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Development and state-of-the art in green elevators technologies: A survey

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ABSTRACT

Green elevators represent a new standard in all elevator facilities. This paper analyzes all new technologies that need to be applied, and this refers to the energy efficiency of the drive, the use of a different configuration, and the changed components on the elevator. This paper also deals with models that change the classic motion of the elevator and emit low energy consumption. It is of the key importance to show which countries strive to replace all their plants with new configurations and regulations, where the most important fact is to perform an impact assessment on an annual basis. The main goal of this paper is to show that all components designed at the experimental level should be introduced into standard plants and reduce their production cost. From a comprehensive analysis of the previous research, it is concluded that the most significant advantages are achieved by using new electrical schemes, components, and energy sources that are not connected directly to the power distribution grid. At the end, from the corresponding literature, it is concluded that many major manufacturers in the elevator industry have to apply the modern technology from their development centers to existing standard elevators, in order to meet all new ecological and emission standards.

KEYWORDS

Elevators, Energy efficiency, Power management, Regenerative energy

1. INTRODUCTION AND BACKGROUND

The sustainability and green concepts as relatively new in civil, mechanical and electrical engineering have gained tremendous momentum and have had a profound impact on our environment [1]. Whilst sustainability concentrates on the environment, economy and social equity, green elements entails resource use, energy and water use, waste generation, carbon emissions and biodiversity [2]. Both of them over the past two decades launched the most scientific research based on theoretical and practical approaches. According to that, the main objective of the present paper is to determine a clear scoping of development and state-of-the art in green elevator technologies.

Thanks to the literature, it is possible to trace the development of elevators since the end of the 19th century [3] up to now [4]. Although this fact is very interesting, the present paper conducted analysis of the green elevator technologies by 2004. Therefore, before putting this paper in the context, it is very important to emphasize what elevating technique is. This technique is applying the available elevator technology to satisfy the traffic demands in multiple-and single-purpose multi-floor buildings [5]. It is the process of applying elevators and the building interfaces necessary for the vertical transportation of personnel and material within buildings [6].

Elevators have always been essential for any building, especially in the case of high rise buildings [7]. As it is well-known in the past 30 years the height of the tallest world's buildings have been increasing from 422 m in 1992 to 828 m (2012) and this trend remains up to now (see more in [8]). The average height of the 100 tallest world buildings have been increasing also since 1992, which indicates the number of 221-supertall (300-meters) buildings in 2022 [8]. This exponential growth trend produced by increasing world population and restriction in building space, requested new challenges in elevators' design, technologies and transport engineering.

1.1. Elevators development

Development of the mechanics of hoisting elevators is very long as has previously been stated [5]. At the beginning of the 20th century elevators are changed radically based on electricity which became common and with the introduction of the traction elevator. At the beginning of last century drum-type elevator machines were the principal means of hoisting force. The rope was wound on a cylindrical drum or the hydraulic-type elevator [5]. The second one has been the direct-plunger hydraulic or the roped hydraulic machine. That way, a few types of hydraulic elevators (HEs) have dominated the elevator market in the second part of 20th century, such as: holed (conventional) HEs; non-telescoping (single-stage) HEs; roped HEs and telescopic HEs ([9] and [10]). These elevators are usually used in buildings from two to six stories high with main features like low maintenance cost due to wear free driving components, flexibility of car and machine room design, superior safety features, easy and cost effective installations ([10] and [11]. The drum type of elevators had limitations in the size of the drum, whilst HEs in the length of the cylinder ([5] and [11]).

The drawbacks of two types of elevators which are previously mentioned were significantly improved with the emergence of traction elevators. These elevators are based on the traction principle as a means of transmitting lifting force to the hoist ropes of an elevator by friction between the grooves in the machine drive sheave and the hoist ropes ([5] and [11]). The ropes are simply connected from a) the car to b) the counterweight and wrapped over the machine drive sheave in grooves [5]. The weight of both ensures the seating of the ropes in the groove. For higher-speed elevators, the ropes are double-wrapped, i.e. they pass over the sheave twice. This type of elevating request only a small electric motor pulls the car over a greatly increased vertical distance. This indicated it was feasible to lift cars up high-rise buildings with dozens of floors. These elevators were of the gearless traction type (see more in [5]) which appeared in the United States during 1903 (the Beaver Building in New York City). The 20-year later, the adoption of the Ward-Leonard system of electric motor speed control became an epoch-making advance in the evolution of elevator technology because speed no longer depended on varying water or steam pressure [5]. The system allowed the smoothness of acceleration and deceleration common in elevators of today. The geared traction elevator as an outgrowth of the earlier drum-type elevators utilizes a reduction gear with a high-speed motor to drive the traction sheave [5]. Summary of elevators used in the economic sector in the European Union (EU) revealed that more of 2/3 elevators are the geared type [12].

Further, the machine room elevators and machine-room-less (MRL) traction elevators represent the offer on the elevator market. The first one contains an area set aside for the elevator equipment with the traction machine, controller (series of relays to help the elevator run), electrical disconnects (bring power to the unit, and using for elevator lights) and the pump unit (it is where the oil is housed and the elevator's motor is on top). This type of traction elevator is used in buildings with 25 or more floors, whilst MRL traction elevators are recommended till 25 stories. MRL traction elevators from the middle of 1990th promoted room saving properties of MRL, it initially generated increasing numbers of MRL installations ([5], [13]-[18]).

The next steps of the elevators development had aim to ([15]-[20]): a) get back flexibility while reducing masses in the system (see the TWIN as an elevator system in which two standard cabs are installed within the same shaft but operate independently), and b) reduced the machine sizes and peak power loads compared to conventional systems (Double Decker elevators (DD)).

Also, at the end of the last century, it began installation of the smart elevators ([17], [21] and [22]). Smart elevators allow the users to push a button setting their floor they want instead of choosing to go up or down. It is the simple act of traveling in the shortest amount of time between floors, more efficient with the fewest number of stops. These indicate faster, easier and energy efficient elevators than older ones. That way, a modern elevator control system such as a network-based elevator control system via controller Area Network (CAN) [23], programmable logic controller (PLC) [22] and Speech Recognition [24] can change old devices into smart devices.

There are a lot of studies concentrated on reducing the electricity used in elevators. Also many studies encourage Renewable Energy Sources (RESs) use instead of Conventional Energy Sources (CESs) and recommend installation of elevators based on the RESs in the smart buildings ([1] and [25]). That way green elevator technologies arise with some features and characteristics previously mentioned.

1.2. Types of elevators

Elevators as mechanical platforms transport people and goods vertically inside a building. There are various types of elevators based on their use as presented in Fig. 1. These functions aim to determine elevator design and traffic performance.

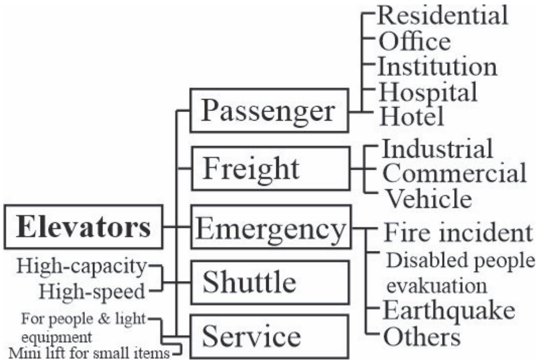

Figure 1: Types of elevators (adopted by [5], [18] and [26])

1.3. Types of elevators

The present paper conducted analysis of previous review studies of elevators technology development from 2015 to 2023 which are given in Table 1. This analysis starts in [15] where are investigate recent advances in elevator technology and examine their impact on tall building development via a few case studies. Another way to study vertical transportation systems (VTS) is the elevator group control system (EGCS) presented in [27] and based on traffic management. A Next Generation VTS and comparison of Circulating Multicar vs. Double Deck elevators are presented in [20]. Further, a brief VTS review about EGCS is shown in [28]. A short evolution of elevators based on digital interaction, physical human interface, intuitive behavior and mega-tall buildings is shown in [29]. Then, the implementation of Smart elevators (SEs) with PLC including green aspect and its value are given in [22]. In the same manner, the same author as in [15], gives extension of elevator technology improvements, application of SEs and elevator sustainable design in [4], [16] and [17].

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Table 1: Previous review studies of elevators (Es) technology development including green concept

	Subject	Approach	Future directions
[15]	Technological Advances, 2015	Descriptive analysis and case studies	“greener” and “smart”
[27]	Group control System, 2015	Es group control systems (EGCSs)	Service quality, twin Es
[20]	Next generation, 2015	Comparative analysis	Twin, MULTI
[28]	Open issues, 2016	EGCSa & dispatching	Ambient intell.
[29]	Es Evolution, 2018	E Technology Drivers	IoT
[11]	Es & multi-car, 2019	Multidirectional Es	Multi-car
[22]	Smart Es, 2020	PLC application	Green aspects
[16]	Sustain. Design, 2021	Descriptive analysis Case studies Comparative analysis	“sustainable” “greener” “smart”
[17]	Smart Es, 2023		
[4]	Technology improvements, 2023		

According to above mentioned and unlike previous emphasized review studies, the present paper conducted systematic review study of development and State-of-the Art in Green elevators technologies based on the published studies. This systematic review process aims to identify the trends and future research directions.

2. METHODOLOGY

The present paper conducted a three-stage approach to identify and to assess research on green elevators technologies through Systematic Literature Review (SLR) as shown in Fig. 2. Research methodology stages and elevator traffic performance assessment by literature review follows a SLR method which is usually defined as “a method that allows the assessment and interpretation of all accessible research relevant to a research question, subject matter or event of interest" (see more in [30] and [31]).

Fig. 2 suggests that many different topics are being addressed related to elevators. In order to have some baseline to assess the extent to which green elevators topics/technologies are being addressed, the first is to consider how well the SLRs of relevance both to vertical transportation problems as multi-objective problems. In the first stage of the methodology, the SLR was conducted to delimit the gaps by identifying, assessing, and combining the vertical transportation traffic and elevators research to examine determination of the status of green elevators technologies.

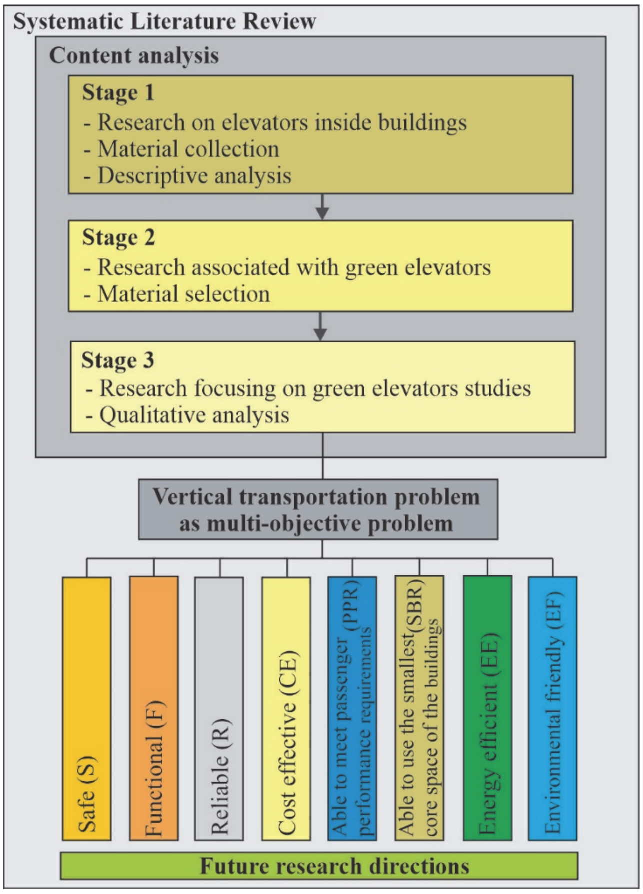

Figure 2: Research methodology stages and elevator traffic performance assessment by literature review

The second stage, studies that match the search query were analysed using the manual review through the full text. Each study was screened and included in this SLR by meeting the criteria such as: a) coverage of elevators inside buildings and its practice; b) contain determination of the key issues on the elevators design and traffic patterns; c) coverage studies that explore explicit modelling concept of vertical transport; d) conducted studies based on literature review; e) coverage practical aspects and conducted experiments in relation to vertical transportation improving; f) contain application of new sustainable design of elevators and recent technological advances; g) coverage some elaboration of smart elevators system, elevator modernization and upgrading systems, as well as green elevators technologies.

A qualitative analysis was performed in the third stage by taking the results from the previous stages. The selected studies were then tabulated and categorized based on their research focus as shown in Table A1 (Appendix A). According to [26] the elevator traffic engineering aims to achieve a compromise between cost and performance. Therefore, the vertical transportation problem defined in [26] is a multiple constraint-multiple-objective problem that aims to produce a solution that is: a) Safe (S); b) Functional (F); c) Reliable (R); d) Cost effective (CE); e) Able to meet the passenger performance requirements (PPR); f) Able to use the smallest possible core space of the building (SBR); g) Energy efficient (EE) [26] and h) Environmental friendly (EF). As pointed out in Fig. 2 (the last part), these problems were then discussed. This research adopted this problem categorization which dealt with research on vertical transportation and elevators, as well as adjusted accordingly to suit the context of various elevators studies.

In addition, this research divided papers based on its considered problems, interrelationships and comprised subcategories that have a similar focus. In case several studies had multiple focus, it has been underlined and emphasized to determine the multi-objective problem and sub-problem categorization.

There is a need for a review which would offer a succinct description of the progress in the arising topic of sustainable design of elevators with application of smart technologies and green initiatives. In that way, the main aim is to summarize the current state of knowledge with focus on the scientific methods used in modelling procedure and would assess the findings provided in the various research studies with focus on the future research directions and known elevators design challenges.

The goal of this state-of-the art survey in green elevator technologies is therefore to attempt to answer the following research questions (RQs) related to multi-objective problems of vertical transport which were not answered before:

RQ1: What common themes were predominant?

RQ2: What modelling techniques are presented for VTS?

RQ3: What current and future technologies are leading?

The RQ1 tries to highlight the achieved progress in the previous published literature. The employing modelling approach needs to be emphasized in order to enables technological advancements in smart elevators (i.e. Industry 4.0 such as big data and analytics, autonomous robots and IoT among others) by RQ2. The known challenges in the near future using hardware and software technologies on the sustainable elevator design will be highlighted through RQ3. Then, a brief description of the progress and challenges in sustainable elevator design with future research directions can be summarized.

3. RESULTS AND DISCUSSIONS

The database in the present paper compiled (*n* = 101 studies ([4], [7], [9], [10]-[25], [27]-[29] and [32]-[110]) in Table A1, Appendix) comprises 66 journals' papers, 23 papers published in various International Conference Proceedings, 5 papers from Elevator World - the magazine for the international building transportation industry and 7 publications from other sources (i.e. Book Chapter, MSc thesis, Project Report among others). It might be noted that most of the collected studies referred to the elevator analysis involved a deeper investigation of some specific problem according to Fig. 2. The scientific profile of each study is highlighted to examine the relevant problem investigated, modelling approaches and empirical nature of the studies as shown in Table A1. The results given in this table for each study contain bold (**√**) and normal (√) marks, where first one indicates primary subject, while second implies secondary point of view related to problems study, modelling approach and empirical nature of the studies. When there were no second problems considered, the modelling approaches used and the empirical nature of each study, they were not emphasized.

In the following subsections, the eligible and selected studies were analyzed in further detail in order for answering the RQ1-RQ3. The analysis process related to research methodology stages shown in Fig. 2 is presented in the subsequent sections.

3.1. Main research themes

A schematic classification of the main research problems, i.e. thematic problematic - themes of considered papers shown in Fig. 3. This distribution indicates that two themes (EE and EF) dominate in more than 60% papers in order to better understand implementation of green elevator technologies.

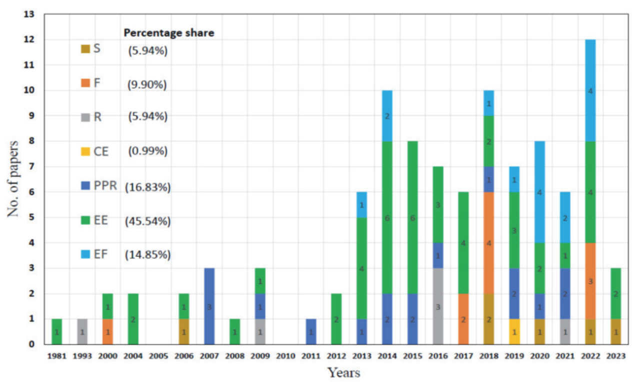

Figure 3: Main research problems – themes (Safe (S); Functional (F); Reliable (R); Cost effective (CE); Able to meet the passenger performance requirements (PPR); Energy efficient (EE); Environmental friendly (EF))

3.2. Trending methodologies

Simulation, analytical, empirical and combinatorial optimization, as well as AI techniques recently are the modelling methods that have been frequently used in 85 of 101 papers as shown in Fig. 4. As was pointed out in table A1, there is an attempt in most studies to use more than one method to solve problems and eliminate limitations. Simulation procedure and algorithm have been very often used as primary or secondary method to describe investigated problems or to validate obtained results and testing proposed technologies application.

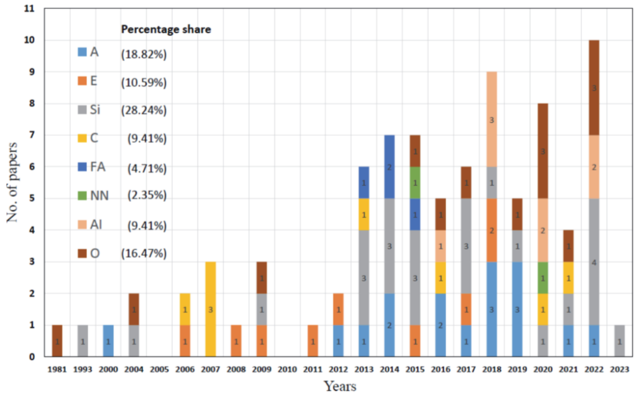

Figure 4: Application of various methodologies (A – analytical, E – empirical, Si – simulation, C – Combinatorial optimization, F – Fuzzy approach, NN – neural network, AI – artificial intelligence, O – other methods)

3.3. Empirical nature of the studies

To show a consistent picture of collected studies, Fig. 5 presents their empirical nature (T, Ap, CS, TS and LR). These features are very important and could be dimensions of the real problem-solving (Ap and Cs) and methodology approach (T) as empirical nature of analysed studies based on smart or green or sustainable elevator concept in near future and its common use.

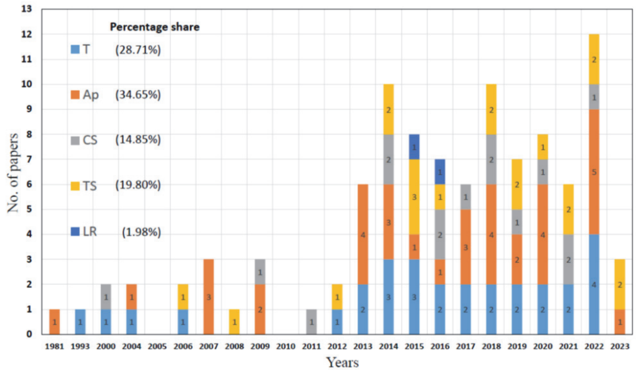

Figure 5: Empirical nature of consider studies (T – theoretical, Ap – application, CS – Case Study, TS – Technology survey, LR – literature review)

3.4. Implementation of elevator technology improvements

Elevators are becoming subject to scrutiny with the drive to net zero when considering green buildings. Their energy consumption is a major part of their environmental impact. The energy transformation over the world implies growing capacities of renewable energy (e.g. wind and solar power, see more in Fig. 6) used in industry much more than in the smart buildings or city. As literature said [25] "green elevators are elevators with low energy consumption" that way this major component is influential to the environment significantly reduced [25]. Therefore, the first part of this section could support modelling of elevator energy consumption as a multi-objective complex problem. On the other hand, the various elevator traffic solutions which directly affect the passenger service quality, such as principles of elevator control systems, passenger access and guidance provided by each control system also need to be modelled. In that way a lot of obtained results have to be validated by simulation [111] or optimized using some metaheuristics, enabling adequate responses to passenger demand and energy consumption.

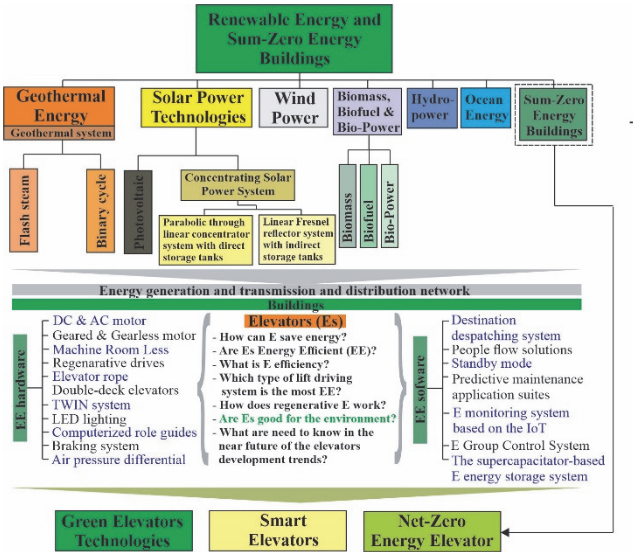

Figure 6: Framework of sustainable energy sources, smart buildings and green elevators technologies (adopted by [1], [4], [18], [15]-[17], [20], [22], [27]-[29], [112] and [113])

Sum-Zero energy building is "a building that produces at least enough emission-free renewable energy to cover the emission generated by its non-renewable energy sources" [1]. Although each elevator consumes resources to fulfil their function, its environmental impact will last their whole lifetime. In that way, the selection of the most environmentally friendly lifts during the building design phase is very useful. Also, the concept of smart building offers continuous monitoring of energy consumption based on sensor technology. A very well-known system is Heating, Ventilating, and Air Conditioning (HVAC) that utilizes these technologies. The second one is the elevator operating system (EOS) based on multiple sensor devices which allows it to detect elevator passengers' behavior before they arrive at the elevator door and press the elevator call button, then elevator scheduling and so on. A lot of complaints can be found in building tenants' comments related to HVAC and elevator service [18]. EOS enables optimization of several elevator performance scheduling systems such as minimizing the waiting time, minimizing the riding time, and reducing the energy consumption.

Energy efficient traction elevators are often used for mid- and high-rise buildings with significantly improved controls (such as scheduling and dispatching), hardware and other systems. All of these that not only use less energy, but are much more compact, efficient, and even generate electricity that a facility can use. Therefore, these elevators are characterized by [92]: software-based controls which have changed electromechanical relays; a lot of sensors and software that automatically handling idle or sleep mode, lights turning, ventilation, music, and video screens; destination dispatch control software and other software which control peak load, low load, and empty trips among others. In that way, by using a lot of simulation experiments it is easy to achieve the optimal mode of operation at the operational or tactical level.

According to the below central part of Fig. 6, there are important inquiries which request Energy Efficient Hardware (EEH) and Energy Efficient Software (EES) as remarkable advancement in energy-efficient elevator technology. The advancements of the first one could be summarized as follows.

- An electric motor which is used for up and down movements of elevator cars is DC (direct current) AC (alternating current) motors. Advancement in elevator technology is the switch DC to more efficient AC motors, where the second one, gearless motors are able to be EE and send extra power back into the buildings' electrical grid ([4], [15], [16] and [17]).

- As traction elevators are primarily used in high-rise buildings, they can either be geared or gearless. Gearless elevator motors do not have gears and that way can be much smaller than geared elevator motors (if the engine is smaller, the other parts would also be smaller). It implies that smaller ones are more effective for electricity use, have higher overall efficiency and may be utilized for a greater amount of time ([15] and [16]). Although the costs of these elevators (materials, installation and maintenance) are often higher than that of geared elevators, they are more expensive and are used in more buildings today.

- As the mentioned in subsection 1.1, the features of MRL elevators have the key benefits: lesser usage of space, more EE, design and use in the small and mid-size buildings, noiseless operation, reconfiguration the motors and other equipment does not require machine room, EE is higher by the reduced starting current needed, use a smaller percent of the energy than traction and hydraulic motors, EE becomes even more if it is combined with regenerative drives.

- It is well known that the power generated by the traction machine is dissipated as heat in the building for conventional elevators. Elevators with regenerative function are powered from an electrical supply network, when it travels downwards with heavy load or upwards with light load, the traction machine will act as power generator and the lift is running at "regenerative mode". In that way elevators function by accumulating and transforming the energy expended during braking to keep the elevator's speed constant. Elevators convert the energy generated from the elevator motor driven by gravity into electricity for other uses. This EE installation provides a green lift option for client departments to consider applying in their venues. These elevators are 20% to 30% more EE than conventional elevators. The amount of energy saving arising from lift regenerative power varies with the lift traffic pattern such as the length of travel, frequency and device age which implies that longer distances and more trips generate more energy.

- Ropes are commonly used for hoisting in elevator cars. They are a main part of traction elevators to hold cabins. Some problems arise when the rope gets too long in the skyscrapers that it cannot support its own weight. It implies that starting currents and energy usage rise, increasing energy consumption when height increases inside a skyscraper. In that way have been strengthening cables (e.g. ultra-thin wires encased in polyurethane instead of steel ropes, denser string with concentric steel wire, lighter cords move elevator cabs more efficiently and conserving energy, transition from conventional wire ropes to PU-coated multiple-rope belts has significantly increased energy efficiency of lifting mechanisms [114]). These expanding experiences to the design of gravity energy storage systems seem very promising [105]. Then, "a new benchmark for high-rise buildings is the super-light KONE UltraRope technology that provides unrivalled elevator eco-efficiency, reliability and durability, while also improving elevator performance. It eliminates the disadvantages of existing steel ropes – high energy consumption, rope stretch, large moving masses, and downtime caused by building sway. This rope can enable future elevator travel heights up to 1,000 meters", https://www.kone-major-projects.com/.

- TK Elevator (formerly ThyssenKrupp Elevator) created MULTI, the world's first ropeless elevator as design to make high-rises more efficient. Conventional ropes are replaced with linear drive technology for a multi-level brake system that can move multiple cars in a single shaft both vertically and horizontally on magnetic rails. Electromagnets are placed on guide rails alongside permanent magnets behind the cabin on the ledge. Electromagnetic forces either pull the cabin up or control the elevator's downward movement. Most standard rope elevators can only travel about 151 stories, whilst MULTI hasn't this limit. It works like a continuous train, meaning that waiting times are reduced by an average of 15-20 seconds, requires much lower peak power by allowing for better management of the building's energy needs, reducing peak power demand by as much as 60 percent, https://www.tomorrowsworldtoday.com/2022/11/14/. Additionally, "*a study of linear permanent magnet synchronous motors* (*PSMSM*) *driven ropeless elevators*" and "*the ropeless elevator - new transportation system for high-rise buildings* (*and beyond*)" are given related to scientific approaches in [115] and [116].

- The Multi-Car Elevator System (MCES) presents a new trend in elevator systems since 2002 due to its low cost of construction and is able to minimize the waiting time of passengers. To optimize performance in reducing waiting time of passengers and energy consumption various approaches have been used as shown in Fig. 4.

- There are double-decked elevators consisting of two stacked cabs together so that two floors, one directly above the other, can be served simultaneously (one serves floors with even numbers, and the other serves floors with odd numbers). They performed better than single-decked elevators, especially when used in skyscrapers and for shuttle services depending on which algorithm is used for traffic scheduling.

- An invention of elevator technology with two elevator cabs which function completely independent from one another while utilizing the same hoistway is the TWIN elevator system. There has been significant progress which implies the incredible amount of energy that it saves (e.g. although one of the cabs can be parked, the other cab remains in operation during non-peak hours which can significantly reduce the amount of energy used). This system enables an energy recovery function to feed about 30% of its energy generated through braking back into the building's power grid which means decreased energy consumption by regenerative drive.

- The most energy efficient, cost effective, and eco-friendly method of elevator cab interior lighting is energy-efficient light-emitting diode (LED). The main features of this lighting are 80% efficiency (more energy efficient) and ecologically friendly materials which don't contain toxic chemicals what implies that are recyclable.

- Elevator roller guides should be reliable with smooth rails and rail joints to travel quickly, especially for fast-moving elevators. ThyssenKrupp created automated roller guides (ARG) which exert forces in the opposite direction from the guide rails' normal direction of travel, reducing the effects of the bumps. To decrease the vibration of elevator cabin, it is useful to install ARG and conduct a modelling process of cabin response with these clever real-time shock absorbers which can contribute to the reduction of energy consumption and maintenance frequency.

- The round-trip efficiency (RTE) of gravity energy storage systems with a rope traction mechanism using PU-coated multiple-rope belts is demonstrated in [114], whilst Lift Energy Storage Technology (LEST) is presented in [105]. LEST is a gravitational-based storage solution, which would make use of the existing elevator systems in tall buildings.

Many of these are already designed with regenerative braking systems that can harvest energy as a lift descends, so they can effectively be looked at as pre-installed power generators. The LEST would also make use of vacant spaces throughout the building, ideally close to the top and bottom. According to [105] "*the LEST could be a viable alternative to long-term energy storage in high-rise buildings. LEST could be designed to store energy for long-term time scales (a week) to generate a small but constant amount of energy for a long time. This small but constant electricity generation could be combined with other storage technologies, such as batteries, to balance the short-term variations of electricity demand, solar and wind generation*".

Following the literature, a very common question may be "is elevator able to meet service demand in various scenarios at an acceptable cost with minimum environmental impact"? It implies using digital devices instead of manual devices. This intelligent system modularizes the software into elevator components so that it enables the development of flexible and scalable elevator scheduling algorithms. An new Programmable Logic Controller (PLC)-based elevator control system is introduced ([9] and [22]), then a network-based elevator control system via Controller Area Network (CAN) [9], smart sensor technologies in the design of an efficient elevator operating system (EOS) [18], up to Green Elevator Scheduling Based on Internet of Things (IoT) Communications [89]. The last one system presents energy-saving elevator scheduling that reduces the car moving steps to attain energy reduction and green communications under wireless communications. Further, some of them have been pointed out as significantly improving elevators' operations.

- Timeline of group elevator control system development since 1960th up to now is based on hardware (relays, integrated circuits, microprocessors, personal computers and multicore central processing unit (CPU)), optimization objectives (interval, call time and multi-objective optimization), software methods (artificial intelligence, fuzzy logic, genetic algorithm, neural networks and software agent), control system technology (continuous call allocation, immediate call allocation (Japan), destination control, double-deck (DD), destination control system, TWIN, multicar among others), see more in [117].

- People flow solutions including push-button control systems, collective group control system with software-based collective control system, intelligent group control systems, artificial intelligence in elevator dispatching, destination control system (adaptive call allocation algorithm, destination control system, hybrid destination control system, harmonized' elevator dispatching), multi-car control systems (DD, TWIN, MULTI) and access control systems.

- Although the elevators are the primary consumer of energy, after decades of technology advancements, new elevator systems are relatively small energy consumers (a few percent of a building's energy). To further improve energy saving (lighting style, floor displays, and operating consoles in each level and elevator cabin) the standby mode has to be kept powered when cabs are idle, so elevators are prepared for the next passenger call. In that way energy is conserved because the standby solution shuts down elevator machinery.

- The elevator systems could be under predictive maintenance policy today. This intelligent system for service is based on the concepts of industry 4.0 where the main technical components in the system are Cyber-Physical Systems, IoT and Data Mining [67]. It allows real-time insights by mobile devices to elevators operate better.

The most relevant criteria such as the elevators' average waiting time, the average transit time, the average journey time and the energy consumption could be optimized by Elevator Group Control System to dispatch landing calls, interfloor and peak traffic analysis using Fuzzy Logic and Evolutionary algorithm among others ([47] and [95]). To confirm satisfaction of proposed approaches by experiments could be used some software like as Elevate (https://www.elevatesoft.com/).

4. CONCLUSIONS AND FURTHER RESEARCH

This paper presents development and state-of-the art in technological advances of elevators to predict green elevator technologies. As a starting point for new research some main features of implementation of elevator technology improvements are highlighted. Firstly, a trend existing related to the elevator technology development summary is extended. Secondly, the initial database of multi-objective problems in the vertical transportation was collected and analyzed via the main research problems - themes, trending methodologies and empirical nature of collected studies. The obtained results show that main themes (elevator energy efficiency and elevator environmental friendly) dominate in more than 60% papers as base to further implementation of green elevator technologies. Simulation procedure and algorithm (with almost 30%) and artificial intelligence techniques (more than 17%) have been very often used as the primary method to describe investigated problems or to validate obtained results and testing proposed technologies application in elevator systems in recent two decades. Last but not least regarding empirical nature of the considered studies, the theoretical approach accounted below 30% of investigations, whilst experimental applications with technology and literature reviews including case studies were above 70%. The almost 1/3 of studies that are based on improving the energy efficiency and the some others multi-objective problems of elevator systems used analytical and empirical modelling approaches rather than combinatorial optimization and AI techniques which mostly would complicate the design unnecessarily.

Although the main goal of the present paper has been focused on selecting relevant published studies to indicate overall trending in elevator green technologies, another goal also exists to highlight how it could be possible that net-zero elevator systems present the more common sustainable solution of vertical transportation. Therefore, the main features of green elevators could be summarized as: MRL, Gearless traction motor, drive systems that regenerate energy, computerized precision traffic control that optimizes the performance of a group of elevators and decreases light-load trips, in-cab sensors and software that make the elevator go into sleep mode when not in use, turning off the music, video, lighting, and ventilation; destination dispatch control software to improve passenger traffic flow.

Recent development and advances in elevator systems (such as regenerative drive, elevator ropeless double-deck elevators, the TWIN system, multi car elevators), elevator modernization and upgrading systems (full replacement, traction modernization, hydraulic modernization, smart devices, holographic elevator buttons), key future developments trends (circulating multi-car elevator system, multi-directional elevators, virtual reality diagnostics), efficient movement of people and algorithms, technologies that aid in hygiene, remote on-time services and speed, have become common in new high-rise buildings and skyscrapers. Therefore, the main future research directions should focus on merging the simplicity and efficiencies of the modelling, whilst many uncertainties in real-life which needs to be solved by advanced approaches such as AI techniques, stochastic programing and robust optimization among others. As the elevator is a complex system which should give adequate response to the users demand, the experimental test is much needed to validate proposed solutions by simulation as previously pointed out.

Future research directions will be based on the extending of database, taxonomy of the different tasks that an elevator system performs, interrelation among the subsystems (machinery, mechanically, movement, control; performance optimization; data capturing, filtering and analyzing; modelling methodology like AI techniques or stochastic programming; and validation, verification and calibration). Also, classification according to the objectives/criteria employed/methodology used will be also employed to achieve results meta-analysis to perform conceptual structure map by multiple correspondence analysis.

New orbital transportation systems projected for transport satellites and other payloads to and from space are also found in literature recently ([118] and [119]). They are known as space elevators, mainly the climber type (a cable connects the ground to a space station and the payload is transported by climbers ascending and descending along the cable). The life cycle assessment for a few types of them was completed to quantify, compare, and suggest improvements to the potential environmental performance [118]. This research could be useful for future buildings' elevators development.

How to attempt to systematically address elevator energy use and environmental concept could be found in [113] and [120]. In that way, VDI elevator energy efficiency certificate is available by Verein Deutscher Ingenieure (VDI), as well as Building label programs, notably the USGBC LEED (U.S. Green Building Council) and ENERGY STAR® (U.S. Environmental Protection Agency program) Portfolio Manager programs [113]. These standards provide default options of elevator energy efficiency and may be useful for elevator green technology development in near future.

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APPENDIX A

Table A1: Classification according to the multi-objective problem, methodology and empirical nature

	Vertical transportation multi-objective problem							Modelling approaches									Empirical nature of the studies				
	S	F	R	CE	PPR	EE	EF	A	E	Si	C	FA	NN	AI	O	T	Ap	CS	TS	LR
[4]						**√**	√											√	**√**	
[7]						**√**	√										√	**√**		
[9]	**√**					√			**√**									√	**√**	
[10]	√					**√**			**√**									√	**√**	
[11]			√		**√**												√		**√**	
[12]		√				**√**			**√**									√	**√**	
[13]		**√**	√															**√**	√	
[14]	√					**√**			**√**									√	**√**	
[15]					√	**√**												√	**√**	
[16]			√				**√**											√	**√**	
[17]						**√**	√											√	**√**	
[18]				**√**		√		**√**									**√**	√		
[19]						**√**	√											√	**√**	
[20]					√	**√**												√	**√**	
[21]		√				**√**				**√**						√	**√**			
[22]			√				**√**								√	√	**√**			
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[27]		√			**√**										**√**					**√**
[28]		√	**√**																	**√**
[29]		√			**√**													√	**√**	
[32]				√		**√**									√	√	**√**			
[33]		√	**√**					√		**√**						**√**	√			
[34]		√				**√**		**√**							√	**√**	√			
[35]		√				**√**			√	**√**						√	**√**			
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[42]					**√**					**√**						√	**√**			
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[44]		√				**√**		**√**								**√**				
[45]					√	**√**				√	**√**					√	**√**			
[46]		√				**√**				**√**						√	**√**			
[47]		√				**√**						**√**				√	**√**			
[48]		√			**√**			√		**√**						√	**√**			
[49]						**√**	√	**√**		√						**√**	√			
[50]						√	**√**			**√**						**√**	√			
[51]						√	**√**	√		**√**						**√**		√		
[52]						√	**√**			√		**√**				**√**	√			
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[56]						**√**	√	**√**		√						√	**√**			
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[64]					√	**√**		**√**								**√**	√			
[65]		√			**√**					√	**√**					**√**	√			

Table A1 - Continued: Classification according to the multi-objective problem, methodology and empirical nature

	Vertical transportation multi-objective problem							Modelling approaches								Empirical nature of the studies				
	S	F	R	CE	PPR	EE	EF	A	E	Si	C	FA	NN	AI	O	T	Ap	CS	TS	LR
[66]						**√**	√	**√**							√			**√**		
[67]			**√**				√							**√**				**√**		
[68]						**√**	√	**√**	√									**√**		
[69]					√	**√**			**√**							√	**√**			
[70]		**√**	√							**√**						√	**√**			
[71]		**√**	√							**√**						**√**		√		
[72]		**√**	√					**√**		√						**√**		√		
[73]	**√**		√					**√**		√						√	**√**			
[74]					√	**√**		**√**		√						√	**√**			
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[76]		**√**	√											**√**		√	**√**			
[77]		**√**	√					√		**√**						√	**√**			
[78]		**√**	√											**√**				**√**		
[79]	**√**		√							√				**√**		**√**	√			
[80]			√			**√**			**√**	√								**√**		
[81]		√			**√**			**√**	√							**√**	√			
[82]		√					**√**	**√**							√	√	**√**			
[83]						**√**	√								**√**		√		**√**	
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[85]						**√**	√									√		**√**		
[86]	**√**	√													**√**			**√**		
[87]						**√**	√			√		√	**√**			**√**	√			
[88]						**√**	√			**√**						**√**	√			
[89]					**√**		√			√	**√**			√		√	**√**			
[90]			√				**√**								**√**	√	**√**			
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[92]					√		**√**							**√**		√	**√**			
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[94]						**√**	√	**√**	√							**√**	√			
[95]					**√**						**√**					**√**	√			
[96]		√	**√**												**√**			**√**		
[97]					**√**													√	**√**	
[98]						**√**	√			**√**						**√**	√			
[99]					√		**√**								**√**	√	**√**			
[100]					√		**√**							**√**		√	**√**			
[101]		√	**√**							**√**						√	**√**			
[102]						**√**	√	**√**		√						√	**√**			
[103]						**√**	√											√	**√**	
[104]	**√**						√			**√**						**√**		√		
[105]						**√**	√								√	**√**		√		
[106]		√	**√**							**√**						**√**		√		
[107]			√				**√**								**√**	√	**√**			
[108]			√				**√**											√	**√**	
[109]		√	**√**											**√**				**√**		
[110]	**√**	√								**√**						√	**√**			

Legend: Safe (S); Functional (F); Reliable (R); Cost effective (CE); Able to meet the passenger performance requirements (PPR); Energy efficient (EE); Environmental friendly (EF); Analytical (A); Empirical (E); Simulation (Si); Combinatorial optimization (C); Fuzzy approach (FA); Neural network (NN); Artificial Intelligence (AI), Other approaches (O); Theoretical (T); Applied (Ap); Case Study (CS); Technology survey (TS); Literature Review (LR)