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OPTIMIZATION AND ENHANCEMENT OF THE PERFORMANCE OF SMART SYSTEMS IN HIGH-RISE BUILDINGS BY MEANS OF META-HEURISTIC ALGORITHM

M. Danesh[*], [†] and J. Abdolhoseyni
Department of Civil Engineering, Urmia University of Technology, Urmia, Iran

ABSTRACT

Nowadays, energy crisis is one of the most important issues faced by most countries. Given the accommodation of a large population, high-rise buildings have a significant role in creating or resolving this crisis. A recent solution with regard to the optimization and reduction of energy consumption is using smart systems in buildings. In fact, with the help of modern knowledge, smart buildings consume energy in the right place and time. By transforming a simple building into a dynamic one, not only will it be able to adapt to changing environmental conditions, it will also consider the living habits of dwellers and comfort standards in order to provide maximum satisfaction. Moreover, the money spent on making smart appliances will be fully compensated after a short while, saving the overall costs and energy. This descriptive-analytical study, conducted using library resources, e-books and papers, is an attempt to examine the effect of smartization on optimizing and increasing the efficiency of high-rise buildings. The results of comprehensive surveys in various sectors related to smart buildings show that one can optimize energy consumption to take an effective step in solving global energy issues using smart systems in buildings. This study is devoted to energy consumption of smart systems employing an efficient continuous evolutionary meta-heuristic algorithm.

Keywords: energy consumption optimization; high-rise building; smart; meta-heuristic algorithm.

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1. INTRODUCTION

Due to the ever-increasing population and human need for shelter, housing has turned into

[*]Corresponding author: Department of Civil Engineering, Urmia University, Urmia, P.O. box 165, Iran
[†]E-mail address: m.danesh@uuy.ac.ir (M. Danesh)

one of the basic issues in urban development. Along the growth of urbanization as well as the population increase and scarcity of construction land, meeting this increasing need requires building residential complexes [1]. Moreover, unplanned population growth has caused excessive energy consumption and global warming, increasing pollution and reducing fossil fuel resources [2].

The rapid and unplanned population growth and the increase in land prices have made story-building or vertical growth of cities inevitable. Among the advantages of vertical urban development are land conservation, reduced environmental degradation, reduced transportation and urban traffic, as well as reduced environmental pollution and energy consumption due to horizontal development [3].

The basic idea behind many urban plans is to increase the density and construction of high-rise buildings as much as possible to shrink the ground floor, hence accommodating a larger population and optimally using the public space, services and urban infrastructure [4]. In practice, this allows more space for open green areas such as parks. Nonetheless, this open space may become a hazardous piece of land with no undesirable elements and controls [5].

While today's world is experiencing the climax of high-rise buildings, one should not forget many of them are environmentally unfriendly, have low standards, efficiency, high consumption and notable pollution, and lack energy management [6].

2. BACKGROUND OF HIGH-RISE BUILDINGS

If, by definition, a high-rise building has more than three stories, then perhaps the history of these structures should be traced back to the Pyramids of Egypt and the Tower of Babel. The ancient Egyptians were possibly the first to use scientific knowledge to set up their buildings. Their astonishing structures are the prototypes of the oldest high-rise buildings ever found. These gigantic stone structures, including winding rooms and corridors, have been constructed with very sophisticated calculations and meticulous accuracy [7].

Modern engineers are also amazed by the implementation of arched ceilings and suspended brackets in the design of great Gothic cathedrals of Europe [8]. With the invention of elevator and air conditioning in the late 19th century, the first buildings known as high-rise buildings were built in Chicago, America. The first real skyscraper, called the Home Insurance Building, was built in the city.

In recent centuries, "high-tech" architectural styles have been built in line with modern technology and the "eco-tech" in response to environmental crises. Eco-tech architecture tries to satisfy one's spiritual and physical needs, providing increased productivity and sustainable development in society [8].

3. SMART BUILDINGS

In the current era, new materials, computers and construction technologies have helped architects develop new designs for the optimization of high-rise buildings with the invention of planned and smart systems.

One of the benefits of the rapid expansion of information technology is the development of systems that can measure and evaluate changes in the environment and respond to them based on rational conclusions. This ability to control changes has led to alterations in the physical environment around us, especially buildings with living and working applications. A smart building is the one that encompasses a dynamic and cost-effective environment by unifying the four core elements of the systems of structure, services, management and the relationship between them. In other words, a smart building is a building whose all internal components interact with one another as a whole piece and create an environmentally friendly logic [9].

Overall, a smart building is a structure equipped with a robust communication infrastructure, able to respond and adapt to changing environmental conditions continuously. Moreover, it allows residents to use existing resources more effectively, hence increasing their safety and security. On the other hand, energy management, by definition, signifies cost-effective and efficient use of energy. Employing energy management systems (EMS) can bring about savings of about 10 to 30% [9].

EMSs are control systems that prevent energy loss by adjusting the hourly or periodic operation of equipment. To a large extent, various control systems, known as intelligent building systems (IBSs), can be used [9].

In this regard, a building management system (BMS) or building automation system (BAS) refers to a system installed in a building to control the energy needed in various parts of the building through self-control components while enabling users to apply their preferences via displaying appropriate outputs. The various parts under control usually include mechanical installations, heating, ventilating and air conditioning (HVAC) in addition to lighting equipment that can be evaluated by safety systems, firefighting, access control, emergency power supply, among others. Overall, the purpose of using BMS in a building is to adapt the operating conditions of different components to the environmental requirements and necessities of the building at that time [10].

Figure 1. Smart building systems

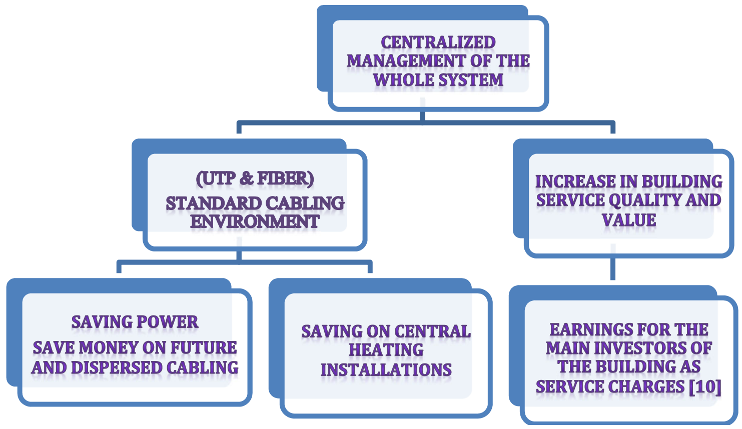

Figure 2. The Advantages of Smart Buildings

4. THE BENEFITS OF SMART SYSTEMS

A smart building integrates four key elements: structure systems, services, management, and their relationship into a dynamic and cost-effective environment [11], offered by smart control systems. These systems are shown in Fig. 1.

It is known that the only real cost of a smart building is not the initial cost (IC), but the additional life cycle cost (LCC). A smart building reduces all these costs by automatic and integrated control, telecommunications and management systems. Another point is the computer-to-human error ratio, which is much lower in a smart building. In the old management style, in contrast, this quantity increased with increasing human interference as the building was run by several people. However, in the new management system, such errors will significantly reduce. Smart control systems have a high level of flexibility that can be easily adapted to different needs. Conversion and optimization operations can also be easily optimized during operation, reducing energy and maintenance costs. Moreover, a BMS is highly controllable and has proper structures, making the control of its various components possible from all over the world. By defining various access levels, one can classify the controllability of various components, so that some changes can be made only to authorized users by entering a defined password. In addition to these advantages, a smart building provides other benefits to the owners of these types of buildings, as shown in Fig. 2.

5. EXAMPLES OF SMART SYSTEMS

At the beginning of the 21st century, cultural and technological changes as well as the way people view their work and living conditions in the commercial, industrial and even residential sectors require an environment that can be optimally utilized at the least cost. In the next sections, various systems used in a smart building to accomplish this task are discussed.

5.1 Smart energy management system in thermal installations

A smart energy management system in thermal installations offers many functions. For instance, installing such as system reduces energy consumption by up to 65% and 25% in non-residential and residential buildings, respectively [11]. Using this system in the engine room of the building increases the heating water temperature when the ambient temperature is low and vice versa if it is warm during the day, so that the user does not feel frustrated. This system prevents excessive generation of energy in different times of the day. Furthermore, the system intelligently switches off, while it activates before the office hours start to keep the building cool [11].

5.2 Life safety system

Using state-of-the-art technology in life safety, smart buildings have managed to adapt to the principles of life safety and security systems quickly while reducing the costs of such systems. The effective factors in the safety of smart buildings are shown in Fig. 3.

5.3 Light adjustment and control systems

Lighting adjustment systems are generally divided into two main groups of on/off systems and dimmer systems.

Each of the on/off and dimmer settings can be controlled individually or by a combination of manual, temporal, sensor or central modes [12]. Fig. 4 shows the properties of the light adjustment and control system.

6. CENTRAL ADJUSTMENT SYSTEMS

When users leave their homes, they announce the exit status by pushing a button in the central setting. Thus, all doors and windows are locked automatically as planned. All the lights (or some of them) are turned off, the power is cut off in some temporary loads (like radio and television) and security detectors are activated to determine when a stranger enters, triggering an alert siren. Outdoor lights turn on for a few minutes until the people leave. Moreover, the temperature reduces so that the heating system produces less energy [12].

Smart cards are used nowadays instead of keys in smart hotels. The guest information is stored in these cards. After the passenger arrives at the hotel and goes through the reception process, the passengers places their cards in front of the elevator door, and the elevator automatically retrieves the floor information, then stops on the relevant floor. By activating the card at the reception area, the room temperature is adjusted, corridor lights turn on to guide passengers, top lights in the room turn on and off as guidance and a welcome message displaying the guest's name appears on the TV screen of the room.

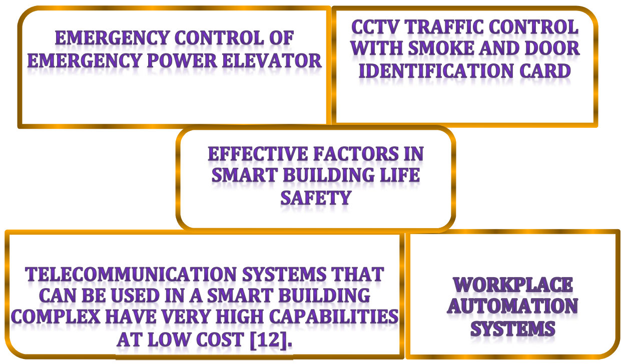

Figure 3. Effective Factors in the Life Safety of Smart Building

7. EXAMPLES

7.1 The Arab world institute, Paris

This building was built in 1987 in Paris, and has a mechanical shell placed behind glass. There are 30,000 diaphragms in the building facade, electrically controlled by photovoltaic sensors to adjust the temperature and control the interior light like the holes on the skin [12]. The facade of this building is shown in Fig. 5.

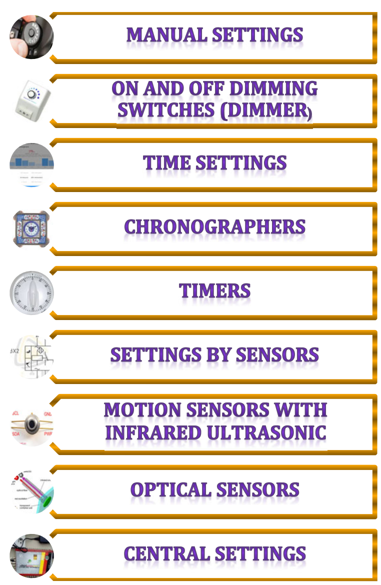

Figure 4. Characteristics of the light adjustment and control system

Figure 5. The Arab world institute [12]

7.2. Crystal tower, Moscow

The tower on the island called Crystal, 10 kilometers from Moscow, is known as the tallest and most dreamy building project in the world. In the interior of the building, there are removable screens that allow daylight to reach all the inner parts. These screens, controlling the indoor temperature in winter and summer, are managed by intelligent systems [9]. Fig. 6 shows the facade of this building.

Figure 6. Moscow Crystal Tower [9]

7.3 SEG residential tower, Vienna

This tower is 60 meters high and located in Vienna. The tower glass facade is smart, which, along with ceiling fans, provides cooling of the apartments in summer and heating in winter. This well-calculated system provides a higher level of comfort in the hot summer weather, and in addition to winter, heat generation occurs faster [9]. Fig. 7 shows the view of this building.

Figure 7. SEG Residential Tower in Vienna [9]

8. SMART SYSTEMS OPTIMIZATION PROBLEM

Given the increasing development in new optimization methods in technical sciences [13-21] including meta-heuristic algorithms, it is suggested to maximize savings using these algorithms along with artificial neural network and defining clear objective functions for energy consumption levels, running costs, and maintenance costs, among others.

For the optimization problem of smart systems, the objective function is the energy consumption of smart building systems while some limitations are usually considered on EMS, BMS and BAS as design constraints. The formulation of smart system optimization problem is written as

$$\text{Minimize: } E=\sum_{i=1}^{n} V_i T_i X_i, \quad i=1,2,\dots,n \tag{1}$$

$$\text{Subject to: } \begin{cases} g_j^{EMS}=\dfrac{P.O.E_j}{\overline{P.O.E}_j}-1, & j=1,2,\dots,m \\ g_k^{BMS}=\dfrac{E.R.E_k}{\overline{E.R.E}_k}-1, & k=1,2,\dots,n \\ g_k^{BAS}=\dfrac{U.T.E_l}{\overline{U.T.E}_l}-1, & l=1,2,\dots,o \end{cases} \tag{2}$$

$$X_i^L \le X_i \le X_i^U \tag{3}$$

where E is the energy consumption; V_i, T_i and X_i are the amount of energy consumed per unit time, using time and energy cost of ith equipment, respectively; EMS, BMS and BAS constraints are represented by g_j^{EMS}, $g_k^{BMS}$and g_l^{BAS} respectively; $P.O.E_j$, $E.R.E_k$ and $U.T.E_l$ are jth periodic operation of equipment, k^{th} estimate the required energy and lth user's taste energy, respectively; $\overline{P.O.E_j}$, $\overline{E.R.E_k}$ and $\overline{U.T.E_l}$ are their allowable values; n, m and o are the numbers of equipment, respectively.

The following exterior penalty function (EPF) is employed to handle the constraints of the above optimization problem:

$$\Phi = E \times \left[1 + r_p \left(\begin{array}{l} \sum_{j=1}^{m} \left(\max\{0, g_j^{EMS}\} \right)^2 \\ + \sum_{k=1}^{n} \left(\max\{0, g_k^{BMS}\} \right)^2 \\ + \sum_{k=1}^{n} \left(\max\{0, g_l^{BAS}\} \right)^2 \end{array} \right) \right] \tag{4}$$

where Φ is the pseudo unconstrained objective function, and r_p is a penalty parameter. During the optimization process, r_p is linearly increased from 1.0 at the first iteration to 10^6 at the last one.

Evaluation of energy performance of buildings (EPB) is an important task which can encourage people to live in smart structures [22]. It can also play a significant role in economical use of energy and reducing energy bills. During the last decades, various strategies have been developed to deal with this problem. HVAC optimization [23] is an effective way as it is responsible for adjusting the air condition inside the building. He et al. [24], for example, conducted a numerical modeling on the impact of the outdoor thermal condition on the EPB. Yao et al. [25] employed analytic hierarchy process (AHP) to weight determination for predicting hourly cooling load (CL). Simulation packages (e.g., BIM environment) are also viable methods for modeling the energy consumption in buildings, but some of their disadvantages have drawn the attention to inverse modeling approaches like data-driven tools [26]. Other attempts in evaluating various aspects of HVAC sets and heat transfer can be studied in the works of Ameri et al. [27] and Alsarraf et al. [28]. Soft computing approaches have provided fast and convenient approaches to solving engineering problems [29]. Artificial neural network (ANN) [30] is a widely-used notion of such techniques which has gained popularity due to its outstanding capability of non-linear analysis [22-30].

9. NMA META-HEURISTIC ALGORITHM [14]

In order to find an optimum of the function f(x), the Newton's method can be effectively used. As the derivative is zero at an optimum point, local optima may be found by applying this technique to the derivative of the function. In this case, the iterative process can be formulated as

$$x_i^{t+1} = x_i^t - \frac{f'(x_i^t)}{f''(x_i^t)} \tag{5}$$

where x_i^t and x_i^{t+1} are the values of x_i at iterations t and $t+1$, respectively, and $f'(x_i^t)$ and $f''(x_i^t)$ are the first and second-order derivatives of the function f(x) at the point x_i^t, respectively.

Determining the explicit form of derivatives for many real-world problems is impossible or at least very difficult. Consequently, numerical approximations of derivatives can be advantageously applied. In this study, to calculate the numerical approximations of the derivatives, three points x_{i-1}^t, x_i^t, and x_{i+1}^t for which $f(x_{i-1}^t)<f(x_i^t)<f(x_{i+1}^t)$ are selected. Moreover, it is assumed that

$$x_i^t - x_{i-1}^t = \kappa\left(x_{i+1}^t - x_{i-1}^t\right) \tag{6}$$

$$x_{i+1}^t - x_i^t = (1-\kappa)\left(x_{i+1}^t - x_{i-1}^t\right) \tag{7}$$

where κ is a positive parameter. The second-order Taylor expansion of the function f(x) about x_i is written as

$$f(x) = f(x_i^t) + \left(x - x_i^t\right)f'(x_i^t) + \frac{\left(x - x_i^t\right)^2}{2} f''(x_i^t) \tag{8}$$

By assuming $\lambda = x_{i+1}^t - x_{i-1}^t$ and using Eqs. (5) to (7), $f(x_{i-1}^t)$ and $f(x_{i+1}^t)$ can be calculated as

$$f(x_{i+1}^t) = f(x_i^t) + \lambda(1-\kappa)f'(x_i^t) + \frac{\lambda^2(1-\kappa)^2}{2} f''(x_i^t) \tag{9}$$

$$f(x_{i-1}^t) = f(x_i^t) - \lambda\,\kappa f'(x_i^t) + \frac{\lambda^2\kappa^2}{2} f''(x_i^t) \tag{10}$$

Substituting Eqs. (9) and (10) in Eq. (5), the iteration process can be written as

$$f'(x_i^t) = \frac{\kappa^2 f(x_{i+1}^t) + (1-2\kappa)f(x_i^t) - (1-\kappa)^2 f(x_{i-1}^t)}{\kappa(1-\kappa)\left(x_{i+1}^t - x_{i-1}^t\right)^2} \tag{11}$$

$$f''(x_i^t) = \frac{2\kappa f(x_{i+1}^t) - 2f(x_i^t) + 2(1-\kappa)f(x_{i-1}^t)}{\kappa(1-\kappa)\left(x_{i+1}^t - x_{i-1}^t\right)^2} \tag{12}$$

Substituting Eqs. (11) and (12) in Eq. (5), the iteration will be as follows:

$$x_i^{t+1} = x_i^t + \left(\frac{\kappa^2 f(x_{i+1}^t) + (1-2\kappa)f(x_i^t) - (1-\kappa)^2 f(x_{i-1}^t)}{2\kappa f(x_{i+1}^t) - 2f(x_i^t) + 2(1-\kappa)f(x_{i-1}^t)}\right) \times \left(x_{i-1}^t - x_{i+1}^t\right) \tag{13}$$

In this study, a new population-based meta-heuristic optimization algorithm is proposed to deal with continuous smart systems optimization problems based on a modified version of Eq. (13) as the updating rule of the position of particles in design space. This new and simple optimization algorithm is named Newton meta-heuristic algorithm (NMA). The basic concepts of the proposed NMA are explained in detail below.

For an optimization problem with m design variables, an initial population of n particles is randomly generated in the design space.

$$\mathbf{P}^0 = [X_1^0 \quad X_2^0 \quad \dots \quad X_i^0 \quad \dots \quad X_n^0] \tag{14}$$

$$X_i^0 = \{x_{1i}^0 \quad x_{2i}^0 \quad \dots \quad x_{ji}^0 \quad \dots \quad x_{mi}^0\}^{\mathrm{T}} \tag{15}$$

where $\boldsymbol{P^0}$ is initial population; X_i^0 is the *i*th particle of initial population; and x_{ij}^0 is the *j*th design variable of *i*th particle of initial population.

At iteration t, the values of the objective function of particles are evaluated and the population is sorted in an ascending order based on the objective values:

$$\mathbf{P}_S^t = [X_1^t \quad X_2^t \quad \dots \quad X_{i-1}^t \quad X_i^t \quad X_{i+1}^t \quad \dots \quad X_n^t] \tag{16}$$

$$f(X_1^t) < f(X_2^t) < \dots < f(X_{i-1}^t) < f(X_i^t) < f(X_{i+1}^t) < \dots < f(X_n^t) \tag{17}$$

where $\boldsymbol{P_s^t}$ is the sorted population at iteration *t*; and *f(.)* is the objective function of the optimization problem.

If the following equation is used to update the position of particles in the design space, the algorithm will prematurely converge to a local optimum:

$$X_i^{t+1} = X_i^t + round\left(\Gamma(X_{i-1}^t - X_{i+1}^t)\right) \tag{18}$$

$$\Gamma = \frac{\kappa^2 f(X_{i+1}^t) + (1-2\kappa) f(X_i^t) - (1-\kappa)^2 f(X_{i-1}^t)}{2\kappa f(X_{i+1}^t) - 2f(X_i^t) + 2(1-\kappa) f(X_{i-1}^t)} \tag{19}$$

$$\kappa = \frac{\left\| X_i^t - X_{i-1}^t \right\|}{\left\| X_{i+1}^t - X_{i-1}^t \right\|} \tag{20}$$

where the function round *(.)* has the role of rounding real numbers to the nearest integer, and ||.|| denotes a vector norm.

In order to improve the performance of NMA, the following equation is proposed for updating the particles' position:

$$X_i^{t+1} = X_i^t + round\left(\begin{array}{l} (\frac{t}{t_{\max}}) \times R_1^t \times \Gamma \times (X_{i-1}^t - X_{i+1}^t) + (1 - \frac{t}{t_{\max}}) \\ \times R_2^t \times (X_B - X_i^t) \end{array} \right) \tag{21}$$

where R_1^t and R_2^t are vectors of random numbers drawn from [0,1] at iteration t, the maximum number of iterations is represented by t_{max}, and X_B is the global best solution obtained so far.

The local and global search abilities of the proposed NMA originate from second and third terms in Eq. (21), respectively, and the results of this study reveal that the coefficients

$(1\text{-}t/t_{max})$ and (t/t_{max}) provide a fine balance between exploitation and exploration of NMA. The flowchart of the proposed NMA is depicted in Fig. 8.

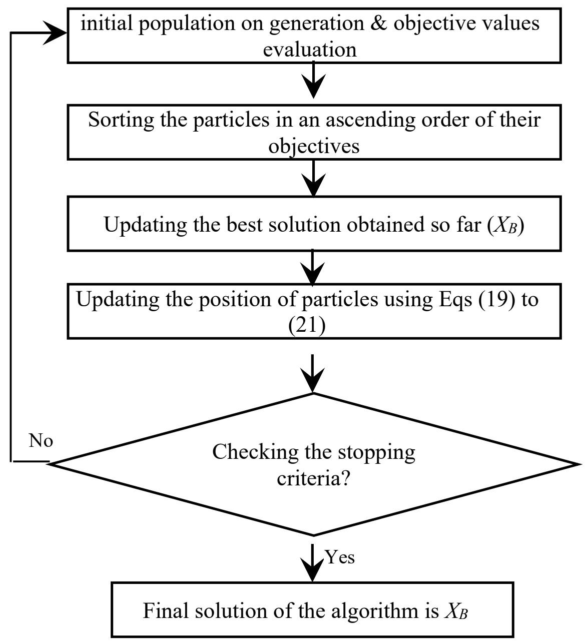

Figure 8. Flowchart of NMA

10. CONCLUSION

In high-rise buildings, the type and extent of energy losses as well as management and utilization of existing facilities require different strategies, and an improper planning can lead to high costs and numerous drawbacks. In a BMS, a notable part of the involuntarily daily routine of residents are performed by smart systems, thus saving time and manpower costs. Moreover, reduced energy consumption and energy expenditures lead to reduced error and increased system efficiency. By using various sensors inside and outside the building and a single system, one can instantly take control of all comfort and safety conditions to attain the ideal state. In doing so, special hardware and software are needed, implemented by collecting environmental information and transferring data to the central system, process control and building management. Using EMS can bring about cost reductions by about 10 to 30% [9]. With the aid of BMS, the costs involved in system installation are usually fully recoverable within 3 to 5 years [9]. Although it initially seems the existence of BMS increases the expenses during installation and implementation, it is actually observed that the costs are fully recovered after 3 to 5 years, so that savings are possible in energy and running costs [9]. Relying on the above references, one concludes that although the implementation of BMS increases IC, the cost savings in the current expense of the building after the employment of this system can, in a short time, offset the IC and provide a higher level of comfort to residents. The results of comprehensive studies in various smart building sectors, compared to other traditional and non-smart buildings, as shown in Fig. 9, demonstrate that by using smart systems in buildings, besides saving wasted energy, one can take an effective step in tackling the overall energy crisis.

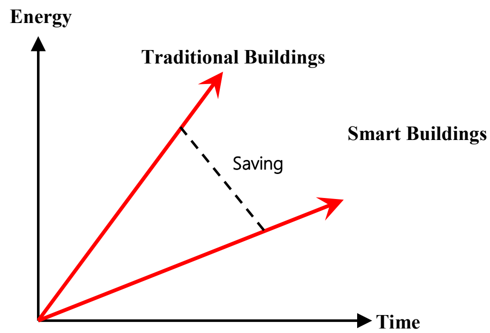

Figure 9. Energy and Time Chart

Evidently, smart high-rise buildings can greatly help enhance the quality of existing facilities, reduce energy waste, and manage resources properly. It is hoped that this study could be a small step towards exploring the importance of intelligent high-rise buildings in optimizing energy consumption and increasing building efficiency. The conducted study exploited a descriptive-analytical approach using library method for data collection and subject review. Moreover, with a close look at books and authoritative papers, journals and dissertations on the same subject through summary checking, direct and indirect quotations were exploited from these sources. Moreover, electronic books and papers and reputable websites were used to collect resources.

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