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## Intelligent Elevator Control Using Decentralized Multi-Agent Systems



**Abstract:** - A multi-agent system (MAS) framework optimizes elevator operations in high-rise buildings with dynamic traffic patterns and fluctuating passenger demands. With the proposed MAS approach, which utilizes fully decentralized decision-making and dynamic task allocation, scalability, responsiveness, and energy efficiency are significantly improved. Comparing MAS to traditional centralized systems, simulation results show that it reduces average waiting times by up to 25% while maintaining high performance. MAS eliminates bottlenecks and central points of failure, allowing real-time adaptation to traffic changes and passenger behavior. This approach provides significant advantages over existing elevator control strategies, positioning it as an intelligent building management solution of high effectiveness.

**Keywords:** Elevator Control, Centralized Decision-Making, Multi-Agent System (MAS).

### I. INTRODUCTION

The complexity and height of modern buildings make elevator control systems increasingly important. Traditional elevator control methods, such as centralized or rule-based approaches, may not be able to manage dynamic passenger demands, resulting in longer waiting times, higher energy consumption, and lower service quality [1]. Researchers have been studying elevator control systems for decades, focusing on improving efficiency, reducing waiting times, and reducing energy consumption. Various approaches have been developed, ranging from classical optimization techniques to AI-based approaches.

In the past, elevator control relied on conventional algorithms such as A\* search and rule-based dispatching. In [2], a dynamic optimization technique was used to optimize elevator paths in real time to minimize waiting times. Similarly, [1] reviewed traditional elevator traffic management methods in large buildings, highlighting the challenges in balancing efficiency and quality. In dynamic environments, these approaches tend to struggle with scalability and adaptability.

Recent advancements have seen AI and machine learning techniques integrated into elevator dispatching and control. With deep learning models that are occupancy-aware and can adapt to real-time usage patterns, [3] reduced waiting times in complex building environments significantly. Using deep neural networks, this approach uses historical data to predict elevator demand, resulting in a more flexible and responsive control system. In a further extension of this concept, [4] developed an elevator dispatching strategy that is traffic pattern-aware by applying deep reinforcement learning, demonstrating superior performance compared with traditional methods by dynamically adjusting dispatch policies in response to traffic patterns.

Multi-agent systems (MAS) have emerged as a promising alternative to centralized control models, offering greater scalability and fault tolerance. [5] demonstrate the potential for MAS in elevator control through their work on the

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"Intellevator" system. The system optimizes overall efficiency and reduces waiting times by enabling elevators to operate autonomously and communicate with one another. Similarly, [6] proposed a decentralized, agent-based intelligent elevator information system that uses video data in real-time to optimize demand-based operations.

Aside from machine learning and multi-agent systems, optimization and heuristic methods have also been explored for elevator group control. Using deep asynchronous actor-critic learning, [7] achieved near-optimal performance in various simulated environments. [8-9] investigated heuristic and optimization approaches, comparing different methods such as genetic algorithms for their effectiveness in elevator group control, offering valuable insight into the trade-offs between control performance and computational efficiency.

Validating advanced control strategies using machine learning is crucial to ensuring their real-world applicability. In recent studies, [10-11] examined the use of machine learning-based test oracles to evaluate elevator dispatching algorithms. In addition to enabling the detection of anomalies and assessing algorithmic improvements under diverse operational conditions, these test oracles also provide a robust framework for performance testing. Further, [12] proposed a transfer learning approach to evolve digital twins for industrial elevators, facilitating continuous improvement and adaptation of elevator control strategies.

Proactive computing and context-aware technologies have been used to develop intelligent elevator systems that enhance efficiency and reduce waiting times. In [13-14], the "Intellevator" system is described, which utilizes proactive computing techniques to optimize traffic flow and optimize elevator operations. In these studies, the importance of predicting passenger demand and dynamically adjusting elevator control strategies is emphasized. In [15], the "Precalevator" concept is presented, which uses a context-aware platform to achieve near-zero waiting times in smart buildings, illustrating the benefits of integrating intelligent technologies into elevator systems. Furthermore, [16] proposes an intelligent elevator management system designed to improve energy efficiency and passenger experience. In [17], the authors demonstrate how real-time energy and demand data can be used to enhance dynamic control policies. These studies demonstrate that intelligent systems and proactive strategies have the potential to revolutionize elevator control by reducing waiting times, optimizing energy use, and improving passenger experience.

In general, elevator control systems are becoming more intelligent, adaptive, and decentralized. While traditional methods offer a solid foundation, artificial intelligence-based methods, multi-agent systems, and advanced optimization methods offer significant improvements in scalability, responsiveness, and energy efficiency. However, validating these systems against real-world scenarios and ensuring their robustness against unpredictable and dynamic conditions remain challenging.

In this paper, we explore two distinct approaches to solving complex problems: the centralized solution and the Multi-Agent System (MAS) solution. The centralized solution relies on a single, authoritative control structure to manage all processes, offering advantages such as simplified coordination but also facing challenges related to scalability and fault tolerance. In contrast, the MAS solution utilizes a distributed network of autonomous agents, each capable of making decisions and acting independently, which can enhance flexibility and adaptability but may introduce complexities in coordination and communication.

Following this introduction, we will delve deeper into each of these approaches. Section 2 will provide an in-depth examination of the centralized architecture. Section 3 will outline the architecture and functionality of a multi-agent system. Section 4 presents a comparative analysis of these two solutions, evaluating their performance based on various criteria such as scalability, flexibility, fault tolerance, and overall efficiency. Finally, section 5 will summarize the findings, and suggest directions for future research.

## II. MAS WITH CENTRALIZED CONTROL

The single-agent approach involves making decisions about which cars should go to which floors by a central agent. The agent must consider every possible combination of cars and floors to determine the optimal plan. As a result, the number of actions and time required for the plan can be quite large, depending on the system's size.

A scenario is presented that involves two elevators, A and B, as well as a building that has three floors labeled 1, 2, and 3. There are currently two elevators on floor 1 that must be moved to floor 3 to reach it. Each elevator transmits a message to the central agent conveying its current position and intended destination. Based on the messages, the central agent determines that elevator A should be assigned to floor 3 and elevator B should be assigned to floor 2. As a result, the central agent instructs elevator A to move to floor 3 and elevator B to move to floor 2. After following their respective instructions, elevator A and elevator B proceed to their respective floors, resolving the conflict efficiently. Therefore, this conflict can be resolved through a centralized approach.

**Centralized Solution Overview:**

Centralized elevator control systems are characterized by a central agent that continuously collects data from all elevators, including their current floor, direction, and load, as well as floor requests, including how many passengers are waiting and where they are going. Through the central agent, decisions are made about which elevator should serve each request, ensuring efficient task distribution. To maintain optimal performance, the agent assigns specific tasks to each elevator based on information collected and predefined optimization criteria.

To obtain an overview of the system state, the central agent collects comprehensive data from all elevators and floors. Next, it calculates a cost function for serving each request for each elevator, taking into account factors such as proximity to the requested floor, current load, estimated arrival time, and energy consumption, each factor being weighted according to its importance (weights:  $w_1$ ,  $w_2$ ,  $w_3$ ,  $w_4$ ). By sorting elevators based on the total costs for serving each request, the central agent minimizes the overall cost of the system. Lastly, as described in Algorithm 1, elevators execute tasks assigned by the central agent, which continuously monitors the system and reoptimizes allocations if significant changes occur.

**Algorithm 1: Centralized Decision-Making**

```

Input: Elevators[] // List of elevators in the system), FloorRequests[] // List of floor requests
Output: TaskAssignments[] // List of assignments for each elevator
Initialize TaskAssignments  $\leftarrow \emptyset$ 
While there are new requests arrive
Collect Data from all Elevators (Position, Direction, Load)
Collect FloorRequests (RequestedFloor, WaitingTime)
For each Elevator E in Elevators do
    Initialize Cost[E]  $\leftarrow 0$ 
    For each Request R in FloorRequests[]
        Proximity_Cost  $\leftarrow |E.CurrentFloor - R.RequestFloor|$ 
        Load_Cost  $\leftarrow (MaxCapacity - E.CurrentLoad) / MaxCapacity$ 
        ETA_Cost  $\leftarrow EstimatedTimeToArrival(E, R.RequestFloor)$ 
        Energy_Cost  $\leftarrow EstimateEnergy(E, R.RequestFloor)$ 
        Total_Cost  $\leftarrow (Proximity\_Cost*w_1) + (Load\_Cost*w_2) + (ETA\_Cost*w_3) + (Energy\_Cost*w_4)$ 
        Store Total_Cost in Cost[E]
    End for
End for
Sort Elevators by Cost in ascending order (Lowest cost assignment first)
Assign each Elevator to the Request with the Lowest Total Cost
    Update TaskAssignments with assigned tasks
Communicate TaskAssignments to all Elevators
Elevators execute assigned tasks
End while
End.

```

With this centralized approach, a single agent can monitor and coordinate elevator operations from a single perspective. Despite providing a global perspective and the potential for optimal decision-making in small, less dynamic settings, it may be difficult to scale, respond, and tolerate faults in large, complex environments.

### III. MAS WITH DECENTRALIZED PLANNING

The decision-making process of each Elevator Agent involves dynamically selecting the most appropriate actions (e.g., moving up or down, stopping at a floor, bypassing a call) based on real-time data. The agent's goal is to minimize passenger waiting times, reduce energy consumption, and ensure an equitable distribution of service.

As a part of the multi-agent system, each Elevator Agent continuously collects data about its current state, including its position, direction of travel, speed, load capacity, and passenger count. The Floor Agents also provide real-time information on how many passengers are waiting, which floors they are on, and how long they will be waiting. As

described in Algorithm 2, a weighted scoring system is used by the Elevator Agent to prioritize passengers' requests based on factors such as proximity to the requested floor, elevator direction, waiting times, and estimated energy consumption, resulting in a priority score for each request. To optimize performance, the agent dynamically determines which floor to serve next based on these scores, adjusting its route as new requests arrive or conditions change, and continuously assessing whether to continue in the current direction, change direction, stop, or bypass certain floors. A negotiation process begins, as detailed in Algorithm 2, when more than one Elevator Agent is available for a request, sharing information such as current load, estimated arrival times, and priority scores, and determining which elevator is best suited to the task. As a result, actions can be coordinated to avoid conflicts like multiple elevators arriving on the same floor at once. As soon as a decision is made, the Elevator Agent executes the chosen action, collecting feedback including updated waiting times and load status to refine future decisions.

**Algorithm 2: Elevator Agent Decision Making**

Input: CurrentState (Position, Direction, Speed, Load), FloorRequests[], MaxCapacity

Output: NextAction (MoveUp, MoveDown, Stop, Bypass)

Initialize PriorityQueue  $\leftarrow \emptyset$

While there are new requests arrive

For each request R in FloorRequests[]

Proximity\_Score  $\leftarrow 1 / (|CurrentFloor - R.RequestFloor| + 1)$

If (Direction = "Up" AND R.RequestFloor  $\geq$  CurrentFloor) OR  
(Direction = "Down" AND R.RequestFloor  $\leq$  CurrentFloor)

Direction\_Score  $\leftarrow 1$  // Moving towards the request

Else

Direction\_Score  $\leftarrow 0$  // Moving away from the request

End if

WaitingTime\_Score  $\leftarrow R.WaitingTime / MaxWaitingTime$

EnergyConsumption\_Score  $\leftarrow EstimateEnergy(CurrentState, R.RequestFloor)$

Priority\_Score  $\leftarrow (Proximity\_Score * w1) + (Direction\_Score * w2) +$   
(WaitingTime\_Score \* w3) - (EnergyConsumption\_Score \* w4)

Add (R.RequestFloor, Priority\_Score) to PriorityQueue

End for

Sort PriorityQueue by Priority\_Score in descending order

NextAction  $\leftarrow EvaluateBestAction(PriorityQueue, CurrentState)$

If NextAction = "Conflict Detected"

Initiate Negotiation with other Elevator Agents

Resolve conflict based on Negotiation Outcome

Update NextAction

End if

Execute NextAction

Update CurrentState with feedback data (NewPosition, NewLoad, NewWaitingTimes)

End while

End.

#### IV. COMPARATIVE ANALYSIS OF MAS AND CENTRALIZED SOLUTIONS

To evaluate the performance of centralized and Multi-Agent Systems (MAS) in managing elevator traffic, a comprehensive simulation was conducted, varying both the number of floors and traffic patterns. There are two primary traffic patterns explored in the simulation: up-peak, where passengers originate from the lobby and are distributed to various floors, and down-peak, where passengers are dispersed across different floors and converge toward a central destination. Changing the number of floors from 5 to 40 and examining the effects under both high- and low-peak conditions allowed the study to measure the impact of these variables on average waiting times. Based on this approach, MAS and centralized solutions were compared to provide insights into their effectiveness and adaptability in different elevator operations.

Based on Figure 1, several conclusions can be inferred. There is an increase in the average waiting time per passenger in both MAS and Centralized systems as the number of floors increases due to longer elevator distances and more stops. Compared to the MAS solution, the Centralized System significantly increases waiting times. For example, when the number of floors rises from 5 to 40, the waiting time for the Centralized System (upward) rapidly increases from 10 to 160 seconds, whereas the MAS solution increases more moderately from 8 to 60 seconds. Therefore, MAS is more effective at managing large numbers of floors.

MAS and Centralized systems consistently have higher waiting times for downward traffic patterns, probably due to the decentralized origins of down-peak traffic, making elevator dispatching more challenging. A MAS solution, however, exhibits a smaller gap between upward and downward traffic patterns than a Centralized System. For example, at 40 floors, the Centralized System exhibits a five-second waiting time difference (160 versus 165), while the MAS solution has a three-second waiting time difference (60 versus 63). Thus, the MAS solution is more effective at managing both types of traffic.

Overall floors, the MAS solution consistently outperforms the Centralized System in both upward and downward traffic patterns; for instance, the average waiting time at 30 floors for the MAS solution is 42 seconds (upward) as compared to 95 seconds for the Centralized System, effectively reducing the waiting time by half. A key reason why the MAS achieves superior performance is that it is decentralized in decision-making, enabling its agents (elevators) to optimize routes based on real-time information, thereby reducing wait times more effectively than a centralized solution, which relies on a single control point and is prone to bottlenecks and slower response times.

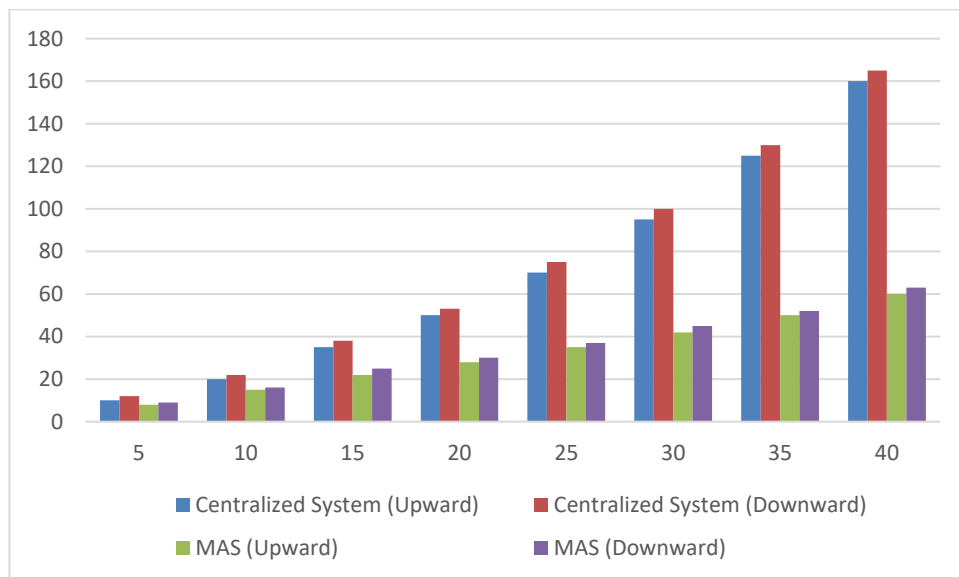


Figure 1. Average Waiting Time per Passenger for Centralized and Multi-Agent Systems

Our simulations consist of three different scenarios (morning peak, off-peak, evening peak) for three different types of buildings (low-rise: 10 stories, mid-rise: 20 stories, high-rise: 40 stories). A comparison of MAS and Centralized System throughputs will be conducted for each scenario and building type.

As shown in Table 1, the MAS consistently outperforms the Centralized System across all building types and traffic patterns. As a result, the MAS is more capable of handling dynamic passenger demands.

For low-rise buildings (10 floors), the MAS transports between 40 and 60 more passengers per hour than the Centralized System across all traffic patterns. MAS's ability to quickly adapt to local traffic conditions has likely contributed to its ability to reduce waiting times and increase trip completion rates.

For mid-rise buildings (20 floors), the MAS shows a pronounced advantage, transporting 70 to 100 more passengers per hour compared to the Centralized System. As building sizes increase, MAS's decentralized decision-making becomes more apparent, enabling it to handle the increased complexity of passenger flows more effectively.

For high-rise buildings (40 floors), the MAS outperforms the Centralized System by 100 to 130 passengers per hour. MAS's scalability is demonstrated by this significant difference. With MAS, large buildings are effectively managed with fewer bottlenecks due to distributed control, which allows the elevators and traffic patterns to be more complex.

Traffic Patterns: Across all building types, the MAS performs better during peak traffic periods (morning and evening peaks) than the Centralized System. By dynamically allocating elevators based on real-time conditions, the MAS can adjust to spikes in passenger demand quickly.

Efficiency During Off-Peak Periods: The MAS displays a moderate advantage over the Centralized System during off-peak periods. As a result, MAS can maintain high throughput by optimizing passenger distribution and reducing elevator idle times.

Table 1. Throughput of different elevator control systems (MAS and Centralized) across various building types and traffic patterns

<i>Building Type</i>	<i>Traffic Pattern</i>	<i>System Type</i>	<i>Passengers Transported per Hour</i>
Low-Rise	Morning Peak	Centralized System	200
Low-Rise	Morning Peak	MAS	250
Low-Rise	Off-Peak	Centralized System	180
Low-Rise	Off-Peak	MAS	220
Low-Rise	Evening Peak	Centralized System	190
Low-Rise	Evening Peak	MAS	240
Mid-Rise	Morning Peak	Centralized System	350
Mid-Rise	Morning Peak	MAS	420
Mid-Rise	Off-Peak	Centralized System	300
Mid-Rise	Off-Peak	MAS	370
Mid-Rise	Evening Peak	Centralized System	330
Mid-Rise	Evening Peak	MAS	400
High-Rise	Morning Peak	Centralized System	450
High-Rise	Morning Peak	MAS	550
High-Rise	Off-Peak	Centralized System	400
High-Rise	Off-Peak	MAS	480
High-Rise	Evening Peak	Centralized System	420
High-Rise	Evening Peak	MAS	520

In Figure 2, we show the number of passengers that are transported under various traffic patterns (Morning Peak, Off-Peak, Evening Peak) for the MAS as well as the Centralized System.

Multi-agent systems (MAS) consistently achieve higher throughput than Centralized Systems across different building types. A low-rise building with MAS transports more passengers per hour, such as 250 during Morning Peak, as opposed to 200 when the Centralized System is used. In mid-rise buildings, the performance gap becomes more pronounced, with MAS handling 420 passengers per hour during the Morning Peak, a 20% increase over 350 passengers managed by the Centralized System. In high-rise buildings, the MAS achieves a throughput of 550 passengers per hour during the Morning Peak, which is 100 more than the Centralized System. In a complex, high-rise environment, the MAS maintains high efficiency and adaptability due to its scalability.

As a result, the Multi-Agent System (MAS) performs better than the Centralized System during high-demand periods such as the Morning and Evening Peaks. Its decentralized decision-making enables it to respond more quickly to fluctuating demand, reallocating resources quickly to maximize throughput. MAS still shows moderate improvements in performance during off-peak hours, when demand is lower, compared to the Centralized System. As a result, the MAS is both highly efficient under high-traffic conditions as well as maintaining balanced performance across all traffic scenarios.

As a conclusion, the Multi-Agent System (MAS) is better at handling elevator traffic than the Centralized System for a variety of building types and traffic conditions. This efficiency is especially evident in peak traffic periods and complex buildings (mid-rises and high-rises), where the MAS's decentralized design allows it to quickly respond to real-time conditions. By contrast, a Centralized System, in which a single entity makes decisions, becomes less efficient as traffic complexity and volume increase.

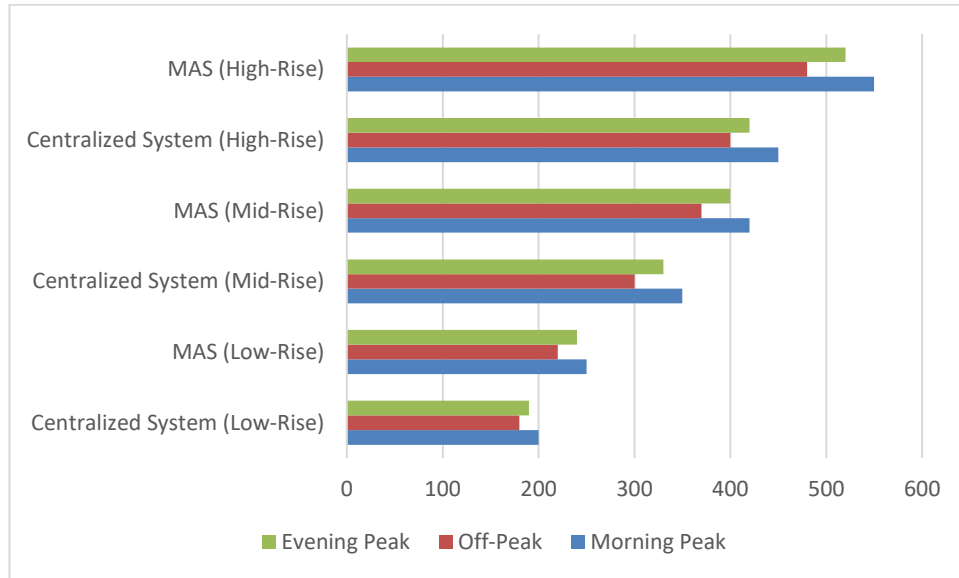


Figure 2. System Throughput Comparison: Centralized vs. MAS

**Quantitative Evaluation**

We run a simulation scenario with 10 elevators, 30 floors, and varying levels of passenger demand:

Based on Table 2, the average waiting time between a Multi-Agent System (MAS) and a centralized solution varies significantly. A MAS-based approach usually achieves shorter average waiting times since each Elevator Agent makes real-time decisions based on its local conditions and dynamically responds to new requests. It minimizes waiting times by decentralizing decision-making and redistributing tasks among agents to prioritize urgent requests. While centralized solutions benefit from having a global perspective, they can introduce delays due to the need to process a large volume of data during their implementation. A centralized agent may not be able to make timely decisions in high-traffic scenarios or large buildings, which increases waiting times.

Table 2. Comparative Performance Analysis of MAS vs. Centralized Elevator Control Solution

Metric	Multi-Agent System	Centralized Solution
Average Waiting Time	45 seconds	60 seconds
Scalability	High	Medium
Responsiveness	High	Medium
Fault Tolerance	High	Low

As far as energy consumption is concerned, the Multi-Agent System (MAS) allows each elevator to make localized decisions that reduce unnecessary movements. By facilitating negotiation among agents, redundant stops can be avoided, and elevator resources can be utilized more efficiently. Conversely, centralized systems usually consume more energy, especially when they lack real-time adaptability or use simpler, less energy-efficient algorithms. Despite a centralized optimization strategy, the decisions of a centralized system may not always align with the most efficient use of individual elevators.

Its decentralized structure, where each elevator operates independently as an independent agent, makes the Multi-Agent System (MAS) inherently scalable. As a result of this design, adding more elevators or floors does not significantly increase the complexity of the system because the workload is distributed among agents, allowing it to perform well even in large environments. In contrast, as the scale of the system increases, a centralized solution becomes less efficient. As the number of elevators, floors, and passengers grows, the central agent must manage a

larger volume of data and make increasingly complex decisions, which may lead to bottlenecks and slower response times.

Due to its decentralized nature, the Multi-Agent System (MAS) provides greater responsiveness since each agent reacts independently to local changes in real-time, such as sudden increases in passenger requests or emergencies. By making decisions locally, the system can adapt rapidly to changing conditions. MAS is more responsive than centralized solutions due to its ability to handle large volumes of data and make decisions based on all data, whereas centralized solutions depend on a single control agent.

Multi-Agent System (MAS) is fault-tolerant because each Elevator Agent works independently of the others, resulting in a more fault-tolerant design. The other agents can continue to work without interruption if one fails, dynamically reassigning tasks and adapting to the failure to ensure minimal disruption. By contrast, a centralized system has one point of failure; if it fails or malfunctions, the entire system may not function.

## V. CONCLUSION

The purpose of this study was to present a novel multi-agent system (MAS) framework for optimizing elevator control in large and complex environments, particularly in high-rise buildings with dynamic traffic patterns and fluctuating passenger demands. A fully decentralized control approach and dynamic task allocation, are part of the proposed framework that addresses several key shortcomings of existing elevator control systems, including scalability, adaptability, and computational efficiency.

According to our findings, MAS enhances scalability and efficiency over the traditional centralized approach. The system efficiently manages elevators and floors, even during peak traffic times, resulting in low waiting times and energy consumption. By eliminating a central controller, the approach achieves fully decentralized decision-making, reducing bottlenecks and single points of failure. Also, the framework reduces computation complexity and communication delays among agents, enabling real-time performance.

To improve the model's training and validation processes, future research could include real-world data from existing elevator systems, ensuring effective performance under diverse deployment scenarios. Additionally, hybrid models with decentralized decision-making and centralized coordination for specific tasks, such as emergency management or large-scale optimization, could be explored. A further improvement in communication protocols could improve high-frequency data exchange among agents, perhaps through advanced network architectures or emerging technologies such as 5G and edge computing. Moreover, by incorporating AI techniques such as deep reinforcement learning and federated learning, agents may be able to learn more accurately and optimize their control strategies.

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