Energy-Efficiency of Smart Buildings with Flexible Exterior Fenestrations: A Study for Thermal Concerns

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Abstract: As we now live in a world that ecological footprint has exceeded ecological the capacity of earth, the need for having sustainable plans for our developments seems life force. There are different data that reveal the pivotal role of buildings in having sustainable environment. One of the most imperative aspects of sustainable architecture is thermal comfort. This effects environmental features and is the cause of remarkable share of costs in all around the world. Passive solar energy is one of the most important energy sources that can be used as a renewable one. Adaptation of an object, like living creatures, is essential for surviving in equilibrium with the related context, either in long history or short individual living periods. Buildings are not exceptions. Planning to enhance buildings energy efficiency, we would consider them as flexible ones, especially when the milieu specification has radical changes. The aim of this research was to find a way for changeable use of passive solar energy in accordance with environmental changes. In this study it has been analyzed how motile exterior walls, as the most important part of an apartment that loses and gains thermal energy, would affect environment and HVAC (Heating, Ventilation, and Air Conditioning) costs. The case study is a 193 square meter flat of an apartment and the Colorado weather data is considered in this case. It has been resulted that the energy needed in flexible façade with motile panels for changing the windows sizes is more than 10% lower than a typical static one.

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1. Introduction

It is axiomatic that our style of using resources affects future resources and can cause limitations. Aiming to tackle today's environmental problems and to let the future generations of human being and other living species exist in a compatible context, propounds sustainability as one of the most imperative approaches for our time.

Sustainable development has been described as a change in which all aspects are in accordance with both current and future potential to meet human needs and aspirations and it requires the least possible use of non-reusable energy sources and seeks developments based on reusable energy sources (World Commission on Environment and Development, 1987). This has become an important approach because Human Ecological Footprint has exceeded the Ecological Capacity of Earth in recent decades. (Borucke et al. 2013) Now, we have been aware of the problems inextricably linked to our built environment. (Rosse 2011)

In such situation, architecture with high sustainability considerations is a life force. Sustainability encompasses a wide range of matters. It should be considered in economic, social, and environmental affairs (Janda 2011; Crawford 2011). As flourished economic and societal well-being are depended on the planet capacity to provide resources and ecosystem services (Borucke et al. 2012), the pivotal role of the environmental affairs would seem more important. Three principles of sustainable architecture has been proposed as *Economy of Resources* which requires the reduction and recycling natural resources in buildings, *Life Cycle Design* that concerns analyzing the building and its environment, and *Human Design* which focuses on the interaction of human being and natural world (Kim and Rigdon 1998, 8).

Buildings are drastically responsible for environmental effects. In 2011, residential buildings consumed 22 percent of energy consumption (U.S. Energy Information Administration 2012, 38; Building Energy Data Book 2012, chap.1 p.2). The growth in population, households, and commercial floor space, are the main important factor of the growth in buildings sector energy consumption which are expected to increase 27% , 31% , and 28% , respectively, between 2009 and 2035 (Building Energy Data Book 2012, chap.1 p.2). Raising energy efficiency standards in buildings is one of the responses to this matter issued by 111th Congress for the requirement of emissions curbs of 20 percent by 2020 and 83 percent by 2050 (Clean Energy Jobs and American Power Act 2009).

Different investigations have underpinned diverse factors to approach to zero-emission housing via active systems and passive systems (Simm and Coley 2011; Samant 2011). Also, Increased daylighting has been scrutinized in numerous researches in official buildings (Heerwagen 2000; Fisk et al. 2001; Heschong 2003b; Heerwagen, and Zagreus 2005; Abbaszadeh et al. 2006; Seppänen, Fisk, Lei 2006), and educational spaces (Hathaway et al. 1992; Kuller and Lindsten 1992; Nicklas and Bailey 1996; Heschong 2002; Heschong 2003a; Spengler 2007).

Some of the investigations have propounded the passive building design guides can be altered by local conditions like an investigation on 200 sample houses has showed the extra winter energy consumption and different factors (Su 2011). Diverse social, cultural, and physical situations may create the requirements other than standard ones that has been designed and constructed (Cummings 2012). There are different examples around the world that people respond to cultural and economical considerations rather than climatic and environmental issues. (El fiky 2002). This can be the matter that can convince us to design buildings which can response to user's desirability. In other words, if we consider the building, its environment, and users as an ecosystem, and as the interconnection and interrelation in an ecosystem play the key roles in it (Attmann 2010, 1-2), we come to this essential conclusion that this system needs to interact with its users' desirability. If we consider the whole globe as ecosystem, it becomes obvious that the building should response to environmental effects. Therefore we need a system that can be adjusted by its users in a defined boundary that is acceptable in environmental affairs.

Furthermore, some investigations have focused on the impacts of the role of occupants in energy consumption of a house (Janda 2011). An example of this is an inquiry on the Sweden has showed variant electricity use among buildings with similar levels of insulation, unit cost for electricity, and heating systems (Schipper et al. 1989). Also, the investigations of two office buildings which were designed and built in accordance with high standards for sustainable design did not show a tight relation between occupants' satisfaction and the sustainability (Monfared and Sharples 2011). This can be because of different biological features of people, customs, habits, cost policies of the area, and other factors. The problem described erstwhile makes it more imperative to enhance the flexibility of the building design so as the occupants' satisfaction be met with the lowest costs and effects.

HVAC systems consume a large proportion of residential total energy consumption (Figure 1). Although some investigations have been accomplished in kinetic architecture for alleviating environmental effects in roofs specially (Asefi 2012), the mentioned system is designed mostly for a static situation that is a designed building. This optimum solution would be inflected by the deviations from the median situation at which the static building design has been designed and constructed. So, it is obvious that we need a kind of flexible fabrication to enhance the building performance.

In this study, it has been tried to analyze if the flexible construction helps to have better environmental effects, how it affects costs of HVAC and environmental affects, how it adapts to users' desirable conditions, and what is the applicable situation of this concept.

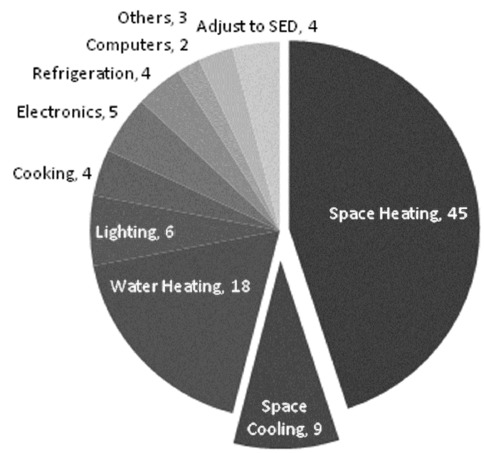

Figure 1. Residential site energy consumption by end use as defined by the U.S. Department of Energy (Building Energy Data Book 2012), chapter 2, page 1

2. Material and Methods

The aim of this research was to study an effective way to change the size of the windows installed in exterior walls in order to lessen the environmental effects and HVAC systems costs. The size of the windows depends on different factors. Allowing the daylight to come through the interior spaces, thermal concerns, and outside view are the main parameters in manipulation of the size of exterior windows. Thermal concerns of these fenestrations are based on the size, shape, fabrication materials, and detail of them. Changing these parameters would alter the solar thermal and lighting gain, and consequently the costs for HVAC system costs. Mostly, the optimum size for windows is based on the aforementioned parameters, weighed by the design group, for all days and nights of the whole year. The flexibility of the building in response to environmental changes is limited to some accessories like interior or exterior shades, curtains, or other similar things. As the environmental features of an especial ecosystem fluctuates more drastically, the need for a more dynamic system in building fabrication would seem more imperative. This consistency is greatly interlinked into solar status as one the main environmental features. This is mostly attainable via the specifications of exterior windows.

In this paper, a typical flat with 198 m^2 area in an apartment was inquired (Figure 2). Ecotect Analysis 2011 was used for the simulations. The weather data of this investigation is the weather data of Colorado Denver. The exterior walls, in the sequence of interior side to exterior one, are composed of 3 *cm* thick gypsum plaster, 5 *cm* thick polystyrene foam, 20 *cm* thick brick masonry, and a 3 *cm* thick cement plaster. All of the window types are "DoubleGlazed_LowE_TimberFrame" with U-Value of 2.410. Other specifications remained as default settings.

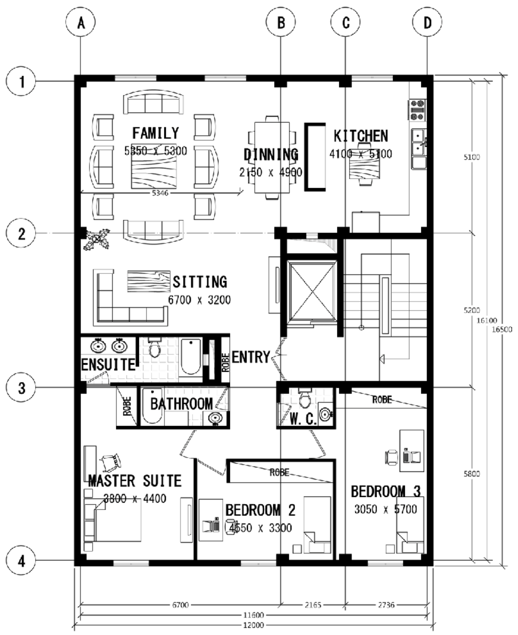

Figure 2. Plan of a typical flat

First, the *Annual Heating and Cooling Loads* of the building with a typical size of windows is evaluated (Table 1) The *Hourly Heat Gains/Losses* values are calculated for two hypothetical buildings with two extreme windows size; the first one is a building with the maximum capability of gaining light which is a building with glass exterior walls, and the other one is that building with minimum windows sizes those meet the minimum desirabilities in a flat. In this case, requirements of Emergency Escape and Rescue Windows (building guide 2010, 4), and psychological parameters may play an important role. Therefore, the minimum windows size is not zero, and it has been considered that in the aforementioned building occupants need approximately six windows with 100 *cm* length and 80 *cm* height in both north and south sides of the building. Besides conforming the requirements of Emergency Escape and Rescue Windows (building guide 2010, 4), the mentioned dimensions for exterior fenestrations meet the minimum acceptable view. For easing the reference to these two modifications of our sample building in this paper, the first one (one with total glass exterior walls) would be called "building A", and the other one (one with six 100×80 cm^2 windows) would be called "building B". Specifications of "building A" and "building B", other than exterior walls, are the same as the typical flat showed in Figure 2.

The optimization process was based on scrutinizing the expedient windows size for different hours during all year days and nights. For achieving a pragmatic way for real fabrication of this concept, as described above, two windows sizes were considered instead of multifarious ones. Two sets of *Hourly Heat Gains/Losses* values illustrating the analyzed amounts of each hour of a day for buildings "A" and "B" were extracted. Each of these values of "building A" is compared with its equivalent one in "building B". Selection would obviously be based on using passive solar energy and requiring less mechanical equipments. Of course this achievement is considered with thermal conduction, convection, radiation, and evaporation of that special exterior wall type.

Positive values shows the amount of energy needed for cooling and negative one for heating the space in watt hour (Wh). In this research, the absolute amounts are important for us. As an example, the optimization process of the first day of January is showed in Table 2. These sets of values show the required energy for HVAC systems. Therefore, these show the total environmental effects of HVAC systems of that flat and their costs. The annual summed amount of these values is showed in Tables 3, 4, 5.

Fabrication Method

Architectural design is got to be modulated for design and construction concerns in today's industrial world. For lessening the fabrication problems, the sample building façade is divided into three equivalent segments. The height of walls is 240 *cm*, so we would have three 80 *cm* high horizontally parallel segments. The 1200 *cm* building length is divided to twelve equal one meter segments. Three compartments have been omitted in each side for attaining the minimum demands of rescue windows, view, and other considerations in building "B".

The conversion mechanism of building "A" to "B" is depicted in three steps in Figure 3. As illustrated in Figure 3, when the position of the building is in step "1", the exterior sides of the panels are either protected by upper levels panels or faces downward. This situation helps to keep panels cleaner while they are horizontal. The interior flanks of the motile panels are finished with reflective materials. Since building "A" would be the current situation of the exterior walls when the requisite is to enhance solar gains, the mentioned reflectors boost the process of gaining solar energy and of course enhance the total results. Also, the lower panels reflect the sunlight to the ceiling of the room which helps to have a desirable diffuse light along the space. On the other hand, the upper panels play the role of shadings which would occlude the severe direct sunlight to a great extent.

Sealing is an important challenge in motile components of a building. Here we have panels that when they are closed, they should play the role of exterior walls attached to the fixed double glazed glass. If these compartments are penetrable, it is obvious that does not satisfy our desires in the case of thermal concerns. So, it has been considered that some elastic studs, in this case rubber studs, those have been fixed to the glass curtain walls would create a closed cap of air between the panels and the double glazed glass when the building is in step 3 (Figure 3). As these studs have elastic characteristic, they can absorb the pushing pressure of panels in order to create the closed gap.

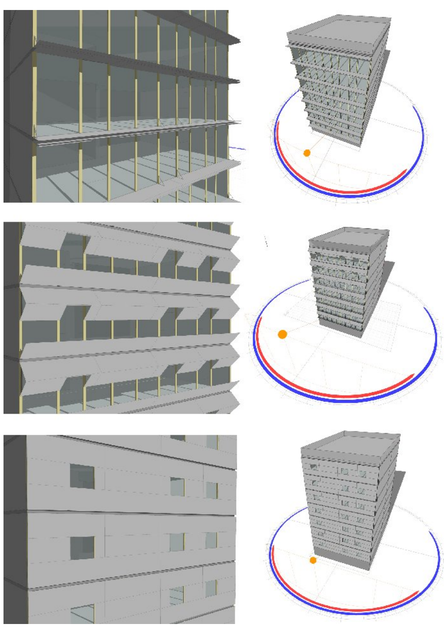

Figure 3. The conversion mechanism of building “A” to “B”; top: step 1 (“building A”); middle: step 2; bottom: step 3 (“building B”).

It has been investigated that the comfort of occupants may differ from each other. So, the system can be controlled by microprocessors to be programmed in order to change the flexible facade based on thermal comfort of the occupants. This means that the occupants would give their satisfactory thermal conditions to the microprocessors, and then the whole calculations and manipulations of the smart dynamic windows would be upon these data.

4. Results

The results of thermal analysis of a sample residential building have been illustrated in Table 1. The results of the optimum situation of buildings “A” and “B” is depicted in Table 3.

For changing the building façade we need to have engines that their power should be considered in evaluations. The panels in each side has been divided to six parts, two compartments in lower 80 *cm*, and four compartments in upper 160 *cm*, each one has its own engine. The lower divisions have 6 *m* length, 80 *cm* height, and 26 *cm* thick. As the exterior walls in the typical building have been considered with a detail that has the density of 270 kg/m2, each of the aforementioned lower compartments have 270×0.8×6 which has 1296 kg weight. The working time of the engine is lower than 12 seconds. The “DJM-1.5T-3P” operator has 1300 kg lifting force and can be implanted for each part. This has 600 *Watt* power. Consequently, the energy needed for lifting up or pushing down the lower panels is 600×12 or 7200 *Watt second* energy which is equal to 2 *watt hour*. We have four of these engines in both north and south for all lower compartments; and these should be operated twice a day. Therefore, the total annual energy needed for closing and opening the four lower compartments is 2×4×2×365 which is equal to 5840 *watt hour*.

Each of the upper divisions has 1296 *kg* excluding window voids in “building B”. So, each of these compartments can be lifted up or pushed down by “DJM-1.5T-3P” engine. Consequently, the total annual energy for the north and south upper compartments of the façade is 2×8×2×365 that is equal to 11680 *watt hour*.

Total annual energy needed for the motile façade is 17520 *watt hour*. This amount is added to the optimum of buildings “A” and “B” and the result is showed in Table 5. So, 1/12 of 17520 *watt hour*, which is equal to 1460, is added to the optimum results of buildings “A” and “B” in each month. The final results are showed in Table 7, 8. It is worthwhile to mention that we can build the motile compartments with materials with the same thermal conditions and lower weights that can result in lower energy needed for moving these parts. But here for considering the situations of different buildings with exact specifications, the mentioned massive walls have been considered for all constructions.

Table 1. Monthly heating and cooling loads of a typical flat

MONTH	HEATING (Wh)	COOLING (Wh)	TOTAL (Wh)
Jan	4009478	0	4009478
Feb	3302921	0	3302921
Mar	2565613	0	2565613

Apr	1290253	0	1290253
May	495025	1035	496060
Jun	126751	186150	312902
Jul	199	800748	800946
Aug	0	491430	491430
Sep	266012	200198	466209
Oct	1339389	0	1339389
Nov	2424923	0	2424923
Dec	3619005	0	3619005
TOTAL	**19439568**	**1679560**	**21119128**
PER M²	**115825**	**10007**	**125833**
Floor Area:	**167.835 m2**		

Table 2. Hourly heat gains and losses of "building A" on 1st of January

HOUR	**HVAC of "building A"**	**HVAC of "building B"**	**HVAC of flexible facade**	**The building from which the value has been extracted**
	(Wh)	**(Wh)**	**(Wh)**	
0	-5615	-4693	-4693	"Building B"
1	-5641	-4696	-4696	"Building B"
2	-5723	-4801	-4801	"Building B"
3	-5710	-4758	-4758	"Building B"
4	-5752	-4795	-4795	"Building B"
5	-5788	-4827	-4827	"Building B"
6	-4654	-4195	-4195	'Building B"
7	-5050	-4475	-4475	"Building B"
8	-4085	-4029	-4029	"Building B"
9	-2965	-3267	-2965	"Building A"
10	-1805	-3099	-1805	"Building A"
11	-1079	-2401	-1079	"Building A"
12	-656	-1678	-656	"Building A"
13	-395	-842	-395	"Building A"
14	-864	-656	-656	"Building B"
15	-1408	-662	-662	"Building B"
16	-2347	-954	-954	"Building B"
17	-2544	-1294	-1294	"Building B"
18	-3282	-1756	-1756	"Building B"
19	-4436	-3021	-3021	"Building B"
20	-4539	-3154	-3154	"Building B"
21	-4888	-3848	-3848	"Building B"
22	-5956	-4862	-4862	"Building B"
23	-7134	-5507	-5507	"Building B"
Total	**-92318**	**-78273**	**-78273**	

Table 3. Monthly heating and cooling loads of "building A"

	HEATING	**COOLING**	**TOTAL**
MONTH	**(Wh)**	**(Wh)**	**(Wh)**
Jan	4531813	0	4531813
Feb	3722826	0	3722826
Mar	2919460	0	2919460
Apr	1510781	0	1510781
May	624060	889	624949
Jun	202826	109908	312735
Jul	3299	664968	668266
Aug	7635	288567	296202
Sep	362494	83259	445753
Oct	1561998	0	1561998
Nov	2763906	0	2763906
Dec	4091567	0	4091567
TOTAL	**22302662**	**1147591**	**23450254**
PER M²	**132884**	**6838**	**139722**
Floor Area:	**167.835 m2**		

Table 4. Monthly heating and cooling loads of "building B"

	HEATING	**COOLING**	**TOTAL**
MONTH	**(Wh)**	**(Wh)**	**(Wh)**
Jan	3881550	0	3881550
Feb	3197414	0	3197414
Mar	2481094	0	2481094
Apr	1245738	0	1245738
May	475322	1407	476728
Jun	120801	187013	307814
Jul	130	787900	788030
Aug	0	487866	487866
Sep	250797	197914	448711
Oct	1292871	0	1292871
Nov	2341653	0	2341653
Dec	3498704	0	3498704
TOTAL	**18786074**	**1662099**	**20448174**
PER M²	**111932**	**9903**	**121835**
Floor Area:	**167.835 m2**		

Table 5. Monthly heating and cooling loads of building with flexible exterior facade (optimum of building "A" and "B")

	HEATING	**COOLING**	**MOVING FACADE**	**TOTAL**
MONTH	**(Wh)**	**(Wh)**	**(Wh)**	**(Wh)**
Jan	3625277	0	1460	3626737
Feb	3321784	0	1460	3323244
Mar	2352092	0	1460	2353552
Apr	1183976	0	1460	1185436
May	872	440888	1460	443220
Jun	98645	116594	1460	216699
Jul	537173	130	1460	538763
Aug	0	257074	1460	258534
Sep	80156	230007	1460	311623
Oct	1139599	0	1460	1141059
Nov	2247336	0	1460	2248796
Dec	3299316	0	1460	3300776
TOTAL	**17886226**	**1044693**	**17520**	**18948439**
PER M²	**106570**	**6225**	**104**	**112899**
Floor Area:	**167.835 m2**			

Table 6. Energy reduction percent of flexible façade compared to typical building, "building A", and "building B".

	Total Heating and Cooling $_1$ (Wh)	**Total Heating and Cooling $_2$ (Wh)**	**Percent of Energy Reduction**
Flexible/ Typical	18948439	21119128	10.27%
Flexible/A	18948439	27219742	30.39%
Flexible/B	18948439	20478997	7.47%

5. Discussions

For considering the exact annual reduction in motile façade from standard one, we should use the Equation 1 and assign the Total Heating and Cooling value of the flexible façade to "Total Heating and Cooling $_1$" and the respective value of the typical façade to "Total Heating and Cooling $_2$". The Energy Reduction Percent of all studied spaces is showed in Table 8.

This has been resulted that the typical flat would consume 10.27 percent more *Watt hour* energy than one with flexible windows sizes. As 54 percent of residential buildings energy consumption is related to HVAC systems (U.S. Department of Energy 2012, chap.2 p.1) and as residential buildings consume 22 percent of energy consumption (U.S. Energy Information Administration 2012, 38; Building Energy Data Book 2012, chap.1 p.2), it can be deduced that more than 1.21 percent of total energy consumption is lowered with the implementation of this concept.

This has been resulted that the typical flat would consume 10.27 percent more *Watt hour* energy than one with flexible windows sizes. As 54 percent of residential buildings energy consumption is related to HVAC systems (U.S. Department of Energy 2012, chap.2 p.1) and as residential buildings consume 22 percent of energy consumption (U.S. Energy Information Administration 2012, 38; Building Energy Data Book 2012, chap.1 p.2), it can be deduced that more than 1.21 percent of total energy consumption is lowered with the implementation of this concept.

The investigations show that the hours that one type of the building "A" and "B" surpasses the other one is in sequence of each other. For example, the results of the Hourly Gains/Losses of "building A" and "building B" for the first day of January are showed in Table 2, 3. It can be seized that the performance of 'building A" is just better that "building B" from 9 *am* to 13 *pm*. The optimum of these two buildings is showed in Table 4. This concatenation seen in all of the days of a year allows to limit the conversion of these two building to each other to just two times during a day. This helps to consume the least amount of energy for the conversion of building "A" to "B" and vice versa.

The problem that may take place here is that urban sites constraints may lessen the opportunity for many passive systems (Mirzaei 2013). So this concept and other similar ones should be propped with sustainable urban planning to prevent solar occlusions by buildings in order to let each individual building to gains sunlight.

$$\text{Percent of Energy Reduction} = 100 \times \left(1 - \frac{\text{Total Heating and Cooling}_1}{\text{Total Heating and Cooling}_2}\right) \quad (1)$$

6. Conclusion

Living in an environmentally better planet for now and future can be achievable via ideas that can amend individuals in order to have momentous environmental impacts. In this research, it has been considered that how flexible façade can change the environmental effects and HVAC costs of a residential flat. It has been deduced that this can lower the energy needed for cooling and heating the flat more than ten percent. This means approximately ten percent reductions in HVAC costs and environmental effects of mechanisms using as HVAC systems.

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