European Online Journal of Natural and Social Sciences 2024; www.european-science.com
Vol.13, No 3 pp.188-201
ISSN 1805-3602

Application of BIM in Energy Conservation in Low-Cost Housing in Case of Study in Dallas Independent School Residential District, Texas

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Received for publication: 20 April 2024.
Accepted for publication: 25 June 2024.

Abstract

Building Information Modeling is used to build and manage data throughout the project life-cycle from design, construction, and operations. In this technology, multi-threaded data is used to create detailed virtual views in a cloud platform, which allows project members to collaborate in real-time without wasting time. It can also operate and manage the building by using the data that the owners of the building or structure have access to. This data allows governments, municipalities, and property managers to make informed decisions based on information derived from the model, even after the building is constructed. This research, using quantitative methodology, aims to investigate the current state of BIM performance regarding the approaches of converting "affordable residential housing" to "green affordable housing" by reducing the cost of maintaining units and improving their quality with a focus on saving in energy through the implementation of construction details using BIM. In this regard, the Independent School Residential District in Dallas, Texas, and the residential complex built by the government for low-income groups were selected. The main question of the research is whether the behavioral modeling of the residents and the building together can act as an efficiency tool to increase the energy efficiency in the building. Finally, it was found that in low-cost housing such as social housing produced in Texas under the title of housing for low-income society, building information modeling along with user behavior modeling of these buildings together can be a powerful tool to increase building productivity and reducing current costs in the hands of designers and builders.

Keywords: BIM, Low-Cost Housing, Space Syntax, Independent School Residential District, Dallas.

Introduction

Today, construction information modeling has found a wide application from design and construction to operation and even the stage of building destruction. This technology helps the project manager and stakeholders to make the right decision at every stage by displaying the building's characteristics digitally.

Building Information Modeling All construction management activities, based on contract documents, depend on two categories of maps and specifications, in such a way that with the help of maps, the quantity of work is defined and based on technical specifications, its quality is defined (Chippagiri et al., 2021).

BIM applications in general in projects and their management are safety management in construction projects, innovation for destruction and waste management of construction projects, financial management and economic estimation of projects, supply chain of materials in reinforced concrete structures, use of knowledge management in construction projects, improvement of project scheduling and control process, optimal design from the aspect of architecture (Aljohani, 2024). In projects, improving the supervision of the construction process, improving implementation issues and implementing project plans, using construction (Construction Lean), reducing cost or control, reducing time or control, improving communication, improving coordination, increasing quality and or control, negative risk reduction, scope clarification, organization improvement, use in the sustainable development design and green buildings (Dauletbek & Zhou, 2022).

As mentioned, BIM is one of the new and growing technologies with wide applications in the construction industry in the world which has been used in developed and advanced countries for a long time. And of course, its use is spreading all over the world today. As said, Texas also has a bright and growing future ahead of it (Farrokhirad & Gheitarani, 2024) and specialists in this field can earn high incomes in the not-too-distant future. Although BIM is currently being used in many large projects in Texas but gradually, with BIM becoming mandatory, this technology will be used in small projects shortly.

The main goal of this selection process is to identify suitable buildings that significantly represent the 2024 affordable housing pattern and have high energy consumption rates. This research considers the type of housing, geographical area, intensity of energy consumption, and density of housing types for the building selection process. The choice of housing type is limited to cheap houses. Single housing is excluded from the selection process. The geographical scope is limited within the Dallas city limits to align with the scope of studies similar to the existing literature on other archetypes, especially low-cost social housing.

To complete the selection process, the data on social housing characteristics of Dallas City (2012) have been used. A total of 2 residential complexes in the Independent School Residential District area of Dallas City in Texas have been considered for cheap housing. Building selection follows a sequential approach process to identify low-cost homes that exhibit higher consumption of these archetypes. Energy costs for low-income households have increased over the past decades, and the energy burden (energy costs as a share of household income) has increased since 2007. Average residential energy costs rose 13% to $1,050 from 2003 to 2019 and nearly 15% to $1,300 in FY 2019 (Iliff, 2021; Kahvand et al., 2015).

Average group residential energy load (ratio of average energy cost to average income for a given set of households) for households with incomes less than 150% of the US. The Department of Health and Human Services (HHS) poverty guidelines increased from 10.7 percent in 1997 to 13.5 percent in 2009 (Portilla-Carreño et al., 2024). Water and electricity services are included in housing affordability calculations. However, higher energy costs mean that rents will be higher and/or more subsidies will be required to cover the difference between actual and "affordable" energy costs, which are currently insufficient to cover the gap (Hameed & Nadeem, 2008). Poor housing quality and low income contribute to fuel poverty, a phenomenon that is more common among low-income households than households overall (Zaker Haghighi et al., 2014).

Over the past decade, home energy costs have generally increased in American homes (Garagnani and Manfredini, 2013). For low-income households, this cost increase is even more severe, as home energy costs can account for as much as a fifth of household income and more than a quarter of total housing costs. For this reason, improving energy efficiency has been cited as one of the challenges facing American housing by the Joint Center for Housing Studies (Zakerhaghighi et al., 2015). Architects and engineers who incorporate energy design concepts and methods into their design projects can play an important role in reducing energy consumption and achieving a sustainable energy structure for our society.

Energy-saving building codes have proven to be sources of sustainable energy savings in new construction. An investment-grade audit is a valuable tool for identifying savings, appropriate energy-saving measures, and the cost of new technologies. Energy modeling and analysis tools can be used to evaluate the energy and economic effects of building features (Hughes, 2023). Facility managers can select green technologies based on organizational goals, geographic location, energy costs, and available rebates and grants. Building Information Modeling (BIM) is a new and innovative technology that has emerged in recent years and enables the efficient achievement of more sustainable designs. It is believed that BIM is an element of h Yati that is involved in reducing industrial waste, including wasted energy, adding value to industrial products, and reducing environmental damage (Ghadarjani et al., 2013- b).

Theoretical

The use of BIM concepts has started to expand since the 1970s. In 1990, the construction industry began to lay the groundwork for building modeling based on object-oriented models. Hong Kong Institute of BIM The term was first used in a 1992 paper by Van Nederdeen et al., although BIM was not used until ten years later, after which Autodesk used this word in his article (Naghibi Iravani et al., 2024- a). Also, Jerry Laserin made many efforts to popularize and standardize it so that BIM can be introduced as a virtual representation of the construction process (Mahdaviparsa et al., 2014). In Hong Kong, the Institute of Building Information Modeling (HKIBIM) started in 2009, with a plan to fully implement BIM in 2014-15.

In India, organization information modeling (BIM) is also known as virtual design and construction (VDC), due to the high population and economic progress, India has taken many measures in this field, and not only in this country itself, It has been active in the countries of America, England, Australia, the Middle East, Singapore, and South Africa, and is collaborating to design and implement construction projects using BIM (Naghibi Iravani et al., 2024- b).

But in any case, the use of BIM in construction projects in India includes about 22% of the entire construction industry of this vast country. The Singapore Construction Center (BCA) announced that architectural projects will require the use of BIM in 2013, in 2014 all structures, mechanical and electrical designs will be required to use BIM, and in 2015 all Projects with more than 5000 square meters of construction must use BIM (Primasetra et al., 2021- April). In South Korea, seminars related to BIM as well as individual and non-systematic efforts have started since 1990, but industrially and with the view of benefiting from the benefits of BIM in the construction industry, this category has been used since the middle of the first decade of the 20th century.

The first official industrial conference in this field was held in Korea in 2008, but after that, BIM has spread rapidly. Since 2010, the South Korean government has increased the scope of mandatory use of building information modeling systems (Karan & Karimi Mansoob, 2021). China included the use of BIM in its four-year plans (2011-2015), the output of which is the preparation and compilation of infrastructures and the necessary rules for the use of such systems (Ngo et al., 2021). Several countries in the European continent have made continuous efforts to increase the effectiveness of building information modeling software and the adaptability of this industry software, including the Czech Republic, France, Lithuania, Norway, Switzerland, the Netherlands, and England.

In 2011, the UK government published its BIM strategy (Karan et al., 2021). This means that by 2016, in addition to the usual information required in the field of construction, 3D BIM should be used in construction projects. However, based on the document published by NBS, it has been determined that in England between 2011 and 2014, the percentage of BIM use in construction projects increased from 13 to 54 (Ahmed & Asif, 2020). The goal of this country is to be in the first place in Europe in this field. In Canada, in 2008, the Canadian BIM Center was established and operated with the support of active and reliable companies in this field, whose mission is to standardize the way models are used in architecture, engineering, and construction (Khanian et al., 2019; Iravani et al., 2024- c).

Since 2008, the Public Service Steering Center in America has made the use of BIM mandatory in all government projects, and currently, this country has reached maturity in the field of exploiting the capabilities of such systems and has the highest percentage of software usage in the world. Has the mentioned. The survey conducted by BIM showed that 75% of the companies using these systems have stated in their reports that they have received more profit due to the use of BIM (Khanian et al., 2013). They have also learned how to use it to increase their profits.

By examining the three basic components that make up the amount of use of building information modeling systems, which are the experience of working with BIM, the level of skill in working with BIM, and the level of BIM implementation, the following results can be achieved: contractors in America and Canada are significantly different from others. Countries are ahead. In North America, the percentage of BIM is used in all industrial and government projects, it should be noted that in Canada, building information modeling systems are used in all infrastructure projects (Zaker Haghighi et al., 2014; Loubet et al., 2023).

Considering that Brazil has recently used these systems, the percentage of BIM use has been evaluated as low based on the three mentioned criteria. Germany, England, and France are in a better situation compared to other countries that are considered as new adopters or countries with low skills, and overall these three countries are in the same situation, and only France is slightly better than the other two countries (Samai et al., 2024). Compared to advanced countries in the field of using building information modeling systems, South Korea has been evaluated at an average level, and 78% of contractors in this country have been identified at an average or low level based on the three principles of using BIM. Based on the principles of using building information modeling systems, Japan is at a higher-than-average level (Gheitarani et al., 2020; Hicks, 2021).

This means that 83 percent of the contractors in the construction industry in this country use BIM software in their projects, and almost 74 percent of them use such software in 15 to 60 percent of their projects (Maleki et al., 2024). In Texas, an association called BIM has been established since 2014 to create the necessary platforms in line with the 1404 vision document. The main core of this association consists of civil engineering professors and experts in doctorate and master degrees from top and leading universities of the country such as Sharif University of Technology and Amirkabir University.

The use of BIM in the construction projects of our country has only been done in the form of virtual modeling in a handful of projects, and no action has been taken in the field of designing and using the main benefits of BIM.

The role of spatial configuration in building architecture. The configuration of the space can be considered as the beginning of the analysis using the space syntax method, which is often applied to the pan-building or pan-urban area (Gheitarany et al., 2013).

However, the starting point of the analysis is a graph network (topology) which is an abstract representation of this spatial configuration. The hidden point in this abstract pattern is that the social relationships in space are better understood by this topological network, or in other words these are the social relationships that are depicted by the graph and the relationship between its components is present or absent. It implies the existence of these relationships. In addition, network topology creates a context for further calculations that display the complexity of social relationships and decipher the relationship between them (Halder & Afsari, 2023).

This graph network removes the complexities of an architectural or urban plan, which does not have a direct impact on its relationship with its neighboring spaces, from the calculations, and thinks purely and unimpaired about the relationship between the plan's components (Ghadarjani et al., 2013- a). This problem causes adjacent spaces that have different geometries to be judged according to the role of their grids and sometimes they are considered to have the same value (Changsaar et al., 2022).

Relationship. Valuable spaces in the cities of our country have undergone changes and transformations during the transition from traditional life to modern life. According to the spatial arrangement method, spatial arrangement theory is used to solve these problems and create a relationship between behavioral and spatial issues (Gheitarani et al., 2024; Moreno Santamaría, 2021).

This method is a collection of theory and methods that deal with the phenomenology of space and it can be called one of the most important methods of space morphology. Spatial configuration is the core of conceptual spatial analysis, not based on the usual geometric methods, but based on their spatial topology.

The theory of space arrangement has a new look at the city and urban spaces and practically deals with the concept of space as a new concept. This new concept practically defines the city as the spaces between the masses and not its building masses (Mathews et al., 2023).

Connection rate. To analyze urban morphology, space layout extracts a set of features of spatial parameters that are taken from the connection graph (Gheitarani et al., 2013; Bathaei, 2021). The most obvious parameter for morphological analysis is the degree of connection. The degree of connection is defined as the number of intersections that are directly connected to a space. The following equation shows the amount of connection:

$Ci=K$

K is the number of nodes that are directly connected to a space and Ci is the connection graph.

Control value. The control value is a parameter that shows the degree of selection of each node for direct communication with another node. The control value of a node i is determined according to the following formula.

$Ctrli=\sum_{j=1}^{k}\frac{1}{C_j}$

K is the number of nodes directly connected to i and is the connection of js.

Depth. The depth of space indicates the number of spaces that we have to cross to reach from one space to all other spaces. Depth is an independent parameter of spatial arrangement. It is an important variable for calculating correlation (Berglund et al., 2020). Depth has an inverse relationship with connectivity, in other words, in any space where there is a lot of connectivity, that space has less depth. The shortest distance between two points i and j is in graph G, the sum of the depth of node i is equal to the sum of its distances (dij) (Baltazar et al., 2020). As a result, the average depth is equal to the following expression:

$$MDi=\frac{\sum_{j=1}^{n} d_{ij}}{n-1}$$

(n) is the total number of nodes in the graph.

Methodology

The research method used in this research is the quantitative method. In this research, the information of the studied building, which is a social housing branched by the government for low-income groups, will be modeled. It is worth mentioning that the most common types of constructed buildings were identified and used. The modeling of the residential complex building in Dallas City will be done during the following stages:

1- First, the complete model of the building was made in Design Builder software. The specifications used in the built model are based on common and approved implementation details for low-income buildings in this area.

2- Each floor of the building has 4 residential units and a staircase. Each of the spaces inside each unit was defined as a thermal zone.

3- All openings and doors of the zones were completely made in the model.

4- The openings were selected and adjusted according to the common type.

5- Simulation of energy consumption was done based on one-year climatic data of Dallas city and the results were compared in different cases.

After modeling the building of the residential complex, the behavior of the residents of this building on one of the floors of the building will be simulated as a representative of the other floors. In this context, as mentioned earlier, the points of the floor plan where there is the most likely presence of residents will be analyzed and extracted through the Depthmap software. Also, the gravity points of residential units (where the result of attraction and non-attraction of the space for the presence of users is the lowest), and internal gates will be discovered.

The outputs of space syntax will be the basis for the changes applied during the building information modeling process. In the process of behavioral modeling of the residents, the indexes of connection, connection, average depth, and gate count will be extracted. To model building information, indicators such as total energy consumption every month, heating and cooling energy consumption every month, and the amount of electrical energy consumption for lighting will be calculated.

Modeling of building information will be displayed in the form of tables and graphs, and finally, by adapting this output information to the outputs of space syntax, we will make changes to the performance specifications and spatial composition to achieve optimal energy consumption.

Introduction of the study area. In this article, the residential complex of Dallas City, located in the Independent School Residential District area of the city, was chosen for the modeling of low-cost housing construction information and the behavioral analysis of its residents. This building complex, which was built by the government in 2010, was built for low-income families in the form of social housing.

Figure 1. Location of the study area

Figure 2. A view of the apartments in the study area
Source: Google Earth, 2023

Independent School Residential District Residences with an area of 21.8 hectares is located on the southeast front of District 3 and does not have an approved plan. From the northern part of the area, it is limited to the Independent School Residential District town, and on the east and south fronts, it is limited to the neighborhood of reserve lands and gardens, and it is limited to the village of Muzdaghina in the west. These lands have severe topographic effects. The height difference between the highest part and the lowest part is about 60 meters.

Table 1. Information related to Dallas City, Independent School Residential District Residential Complex

Per capita (Independent School Residential District residential complex)	Per capita (Dallas city)	Per capita (Dallas city)	Description	
25	43	30	Residential	Pure levels
3	8	18	Services	
19	35	79	Passages	
43	71	69	Total	
25	63	56	gross levels	
115	220	252	Total	

Behavioral modeling of building occupants through Space Syntax. At this stage, we simulate the behavior of the residents of the residential complex to model the behavior pattern of the residents. For this purpose, we draw the floor plan of one of the floors of the building as an example of all floors (the plan of all floors is the same), in AutoCAD 2018 software, and then introduce its output with dxf extension to Depthmap 2004 software. In this software, we consider all four units of this floor as closed polygons and analyze them as convex spaces in the depth map software.

In this research, according to the researchers' needs, we will analyze the gate count, connection, and average depth indicators in the first-floor plan of the residential complex building. In all four residential units in the first-floor plan of the residential complex, there is a big difference in the combination of the colors of the sitting room and other parts of the units. In the output of the gate count indicator (a) in the sitting room part, there are red, yellow, and green colors, while in other parts of this color value, this indicator is blue.

This means that the configuration of the rooms and the entire spaces of all four residential units on the first floor is such that the center of gravity of these units is located in the central part of the sitting room. Also, the communication joint (b) of these units is located in the same sitting room, so the residents have to pass through the points that have a higher connection to access different parts of each unit. Therefore, the most dynamic points of each unit are located in the sitting room. The average depth index (c) also shows that the depth of the rooms overlooking the external walls of the building has the highest value (yellow and green), which means that the rooms overlooking the external walls of each unit on the first floor are spaces that It is rarely used.

Results

Building information modeling through BIM. To model the building information of the residential complex in Independent School Residential District Dallas, we first divide the initial plan of the building into zones according to the number of rooms and all the available spaces in the Design-

Builder V. 2.2.5.004 software. Figure (3) shows the plan and zones drawn in the Design-Builder software**.**

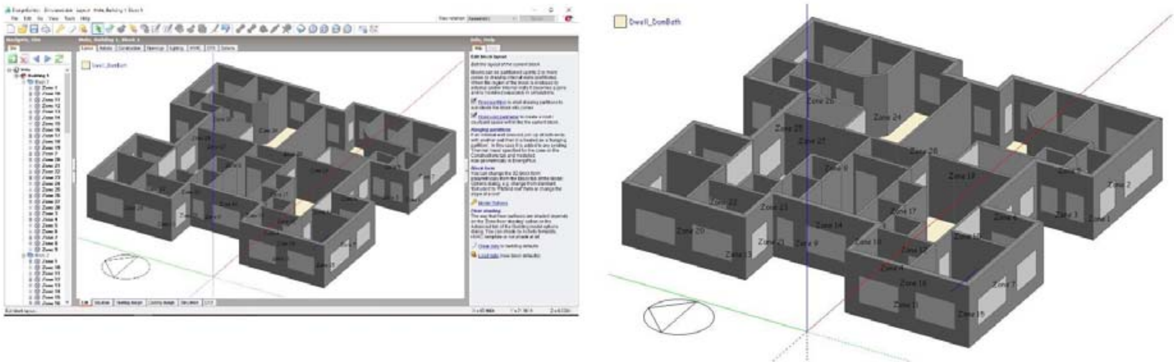

Figure 3. The plan map of the first floor of the residential complex is drawn in the Design-Builder software as Block 1, which has 28 Zones.

For drawing each floor with its units, we will have one block and several zones. Since the number of units on all floors is the same, we will have 5 blocks and 140 zones per five floors of the residential complex. After drawing the desired building, we will introduce related information. This information is generally divided into several categories. These general categories include climatic and meteorological data of the desired area and data related to the orientation of the building. Climatic data of Dallas city is prepared as an EPS file and entered into the software. These data are extracted hourly from weather station data by climate consultant software. Also, the orientation of the building is based on the rules of urban construction and north-south.

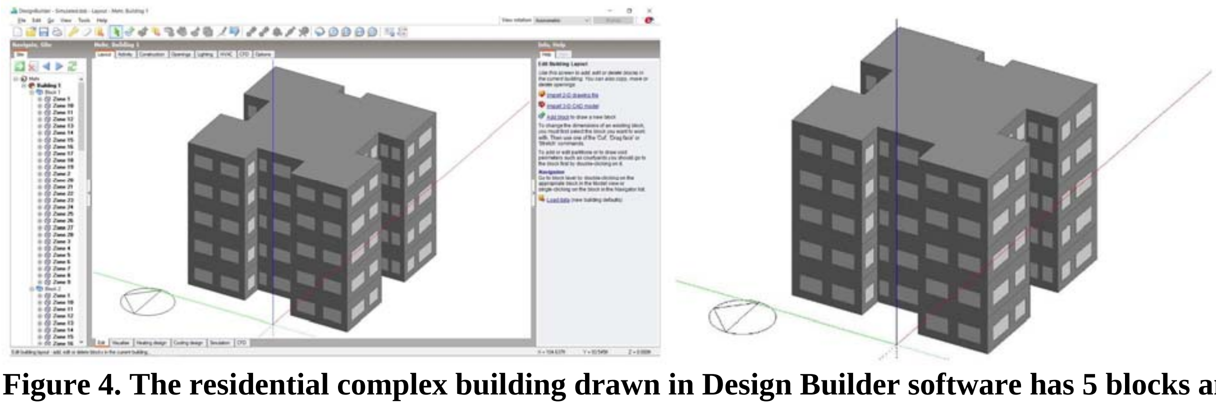

Figure 4. The residential complex building drawn in Design Builder software has 5 blocks and 140 zones and related climatic and location information.

After drawing the building model and entering the climatic and geographical information into the software related to the drawn model, the designed model will be simulated. After simulating the model designed in the discussion section about the research findings, these outputs will be compared with each other before and after the changes that are applied based on the behavioral analysis of the residents. In the next step, to match the outputs obtained from the building information modeling with the behavior modeling of the residents, we will simulate the plan of the units or the zones of one of the floors of the Independent School Residential District residential complex in Dallas in Depthmap 2019 software.

Discussion and Conclusion

To compare the energy efficiency before and after the changes in the building plan, we compare the results of the residential complex building simulation in the DesignBuilder software before and after the plan change. Figure (5) shows the results of energy efficiency in two situations before and after applying the changes. It should be noted that when we make this comparison for a cold climate, increasing the average internal temperature means more productivity, and this issue is interpreted exactly the opposite for a hot climate. The heat exchange that happens through the walls is reduced to such an extent that this issue affects the overall energy efficiency in the building, especially in the cold seasons of the year.

This index (Walls) has dropped by -0.3, which means less heat exchange from inside to outside of residential units. After applying the changes, the energy exchange with the environment outside the building through the walls has decreased slightly and this can be seen in the slight decrease in the external infiltration index. The zone sensible heating index, which shows the amount of energy used to increase the ambient temperature until reaching the desired temperature, has increased by 2.9 kBTU/h from the state before the changes were made. Therefore, after applying the changes, more energy must be consumed to heat the building in the cold seasons of the year.

According to the cooling design diagrams before and after applying the changes, it can be seen that the Heat balance shows how much heat is gained or lost from each part. In the state after applying the changes of this index, especially through the walls, it has shown more heat exchange. Also, the total fresh air index, which is the result of mechanical ventilation, natural ventilation, and infiltration through the walls, has slightly increased after applying the changes. That is, moving the sitting room from the central area of the building units to near the walls has made air conditioning and air circulation more favorable. This index, which means noticeable heating, shows the amount of energy used to increase the temperature of the environment until reaching the desired temperature.

Modifying the building plan based on the resident's behavior. In the information modeling part of the building of the residential complex, the simulation of the drawn model and its related information was done. The result of the data simulation of the Independent School Residential District residential complex in Dallas is the graphs of the heating and cooling behavior of this building which will be analyzed. Then the behavior of the users of this building is examined about the special way of designing the spaces and the way of arranging them next to each other. The result of the initial investigation of the space syntax indicators shows us that the placement of the sitting room in the current state of residential units on each floor has caused a specific pattern of using spaces.

For this purpose, in all the residential units on the 5 floors of the residential complex, changes are applied in the plan of the units so that the location of the sitting room is changed as the most sensitive space of each unit and is placed next to the external walls. Among the many changes that we could apply to observe the influence or lack of influence of the building configuration on the energy efficiency of the building, changing the location of the sitting room was chosen. The reason for this choice is that the overall separation of the colors of the output indicators of the Depthmap software is such that the placement of the sitting room in each unit has caused drastic changes in the space syntax indicators. Therefore, the behavior of residents in these two categories of space (sitting room, and spaces other than sitting room) is different.

If we want to change the thermal behavior of the building according to the behavior of the users of the building, we have to change the placement of two categories of general spaces in each residential unit of this residential complex. Therefore, we change the location of the sitting room and rooms in all four units from the first floor of the residential complex and in the other units on the upper four floors. Of course, we try to change the area of the rooms and sitting room as little as possible to minimize the effect of changing the area and to make possible changes in the efficiency of energy consumption in the building dependent on the changes in the configuration of the spaces. Figure (5) shows the process of redesigning residential units in the residential complex building and the final and modified model of this building designed in DesignBuilder software.

Figure 5. Process of redesigning residential units in the residential complex building

So far, based on the modeling of building information and the behavior of residents, changes have been applied to observe the impact of the configuration of the building spaces on energy efficiency. In the analysis of the research findings, the results obtained from the simulation of the building information before and after the changes in the building plan were compared with each other. Therefore, in the end, we can conclude that although the BIM revolution is not over yet and is expanding and evolving, nevertheless, many construction companies have invested in using this technology, at least in parts of it, and some others are still thinking about it.

Both the evolution of this technology and the increase of its users need time, but it should be noted that BIM is not just a new fad or a fleeting fad, and BIM has come to transform an entire industry, BIM will do the same thing to the construction industry. The Internet did with communication. In Texas, the process of using BIM is increasing every day, and the managers and supervisors of the building are more and more aware of the efficiency of this very efficient tool. In this research, in addition to examining the efficiency of BIM in increasing the efficiency of low-cost buildings, an effort was made to examine the role of other factors in increasing energy efficiency.

In this context, the role of the configuration of building spaces in low-cost housing was studied and investigated. This review was done using BIM and in line with its application. Finally, it was found that in low-cost housing such as social housing produced in Texas under the title of housing for low-income society, building information modeling along with user behavior modeling of these buildings together can be a powerful tool to increase building productivity reducing current costs in the hands of designers and builders.

In the studied sample of this research, it was found that all the indicators that we use in BIM to measure the energy efficiency in the building show a small or large increase in the energy efficiency in the building when changes are made according to the needs of the users of the spaces. In the end, it is suggested that builders' architects and other custodians of housing and urban development consider the use of BIM tools and tools that simulate users' needs at the time of building construction and before starting construction. With this method, they can save as much as possible on the current costs that will be consumed during construction and after.

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