictional and transmission losses. The power required to elevate the full load under steady-state conditions is calculated as [30]:

$$P = \frac{(W_{total} \times g \times v)}{\eta} \quad (8)$$

where P is the motor power (W). This equation defines the continuous electrical energy per unit time required for vertical motion under a full load, adjusted for mechanical inefficiency.

In addition to power, torque is a crucial parameter that governs the ability of a motor to initiate and sustain rotational motion under load. The required torque, denoted as τ and expressed in Newton-meters (Nm), depends on both the output power of the motor (P, in watts) and its rotational speed (n, in RPM). Torque is calculated by dividing the power by the angular velocity (ω), where angular velocity is defined as $\omega = 2\pi n/60$. Thus, the torque is obtained by applying the relation $\tau = P/\omega$, which links linear power requirements to the rotational dynamics of the motor shaft. This formulation allows for an accurate determination of the motor's capability to deliver the necessary force for elevator motion under various operational loads and velocities [32].

$$\tau = \frac{P \times 60}{2\pi \times n} \quad (9)$$

In this formulation, τ represents the rotational force delivered by the motor, P is the calculated power requirement, n is the motor speed, and π is a mathematical constant of approximately 3.1416. These equations link the linear motion requirements of the elevator to the rotational dynamics of its drive system, enabling the precise sizing of the motor based on the actual mechanical demands. Together, these formulations serve as the foundation for determining the energy and mechanical requirements of the elevator system, ensuring reliable, safe, and energy-efficient operation, particularly under peak loading conditions.

2.1.8. Energy consumption estimation

Estimating the energy consumption of elevators is essential for evaluating the overall efficiency and operational costs of vertical-transportation systems. This assessment is particularly relevant during peak periods, such as rush hours, when elevator usage is most intensive. The total energy consumption (E), expressed in kilowatt-hours (kWh), was calculated using the following equation [32]:

$$E = \frac{P \times t}{1000} \quad (10)$$

In this equation, E represents the estimated energy consumption in kilowatt-hours (kWh), P denotes the motor power in watts (W), and t refers to the duration of the elevator operation in hours. This formula provides a simplified estimation by assuming that the motor operates at constant power for a specified time interval.

3. Results and Discussions

The following section presents a comprehensive analysis of the mechanical design calculations performed for the elevator system of a high-rise residential complex comprising three apartment towers in Jakarta. The analysis aimed to determine the required mechanical capacity and service adequacy based on the architectural layout, occupancy load, and regulatory standards.

3.1. *Occupancy load analysis and implications for elevator design*

This section presents an analysis of the residential occupancy load across the three apartment towers, which serves as a critical parameter for determining the elevator demand and system capacity. The calculation was based on the Indonesian regulation Permen PU No. 26/PRT/M/2008, which provides standard floor area allocations per occupant and guides the estimation of theoretical maximum population densities in residential buildings.

Several factors influence the total occupancy load, including the number of apartment units per tower, unit type configurations, and number of floors.

- Tower 1: 436 units, 43 floors
- Tower 2: 165 units, 34 floors
- Tower 3: 156 units, 30 floors

The estimated number of occupants was determined by unit type, with the following occupancy assumptions:

- Type A, B, D, E: 2 persons per unit
- Type C: 3 persons per unit

To evaluate the distribution of residents across the entire complex, the proportional occupancy load of each tower was calculated based on the total estimated residential population of 1,781. These occupancy shares provide a foundation for evaluating the design requirements of vertical transportation systems.

As illustrated in Figure 2, Tower 1 accommodates the largest share of residents, accounting for approximately 51.21% of total occupancy. Tower 2 contributed 27.74%, and Tower 3 accounted for the remaining 21.06%. The figure highlights the population distribution per tower, which directly informs the subsequent calculations related to the elevator capacity, scheduling, and energy efficiency.

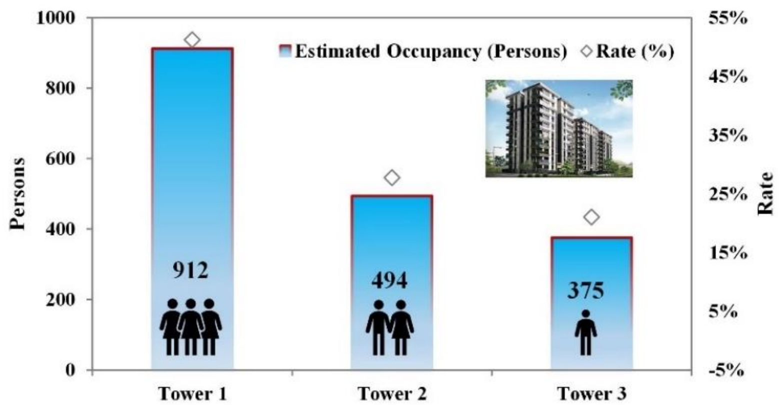

Figure 2. Distribution of estimated occupancy and proportional load per Tower.

3.2. *Peak load estimation and distribution analysis*

The peak load represents the estimated number of occupants requiring elevator service during the most critical five-minute interval of building operation, which typically occurs during morning departures or evening returns. The calculation follows standardized empirical assumptions, as outlined in the Indonesian National Regulation *Permen PU No. 26/PRT/M/2008*, using the following key parameters:

- Gross floor area (GFA): Tower 1 – 47,683.17 m²; Tower 2 – 30,005.37 m²; Tower 3 – 22,669.63 m²
- Total gross floor area (all towers): 100,358.17 m²
- Peak hour coefficient (PHC): 3%

- Net area per person (a″): 3 m²/person
- Elevator capacity (all towers): 1,050 kg (equivalent to 15 persons)
- Number of floors: Tower 1 – 43; Tower 2 – 34; Tower 3 – 30

Based on this regulation, the estimated peak load was derived by applying a 3% PHC to the total gross floor area and dividing it by the net area per capita. The result is the projected number of users requiring elevator services within the critical five-minute window for each tower. The estimation results are presented in Figure 3, which illustrates the proportional distribution of the peak elevator demand across the three towers.

Tower 1 contributed the largest share of peak demand, with 477 persons (47.51%), followed by Tower 2 with 300 persons (29.88%), and Tower 3 with 227 persons (22.61%). These proportions closely corresponded to each tower's respective GFA, affirming a direct correlation between spatial volume and vertical transportation requirements. Given the standard elevator capacity of 15 persons per trip, the number of required trips within the five-minute peak interval is approximately 32 trips for Tower 1 (477 ÷ 15), 20 trips for Tower 2 (300 ÷ 15), and 16 trips for Tower 3 (227 ÷ 15).

This spatial-to-demand correlation plays a critical role in informing future elevator system design strategies for high-rise residential buildings in the area. Prior studies have emphasized that optimizing space efficiency and vertical transport capacity is particularly crucial in supertall buildings, where the average space efficiency in Asian contexts reaches approximately 67.5%, and the ratio between the core area and gross floor area (GFA) significantly influences system performance [33]. Moreover, the implementation of advanced elevator technologies has been shown to significantly improve throughput and service quality, particularly during peak occupancy periods [10]. Group control systems are also vital for managing elevator traffic in tall structures. These systems are expected to ensure high reliability and responsiveness under fluctuating demands [34]. The integration of intelligent control algorithms and real-time dispatching mechanisms enables elevators to adapt dynamically to occupancy patterns and spatial layouts, thereby enhancing the overall system performance and operational efficiency.

The estimation of the required elevator trips thus provides a foundational input for more detailed analyses, including RTT, interval optimization, capacity adequacy, and energy-performance modeling. Among the three towers, Tower 1 exhibited the highest demand for elevator services owing to its greater floor area and occupant concentration. These insights serve as the basis for configuring elevator quantities, refining scheduling frequencies, and enhancing system resilience during peak usage, ultimately ensuring a balance between operational efficiency and occupant satisfaction.

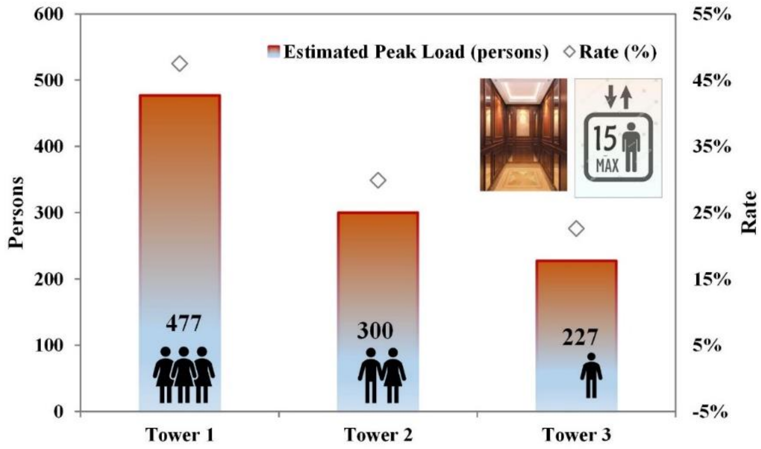

Figure 3. Estimated peak elevator load and distribution per tower within a 5-minute interval.

3.3. *Elevator round trip time, carrying capacity, and system requirements*

Efficient elevator performance is essential for ensuring safe, timely, and comfortable vertical transportation in high-rise residential buildings. This subsection presents the results of the elevator RTT calculations, carrying capacity estimations, and required unit assessments for each tower, based on the input parameters. Using the RTT values and Equation (4), the estimated elevator capacities within a five-minute peak period were determined to be 69, 54, and 59 persons for Tower 1, Tower 2, and 59 persons for Tower 3, respectively, per elevator unit. These capacities were compared with the peak occupancy loads derived using Eq. (1) in Section 3.2. To satisfy the projected peak demands, the minimum number of elevator units required for each tower was calculated, accounting for redundancy to ensure service continuity during maintenance. The analysis concluded that Tower 1 required four elevator units, whereas Towers 2 and 3 required three units each to maintain an efficient performance and acceptable service levels.

A key determinant of elevator system efficiency is the dispatch control algorithm, which directly influences passenger waiting times and operational responsiveness. During peak periods, such as morning departures and evening returns, dispatching strategies play a critical role in maintaining optimal service. Studies have shown that threshold-based dispatching, wherein elevators are dispatched after a predefined passenger count is reached, can significantly reduce waiting times by optimizing car utilization under heavy-traffic conditions [35]. In addition, the configuration of the call allocation logic has a substantial impact on system-level performance metrics such as start times and round-trip durations [36]. Even in moderate traffic scenarios, inadequate algorithmic strategies can lead to system saturation, reinforcing the need for adaptive control systems that can respond dynamically to fluctuating demand patterns.

As summarized in Table 6, Tower 1 demonstrated the highest elevator-carrying capacity (69 persons) and shortest elevator-waiting time (52 s), followed by Tower 3 with 59 persons and 61 s, and Tower 2 with the lowest capacity (54 persons) and longest waiting time (66.7 s). These differences were largely influenced by the floor count and elevator speed of each building. Tower 1 benefits from a higher elevator velocity (1.8 m/s) despite having the most floors (43), whereas Towers 2 and 3, with lower speeds (1.5 m/s), experience longer RTT and, consequently, longer waiting times. This confirms the strong interplay between building height, elevator speed, and system efficiency, reinforcing the necessity of appropriately selecting elevator specifications to match building geometry and occupant density.

Table 6. Summary of elevator capacity, requirements, and average waiting time per tower.

No	Tower	Carrying Capacity (persons/5 min)	Required Elevators (units)	Average Waiting Time (s)
1	Tower 1	69	4	52
2	Tower 2	54	3	66.7
3	Tower 3	59	3	61

Figure 4 illustrates the comparative elevator performance metrics (carrying capacity, number of elevator units, and average waiting time) for the three towers. As observed, Tower 1, with the highest number of floors and greatest population share, demands the most robust elevator service. These findings emphasize the significance of spatial configuration, occupant density, and trip time dynamics in vertical transportation planning, providing a quantitative foundation for system optimization and energy modeling in the future.

3.4. *Total elevator load and motor power estimation*

An essential aspect of elevator system performance is determining the total mechanical load that must be lifted during operation and estimating the corresponding motor power requirement. This ensures that the selected drive system provides sufficient performance under peak conditions. In this study, the total load comprised the elevator cabin mass, passenger/goods load, and counterweight system. For Tower 1, the cabin weight was 4,200 kg (two cabins each weighing 2,100 kg), and the maximum payload was 1,050 kg. The counterweight was configured to balance the cabin and 50% of the rated load, resulting in a counterweight mass of 2,625 kg. Consequently, the effective load requiring motor force was approximately 2,625 kg, and the gravitational force was computed using Eq. (6), with the total weight evaluated using Eq. (5).

Subsequently, the motor power requirement was estimated using Eq. (8), incorporating the gravitational acceleration, elevator velocity, and an assumed system efficiency of 80%. The results indicate that Tower 1, operating at 180 m/min, requires a motor rated at approximately 19.32 kW (≈26 HP), whereas Towers 2 and 3, operating at 150 m/min, each require 16.10 kW (≈21.6 HP). These values are critical for accurately sizing elevator motors according to load demands and operational velocity. The further torque requirements were calculated using Eq. (9), and the energy consumption over the operational periods was evaluated using Eq. (10).

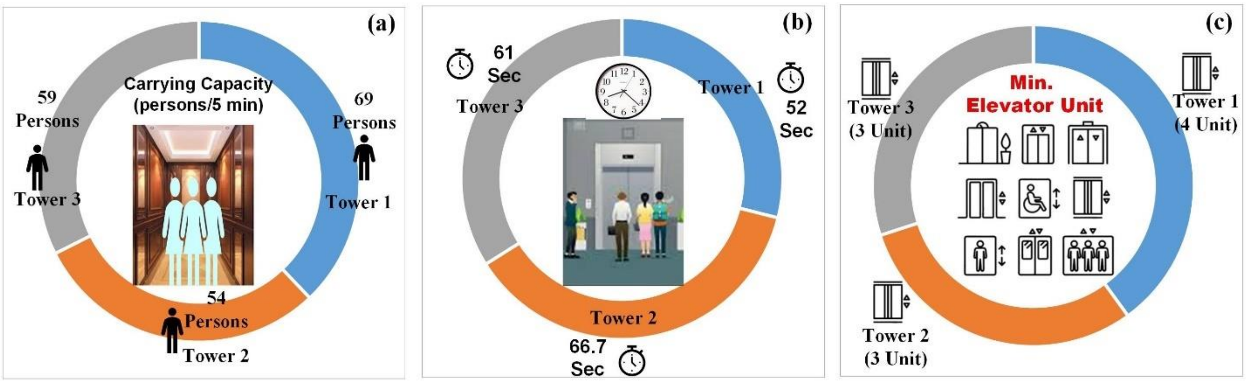

Figure 4. Elevator system performance metrics: (a) carrying capacity, (b) waiting time, and (c) required number of elevator units.

Efficient energy use is becoming increasingly important for the sustainability of elevator systems, particularly in high-rise buildings. Traditional hydraulic elevators often exhibit high energy losses, particularly during downward movement, where gravitational potential is dissipated as heat [37]. In contrast, modern regenerative drive systems, especially those equipped with supercapacitor-based energy storage, can significantly enhance energy efficiency by capturing and reusing braking energy [38]. Advanced elevator technologies, such as ropeless systems powered by linear motors, have redefined vertical mobility by eliminating counterweights and enabling multidirectional travel. These systems offer greater flexibility in core design and substantially improve power density, making them particularly advantageous in dense urban contexts where spatial and energy constraints are critical [39].

3.5. *Total elevator load and motor power estimation*

To complement the motor power estimation, the corresponding motor torque was calculated to ensure proper mechanical performance and alignment with the requirements of the drive system. In this analysis, all elevators were assumed to operate using standard 4-pole induction motors rotating at 1500 RPM. The torque values were determined using Eq. (9), which relates the motor power, rotational speed, and torque. For Tower 1, equipped with a 26 HP motor (approximately 19.32 kW), the torque output was estimated to be 165.53 Nm. Towers 2 and 3, each powered by 21.6 HP motors (16.10 kW), produced torque values of approximately 137.52 Nm. These torque ratings confirmed the capacity of the system to accommodate the dynamic mechanical demands of vertical transportation, particularly under loaded conditions and during acceleration or deceleration. Proper torque specifications ensure lifting adequacy and contribute to operational smoothness, drive-system longevity, and overall energy efficiency [40-42].

In parallel, the total electrical energy consumption of the elevators was estimated based on a standard 5-hour daily operation. This calculation employed Eq. (10) using the motor power values established earlier. The energy demand was calculated as approximately 96.61 kWh for Tower 1, and 80.51 kWh for Towers 2 and 3. These values provide critical data for forecasting building energy loads and evaluating the long-term operational costs of elevators. This analysis also supports the adoption of energy-saving strategies using modern elevator technologies, particularly regenerative braking systems. These systems capture potential energy during downward motion and convert it into usable electrical energy, thereby reducing the net power demand [38]. Elevators represent a key target for retrofitting and optimization when contextualized within broader building energy strategies. A case study from Beijing demonstrated that energy-efficient retrofits, such as LED lighting and frequency conversion devices, can substantially lower total building consumption [43]. In addition, microgrid-based infrastructure enables the effective coordination of building energy resources [44]. ICT-based platforms help engage building occupants in real-time energy optimization, predictive analytics, and behavioral interventions [45]. Overall, these findings reinforce the need for precision in elevator system design by incorporating both mechanical and energy performance criteria. This analysis provides a data-driven foundation for selecting motor specifications, designing control strategies, and aligning elevator operations with broader building energy management frameworks. This integrative approach contributes to achieving the twin goals of energy efficiency and user comfort in high-rise residential buildings.

Furthermore, this analysis supports strategic decisions regarding elevator motor specifications, energy supply infrastructure, and sustainability planning. Energy cost projections can be further refined by applying local tariff structures established by the utility provider (e.g., PLN) or building management authority.

4. Conclusions

This study presents a comprehensive analysis of elevator system performance in a high-rise apartment complex consisting of three towers located in Jakarta. The results and technical evaluations led to the following conclusions:

- The estimated residential population, derived from unit counts and typologies, was 1,781 persons. This distribution adheres to the functional design of vertical housing and complies with Indonesian Regulation Permen PU No. 26/PRT/M/2008.
- The peak elevator demand was estimated at 3% of the total population during the initial five-minute interval of peak hours, resulting in service requirements of 48 (Tower 1), 30 (Tower 2), and 23 (Tower 3) persons.
- The calculated round-trip travel times for each tower, considering the elevator speed, floor height, and number of floors, were 208 s (Tower 1), 200 s (Tower 2), and 183 s (Tower 3), all of which met the efficiency benchmarks for vertical transportation systems in high-rise buildings.
- The carrying capacities of the elevators during the five-minute peak period were determined to be 69 persons for Tower 1, 54 persons for Tower 2, and 59 persons for Tower 3, indicating adequate performance to meet the projected peak load demands.
- The recommended number of elevator units was four for Tower 1 and three for Towers 2 and 3. These allocations account for redundancy and yield acceptable average waiting times ranging from 52 to 66 s, aligning with the comfort and performance criteria for residential buildings.
- The required motor power for elevator operation was calculated to be 19.32 kW (Tower 1) and 16.10 kW (Towers 2 and 3), with corresponding torque values sufficient to support load movement under standard vertical transit conditions.
- The estimated daily energy consumption for five hours of elevator operation was 96.61 kWh for Tower 1, and 80.51 kWh for Towers 2 and 3. These values highlight the importance of integrating elevator systems into broader energy efficiency strategies within the building management framework.

In conclusion, the proposed elevator design satisfies the functional, comfort, and energy efficiency requirements of high-rise residential buildings. The analytical framework and findings may serve as a practical reference for elevator planning in similar vertical developments, particularly in dense urban contexts where reliability, safety, and sustainability are essential.

Author's Declaration

Authors' contributions and responsibilities

Ikhsan Kamandanu was responsible for the conceptual design, data analysis, simulation, and the initial manuscript preparation. **Nanang Ruhyat** supervised the research activities, validated the analytical methods, and contributed to the critical revision of the manuscript.

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Availability of data and materials

All data supporting the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no conflicts of interest related to this study.

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