Title: Prioritisation of old apartment buildings for energy-efficient refurbishment based on the effects of building features on energy consumption in South Korea

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Abstract

Since the 1970s the construction of high-rise apartments has been prolific across Asia. More recently, due to changes in legislation, there has been a growing trend towards refurbishment for those old apartments, however this has primarily focused on the economic benefits and rarely taken energy saving and the reduction of carbon emissions into account. Therefore, this study aims to evaluate what features in old apartment buildings need to be taken into account in refurbishment strategies. The method is threefold: evaluating energy consumption in old apartment buildings; identifying effective building features on energy consumption; ranking the effects of building features on energy consumption. The results show that old apartment buildings have consumed excessive energy for space heating and cooling. Maximum 43.65 kWh/m^2/year in space heating and 5.70 kWh/m^2/year in cooling were reduced as a result of the transformation of eight building features, accounting for 70.9% of total variance in factor analysis. Three most influential features, which should be used to priorities for refurbishment schemes, have been identified by multiple regression analysis: the conditions of building envelopes, heating methods and the sizes of building units. Therefore, the priority should be given to these three features.

Keywords

Refurbishment, energy efficiency, building features, old high-rise apartment building

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1. Introduction

In Asian countries that experienced dramatic economic growth such as Japan, Hong Kong, Singapore and South Korea [1], high-rise apartment building became one of the most dominant types of housing [2, 3]. The refurbishment of those buildings is a common issue after more than 40 years of extensive construction of apartment buildings.This issue can be also extended to some countries such as China and Malaysia that have experienced the economic growth in recent years.

In South Korea,ranked 8th for Green House Gases (GHGs) emissions [4], for instance, the Government has attempted to reduce carbon emissions of the country by enhancing building regulations and policies. Apartment buildings wererequired to be energy-efficient since 2001 [5]. In 2009, a new law, 'Framework Act on Law Carbon Green Growth', required higher levels of energy efficiency in buildings [6]. Despite these attempts, energy consumption in residential buildings has not declined [7], and carbon emissions in South Korea have also not reduced [4]. Several studies such as [8, 9] have criticised this unwanted outcome. Particularly, Kim [9] claims ineffective energy reduction in residential buildings was due to energy consumption in old apartment buildings, which were excluded in the energy-efficient scheme. In the building stock of South Korea, the largest proportion of all building types is residential buildings, which amounts to 67.1% [10]. 58% of the residential building stock is apartment buildings [11], which is the most dominant proportion. 63% of apartment buildings were constructed before 2001 [11, 12] when the higher levels of energy-efficient scheme were applied to buildings. In this aspect, the old apartment buildings constructed over 20 years ago, which occupies the largest proportion in the building stock of South Korea, were not counted to be energy-efficient.

There has been a controversial debate amongst policy makers, building developers and residents in South Korea during the last decadeas to whether old apartment buildings should be demolished or refurbished. However, policy makers have proposed to refurbish old apartment buildings to contribute reducing carbon emissions rather than demolish those buildings. As a result, building regulations have been altered in recent years to encourage refurbishment and reduce demolition of old apartment buildings. The South Korean Government, for example, has permitted developers to increase the number of floors on top of apartment buildings in case of refurbishment [13]. This policy can represent the governmental intention to vitalise refurbishment.

Despite the governmental efforts, there are limits in current and recent literature in terms of creating effective strategies of refurbishment for old high-rise apartment buildingsto reduce energy consumption. Firstly, great attention has been paid to economic profit rather than reducing energy consumption or carbon emissions. The concept of refurbishment in existing literature such as [14, 15] was identified by maximising economic profit, and the strategies of refurbishment were focused on cost-effectiveness. Therefore, the strategies would not necessarily be beneficial to reduce energy consumption. Secondly, existing literature, engaging with energy efficient technologies, does not cover old apartment buildings that need to be refurbished [16-20]. It relies on the 'Standard housing' model which draws the thermal condition of buildings from simplified indices [21], assuming that building features affecting energy consumption in all apartment buildings are the same. However, the building features in old apartment buildings were changed by different design preferences in different periods and contexts. The existing literature does not take into account the transformation of building features in old apartment buildings that have been constructed in different periods and contexts [22-28]. This study argues that the transformation of building features affects energy consumption and needs to be taken into account when creating refurbishment strategies.

This study, therefore, focuses on identifying old high-rise apartment buildings in South Korea which need to be refurbished to reduce energy consumption. Furthermore, the most efficient strategy of refurbishment will be identified by investigating building features and their effect on energy consumption in those apartment buildings. Three questions will be answered:

- What are the levels of energy consumption in old apartment buildings? Do these levels of consumption need to be reduced?
- Which features in old apartment buildings have affected the energy consumption?
- Which building features should be prioritised in refurbishment strategies in order to reduce energy consumption?

2. Methodology

The methodology is designed to analyse the impact of building features in old apartment buildings on actual energy consumption. The results will help to prioritise which building features can most effectively reduce energy consumption and thus guide the creation of refurbishment strategies. The method is threefold: evaluating energy consumption in old apartment buildings; identifying effective building features on energy consumption; ranking the effects of building features to energy consumption.

2.1 Evaluation of energy consumption in old apartment buildings

Energy consumption in old apartment buildings was evaluated to determine the necessity of refurbishment to reduce energy consumption. The consumption in old apartment buildings was, therefore, compared to the consumption in apartment buildings which were certified as energy-efficient. To conduct this, old apartment buildings are defined by those which were constructed before 2001, a year when building regulations for the thermal conditions of apartment buildings was much intensified and building energy rating system was just established. Permission has already given for some of these buildings to be refurbished, others will be available to be refurbished in 2015 by a building regulation in South Korea [29]. In contrast, the comparison group of apartment buildings were certified as energy-efficient in an energy rating system set by Korea Land and Housing Corporation in South Korea [30]. The three values of energy consumption in the both groups were compared: total end-use energy consumption; space heating and electricity consumption by construction years; monthly energy consumption for space heating and electricity. The result is shown in Section 3.1.

2.2 Identification of building features affecting energy consumption

Building features in old apartment buildings were identified by reviewing previous literature and surveying existing old apartment buildings.To prioritise building features in refurbishment, this study was, particularly, focused on the transformation of building features rather than characteristics which are commonly found in all buildings. It is difficult to precisely divide time periods of each feature. Instead, this study used the dominant designs since the 1980s, as described in Figure 1. Three distinctive trends are identified in the transformation of building features in old apartment buildings constructed before 2001.

First of all, the main purpose in the early stage of apartment construction was to accommodatea rapidly increased urban population and building features were chosen accordingly whilst building features in the late stage were transformed to acquire higher levels of privacy in each apartment building [25]. For example, between the mid-1970s and 1980s, large volume apartment clustersof more than twenty buildings were constructed as governmental-led projects [31]. During the 1990s, the size of apartment clusters was reduced when the government handed over apartment construction to private developers [31]. Total cluster areas were also changed with the transformations of the size of apartment clusters, but it was differently evolved as the higher requirements for public space with service facilities [32]. Moreover, apartment buildings constructed in the early stage were designed with longer lengths and smaller sized units. A maximum of eight to ten apartment units were placed on each floor; thus small unit sizes of less than 60m^2 (70m^2 including communal space) were constructed in the 1980s [26]. Since privacy has become a sensitive issue, buildings with a stair type whereby only two units share one vertical access points (called a 'core') are preferred [25].

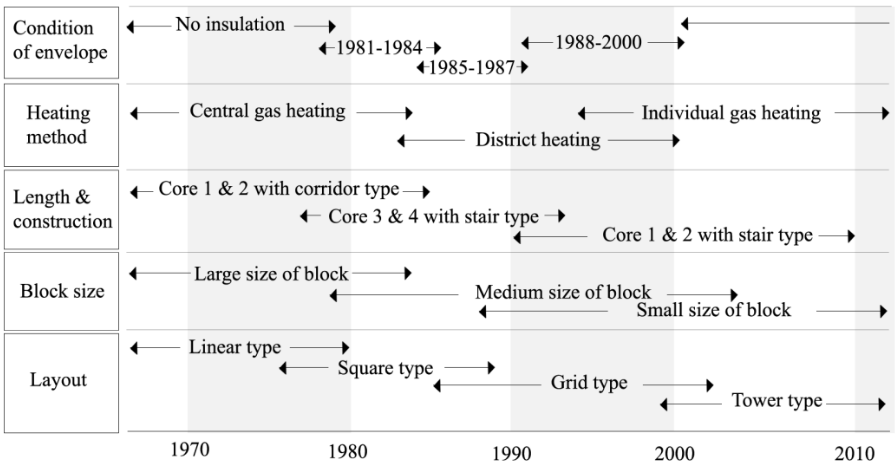


Figure 1) Changes of building features in apartment construction of South Korea since the 1970s

Second, economic profit has also been a significant factor to transform the building features in old apartment buildings. For instance, three types of building layout can be identified [23, 33-35]: the linear type where buildings are long and thin in plan and located parallel to one another; the square type where buildings are square in plan; and the grid type where buildings are located on a grid. According to Jeon [25] , the linear type was the typical design type in the early stage of apartment construction in South Korea, but the design was changed to square and grid type to accommodate more buildings. The sizes of building units were also enlarged; thus the most dominant unit size became about 85 – 100m^2 (about 100 - 120m^2 including communal space) [26].

Third, some building features were transformed by stringent policies and the development of technologies. The thermal conditions of envelopes in old apartment buildings have been determined by a building regulation [36]. The regulation determining the thermal conductivity of materials and the thickness of insulations required was firstly established in 1980. Since 1980, there have been two significant revisions to the regulations in 1984 and 1987, and in 2001, a significant improvement was made. Therefore, buildings constructed before 1980 have no thermal insulation in their envelope which created a poor thermal environment for residents. The second revision, implemented in 1987, required all apartment buildings to be equipped with double glazing. Despite the dramatic increase in apartment construction in the 1990s [11], there was no revision of the regulation to improvethe thermal conditions of buildings until 2001. Also, three different heating methods were found in old apartment buildings: central gas heating, district heating and individual gas heating [37, 38]. Central gas heating was mostly used in buildings constructed in the early stage. Since the district heating was introduced in 1985 [39], apartment buildings constructed in Seoul have been connected to the district heating system. Since the national construction of gas supply lines into the cities, individual gas boilers have become the dominant type of heating.

Table 1 indicates how designs of building features were transformed until 2000. This transformation of those building features was examined as to whether they affect actual energy consumption or not; thus effective building features on energy consumption were identified. The result is described in Section 3.2.

2.3 Quantification of effects by building features

This section is intended to quantify these relations to energy consumption separated by space heating and electricity. Two types of statistical analyses were conducted, which are multiple regression and factor analyses. Multiple regression analysis is one of popular techniques to measure the capability of statistical models to interpret a dependent variable through correlated independent variables, and determine influential independent variables in statistical models [40]. The multiple regression analysis was applied to interpret a dependent variable (energy consumption for space heating and electricity) by using independent variables (building features in old apartment buildings). The values of R-squared demonstrate how efficient this statistical model accounts for energy consumption in old apartment buildings. The standardised regression coefficient (SRC) was used to measure the influences of independent variables (cluster sizes, building lengths, construction types, total cluster area, building layouts, building unit sizes, the conditions of building envelopes and heating methods). The multiple regression models were assessed by power analysis to examine the power of the samples used in this study; f-test was conducted by SPSS.

Table 1 Change in designs of building features in apartment construction in South Korea in pre-2001

Category	**Variables** (CA: categorical, CO: continuous)	**Data range**
Demands of time periods	Sizes of clusters - CA (No. of apartment buildings in clusters)	Large (≥20), Medium (6-15), Small (≤5)
	Total cluster area – CO	12,562 – 515,906m^2
	Types of building access - CA	Corridor type, Stair type
	Lengths of buildings – CA (No. of vertical access points)	1- 6
Economic profit	Types of building layouts - CA	Linear, square and grid types
	Sizes of building units - CO	41.05 – 181.82m^2
Developed policies and technologies	Thermal conditions of building envelopes (insulation and fenestration) – CA	Buildings constructed before 1980, 1981-1984, 1985-1987, after 1988
	Heating system methods – CA	Central gas, District, Individual gas heating

Exploratory factor analysis was, therefore, intended to identify an underlying structure between observed variables consisted of the building features in this study; thus the results can be used to specify efficient targets for refurbishment. The principle axis factoring method was performed by Oblimin rotation (delta 0.4) with Kaiser Normalisation [40]. The criterion used to indicate an adequacy of factor analysis in the sample was followed by a Bartlett's test of Sphericity of significance, and a Kaiser-Meyer-Olkin measure of sampling adequacy [42]. In order to identify robust variables, the variables with the low loadings (< 0.3) and cross-loadings were eliminated. SPSS version 21.0 was used in all statistical analyses and the results of analyses are shown in Section 3.3.

2.4 Sampling

Old apartment buildings constructed in pre-2001

Total 189 apartment clusters with 1767 buildings (171,054 households) were selected as samples. The samples occupy 3.5% of the population size, 4,988,441 households [11, 12] in apartment buildings constructed between 1976 and 2000 in South Korea. The sampling frame was designed with four sampling units: 1) construction years; 2) regions; 3) the number of floors; 4) the availability of data on energy consumption. Firstly, apartment buildings which were built between 1976 and 2000 were only considered, because apartment buildings constructed after 2001 are regarded less urgent to be refurbished with an intensified building regulation, and constructed before 1976 are highly regarded to be demolished as low-rise buildings to rebuild high-rise buildings. Second,sixteen apartment districts in Seoul were selected. The districts were established as parts of enormous housing construction projects between the 1980s and 1990s, leading the dramatic increase of apartment building construction. 60% of apartment buildings constructed before 2000 in Seoul were built in these districts [43]. Therefore, buildings in these districts have used to identify dominant characteristics built in that period. Moreover, these districts in Seoul are in the same climate zone, and the same thermal building regulations are applied to the buildings in Seoul and the central regions of South Korea; thus there would not be significantly different climate impacts in these districts. The impacts of microclimate such as heat island effects may give influence in energy consumption [44]. However, these possible impacts were taken into account in this study as building features related to building clusters. Third, apartment buildings with more than ten floors were considered. This is because that refurbishment would be inevitable for the buildings which have more than ten floors. As they were densely constructed, it is difficult to acquire permissions to demolish them in order to build super high-rise buildings under the current building regulations [13, 45]. Lastly, the availability of data on energy consumption limited the samples in this study. 15.2% of apartment buildings which did not filltheir energy bill records between 2011 and 2012 in AMIS were not counted in this study.

Energy consumption bills between 2011 and 2012 were collected from 'Apartment Management Information System (AMIS). This system is organized by the Ministry of Land, Infrastructure and Transport (MLIT) and managed by the Korean Housing Management Association (KHMA). A policy has been implemented under which all apartment buildings in South Korea should input their expenses into this system. The system displays the expenditure of each apartment building. However, there were some missing data on the energy bills of some apartment buildings in the system. These apartment buildings were excluded in the samples. The collected data from energy bills were converted from Won/m^2 to kWh/m^2. The conversion rates refer to those of the Korean Electric Power Corporation [46] for electricity and Seoul City Gas [47] for gas.

A comparison group of apartment buildings

Total 34 apartment clusters with 319 buildings (13,551 households) built between 2008 and 2010 in one district.

The samples occupy 1.8% of the population size, 740,214 households [11] in apartment buildings constructed between 2008 and 2010 in South Korea. Four sampling units were used: 1) construction years; 2) regions; 3) the number of floors; 4) energy-efficient certificates; 5) the availability of data on energy consumption. Firstly, buildings built after 2001 were selected to compare energy consumption in old apartment buildings becausethose buildings arerelatively regarded as energy-efficient. Secondly, as climate conditions can have a significant impact on energy use in buildings, a district in close proximity to the districts in Seoul selected for the analysis of old apartment buildings was selected to minimise variation between the old and new samples. Thirdly, the same number of floors, more than ten floors,was also applied. Fourth, the certified apartment buildings as energy-efficient in this district were only used in this study as mentioned in Section 2.1. Lastly, the availability of datalimited to choose the samples like old apartment buildings.The certified buildings which did not filltheir energy bill records between 2011 and 2012 in AMIS were not counted.Energy bill data was collected by the same method used for old apartment buildings.

3. Results

The results are illustrated by three parts to answer the three research questions in this study. The first part (Section 3.1) describes energy consumption in old apartment buildings built in before 2001 by comparing the consumption in the group of apartment buildings built between 2008 and 2010. The second part (Section 3.2) indicates building features affecting energy consumption in old apartment buildings. The last part (Section 3.3) quantifies the effects of building features to energy consumption.

3.1 Energy consumption in old apartment buildings

Figure 2 shows a comparison of the total energy consumption of two groups of apartment buildings which are 234.2 kWh/m^2/year and 190.0 kWh/m^2/year respectively. Both numbers are much higher than the 1st grade in energy rating systems set by Korea Green Building Certificate Criteria (GBCC) in South Korea (60.0 kWh/m^2/year) [21] and Passive house standard (25.0 kWh/m^2/year) [48]. This result shows that the energy consumption of both groups of apartment buildings needs to be reduced to satisfy these energy rating systems. Despite excessive energy consumption, detailed consumption (separated by use) indicates different tendencies. Old apartment buildings consumed 109.6 kWh/m^2/year for space heating whilst apartment buildings built between 2008 and 2010 only consumed 66.0 kWh/m^2/year. On contrary, energy consumption of electricity and water heating did not have significant reductions in this period.

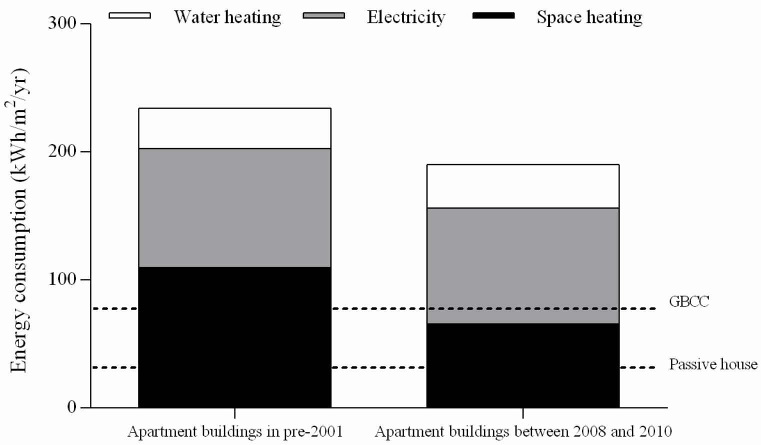


Figure 2) Total energy consumptions of apartment buildings in 2011 and 2012

These tendencies are also shown in Figure 3. The average energy consumed for space heating in old buildings has reduced by their construction years. 100% of old apartment buildings constructed before 1980 consumed more energy for space heating than the average of 108.8 kWh/m^2/year, compared to 53% of old apartment buildings constructed in the 1980s. Only 20% of buildings in the 1990s and none of buildings constructed between 2008 and 2010 consumed above average energy for heating, these results suggest that apartment buildings built before 2001 have been able to decrease energy consumption efficiently regarding space heating.

Energy consumption for electricity was not reduced in this period 92.2 kWh/m^2/year of electricity was continuously consumed by apartment buildings inboth groups. This can be explained by the everyday use of domestic appliances such as refrigerators, televisions and computers. However, Figure 4 demonstrates that the summer use of electricity for space cooling in the old apartment building was especially high in August. In each month, there was only 0.05 kWh/m^2/year difference between apartment buildings in the both groups, except for August when the gap was enlarged to 1.5 kWh/m^2/year in 2011 and 5.7 kWh/m^2/year in 2012.

Like electricity consumption, there was no significant reduction in water heating consumption; 32.6 kWh/m^2/year of water heating was continuously consumed in both groups. However, the old building group demonstrated a higher relative standard deviation with 32.3% while 19.6% was for the new building group.

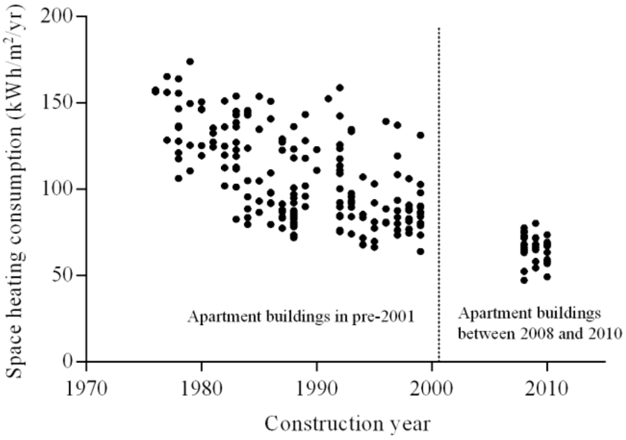
Furthermore, these values are also higher, compared to space heating with 25.2% in old building group and 11.5% in new building group, and electricity with 15.3% and 11.9% in old and new building groups, respectively.

Overall, apartment buildings have been able to decrease energy consumption efficiently regarding space heating and cooling although there were not significant reduction in energy consumption for electricity and water heating. As identified in Section 2.2, physical conditions in apartment buildings constructed between 1976 and 2000 have been transformed. This would probably result in the changes of energy consumption in these buildings.

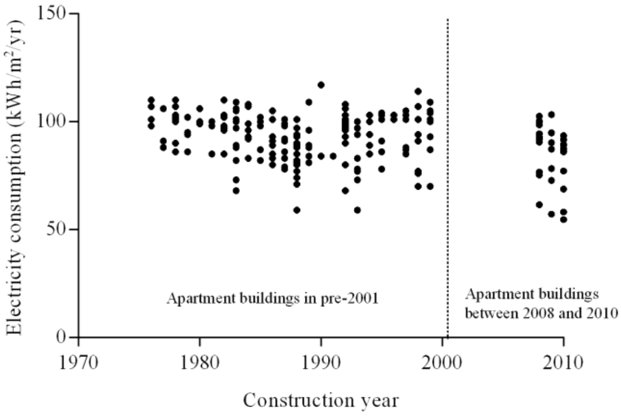
However, the effects of occupants could also be important factors to understand energy consumption in these buildings. Interestingly, residents living in apartment buildings in South Korea showed the extremely unified composition of households. 90% of apartment buildings' inhabitants are parents with their offspring, and families with three or four members occupy 80% of households in apartment buildings [49]. Therefore, the general profiles of occupants such as the number of occupants and types of family may not give meaningful results explaining energy consumption. However, geographical segregations in residential areas caused by socio-economic factors such as the levels of income and education have been identified in South Korea [50]. Their effects would also be useful to identify the continuous energy consumption in electricity and water heating, and the large variations in water heating.[51]. However, this study focused on the physical features of apartment buildings, which were described in Section 2.2, to create the efficient strategies for refurbishment.

3.2 Building features affecting to energy consumption

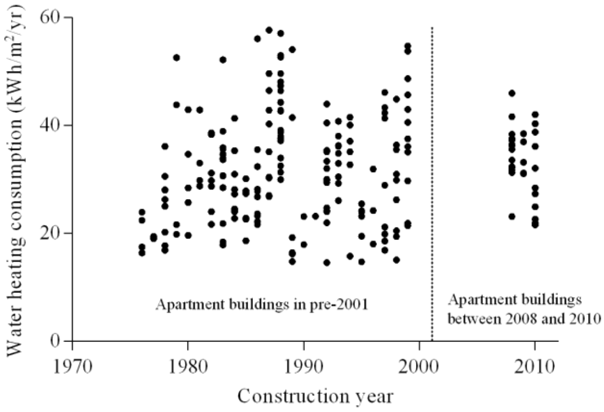
It can be seen that six of the eight features (Table 2) had an effect on energy consumption for space heating while little difference was found in electricity consumption. This can be explained by two opposing tendencies. As expected, one of these tendencies is that old apartment buildings constructed in the early stage consumed more energy than those constructed in the late stage. Three features, the conditions of building envelopes, the lengths of buildings and heating methods, accounted for this increasing tendency in energy consumption. This means that the transformations of the three features reduced energy consumption as seen in Figure 5.



(a) Space heating consumption



(b) Electricity consumption



(c) Water heating consumption

Figure 3) Energy consumption of apartment buildings by construction years: (left) space heating, (right) electricity

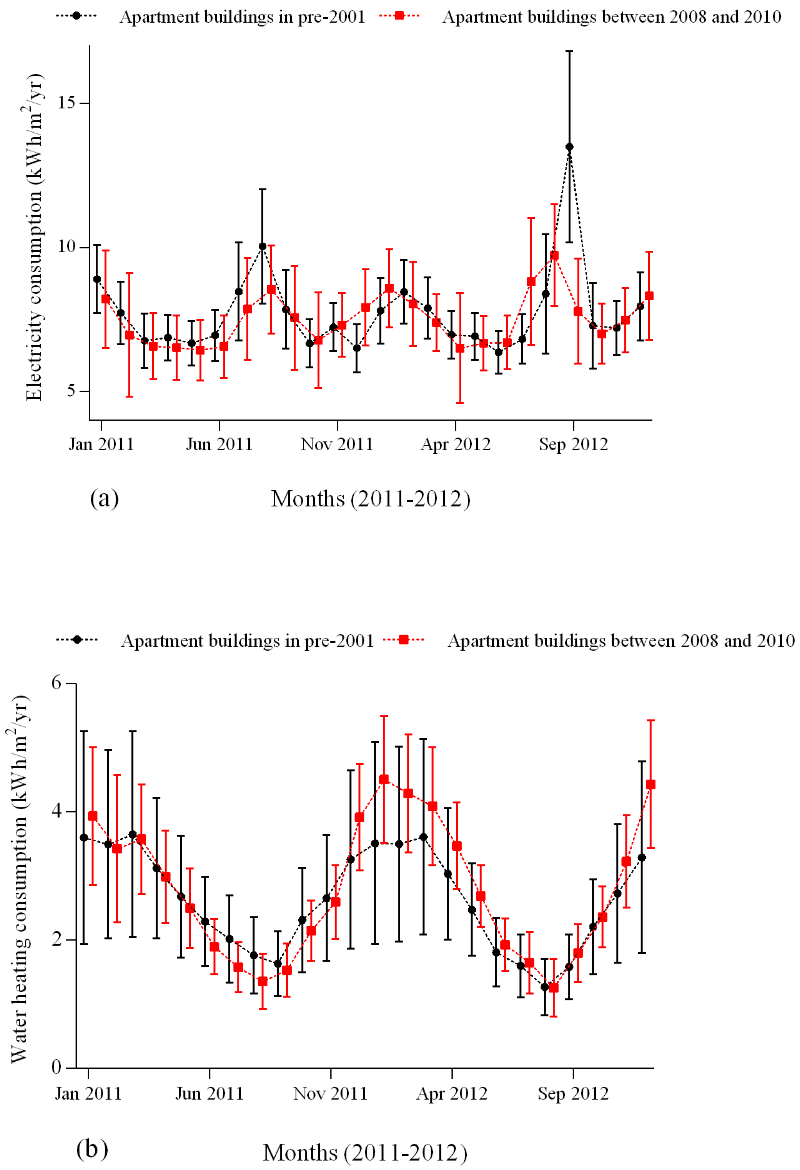


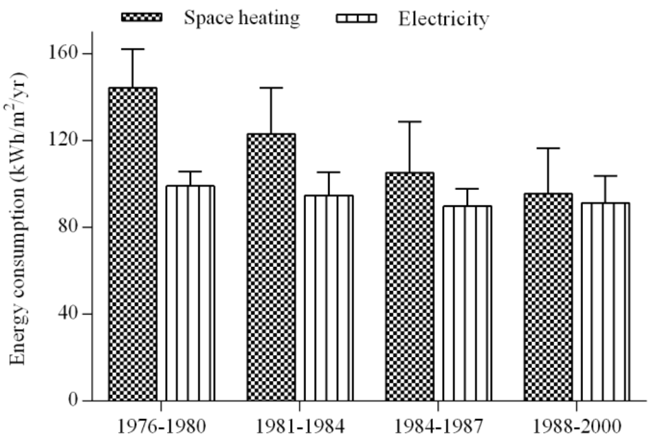
Figure 4) Monthly Energy consumption between for (a) electricity and (b) water heating 2011 and 2012

First, the most effective reduction was found by improving the condition of building envelopes, which was a maximum 48.7 kWh/m^2/year (Figure 5(a)). In particular, the largest reduction occurred between buildings constructed before 1980 and those constructed between 1981 and 1984. This is because buildings built before 1980 did not have insulation on their envelopes while 50mm internal insulations were applied for those constructed between 1981 and 1984. The second largest reduction was between buildings built between 1981 and 1984 and 1985 and 1987. This was achieved by replacing the type of glazing in windows from 3mm single glazing to double glazing. The result indicates the thermal condition of building reduced energy consumption.

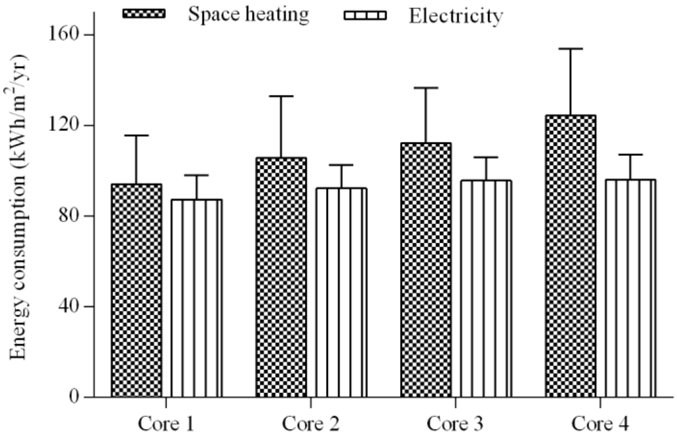
Second, the shorter lengths (that is with fewer vertical access points) the buildings had, the less energy consumed for space heating. Specifically, gradual energy reduction up to 30.2 kWh/m^2/year was found by decreasing the lengths of buildings. As the heights of buildings were mostly fixed either 12 or 15 stories, the total amount of surface area, which is exposed to heat transfer, was reduced. Consequently, this was beneficial in reducing energy consumption. Third, the changes in heating methods also reduced up to a maximum of 26.2 kWh/m^2/year of energy consumed for space heating. Alarge gap was found between buildings with central gas heating, andbuildings with district and individual gas heating. 24.3 kWh/m^2/year was found between central gas heating and district heating, but only 2.0 kWh/m^2/year was found between district and individual gas heating.

The opposite tendency is that greater energy consumption occurred in buildings constructed in the late stage.This is due to three features, namely the sizes of building units, the sizes of clusters and the types of building layouts (Figure 5 (d-f)). Firstly, the sizes of buildings units were increased in response to higher preference for the large sizes of units. This increase in unit sizes caused higher energy consumption in old apartment buildings, which is nearly 30 kWh/m^2/year more energy consumption for space heating and 20kWh/m^2/year for electricity, to maintain a certain level of thermal comfort within the indoor environment. Secondly, old apartment buildings in large apartment clusters consumed less energy than those in small apartment clusters. The amount of energy reduced according to the sizes of clusters, a maximum 12 kWh/m^2/year for space heating and 9 kWh/m^2/year for electricity which were not as significant as the reductions for other features. Third, the types of building layout showed increases with 5 kWh/m^2/year in electricity from linear to grid.

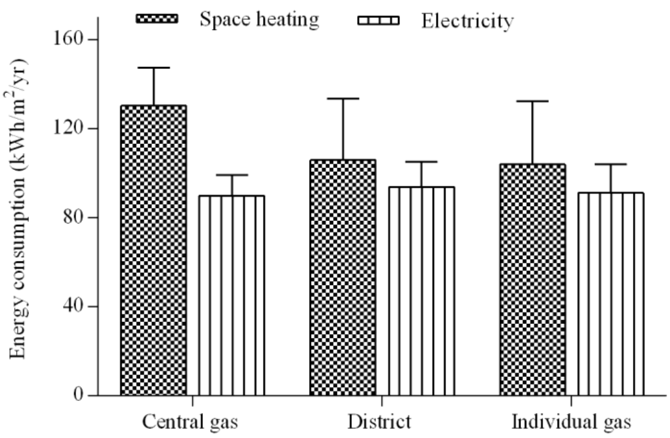
In short, the six building features are identified as being effective in energy consumption. However, the different amount of energy affected by each building feature needs to be evaluated in order to prioritise refurbishment strategies. The results of these evaluations are illustrated in Section3.3.



(a) Conditions of building envelopes



(b) Lengths of buildings (No. vertical access points)



(c) Heating methods

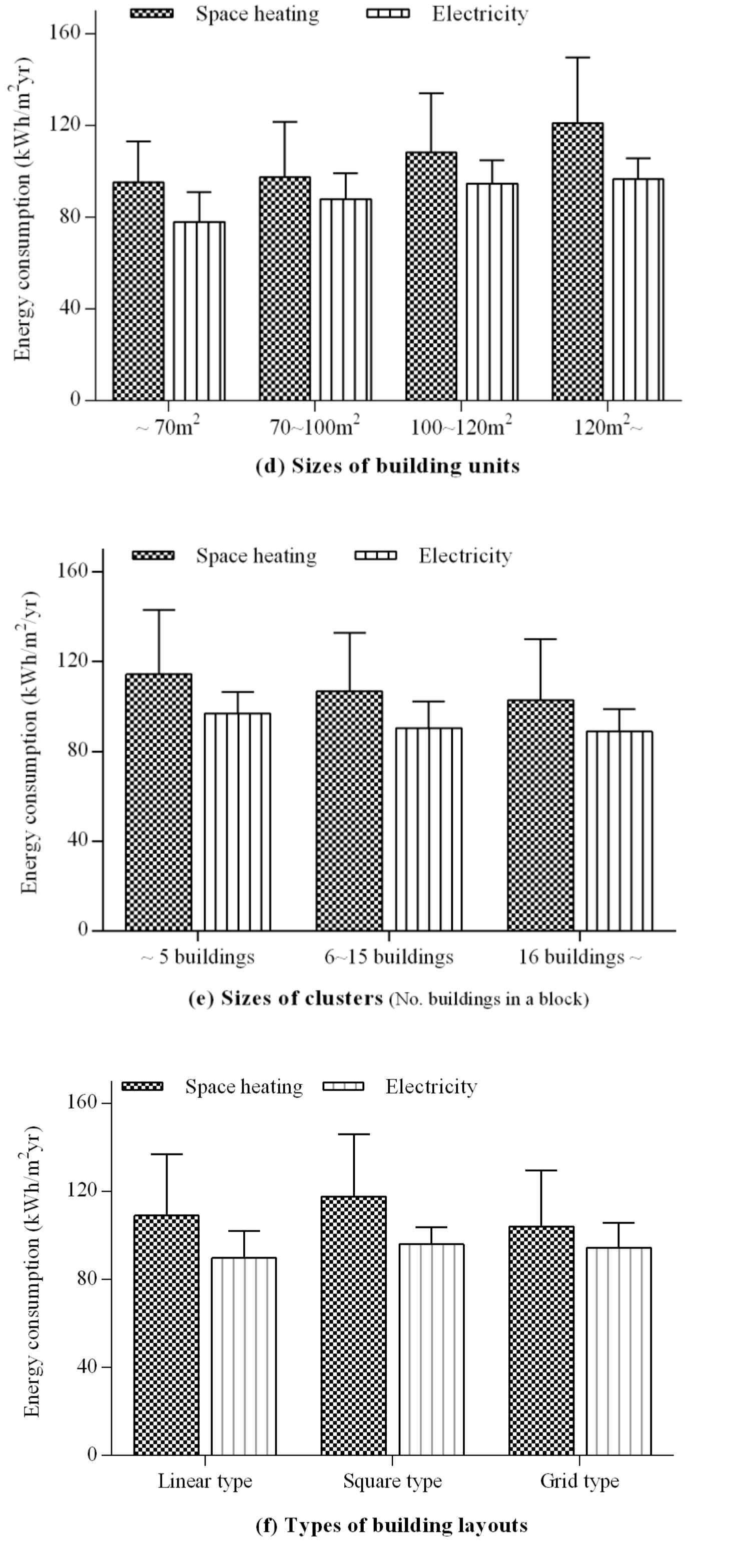


Figure 5) Energy consumptions of old apartment buildings by (a) conditions of building envelopes, (b) lengths of buildings, and (c) heating methods , (d) sizes of units, (e) sizes of clusters, and (f) types of building layouts

3.3 Quantification of effects of building features on energy consumption

3.3.1 Results of multiple regression analysis

In order to reject the null hypothesis, the results of f-test in multiple regression models require not being less than 2.42 with 95% critical confidence interval. The f-test results in this study showed 63.88 with the model for space heating and 15.94 with the model for electricity, which means that the sample sizes were large enough to bring about reliable results.

Table 2 demonstrates the results of multiple regression analysis. The values of R-squared in these two models are 0.580 for space heating and 0.256 for electricity. The both R-squared are not very good to account for energy consumption; the R-square for electricityis relatively low. This could be the primary data on energy consumption were limited to extract gas consumption for cooking and electricity consumption for the everyday use of domestic appliances, which are highly determined by user behaviour rather than building features. Despite it, both models are statistically significant at 5% level.

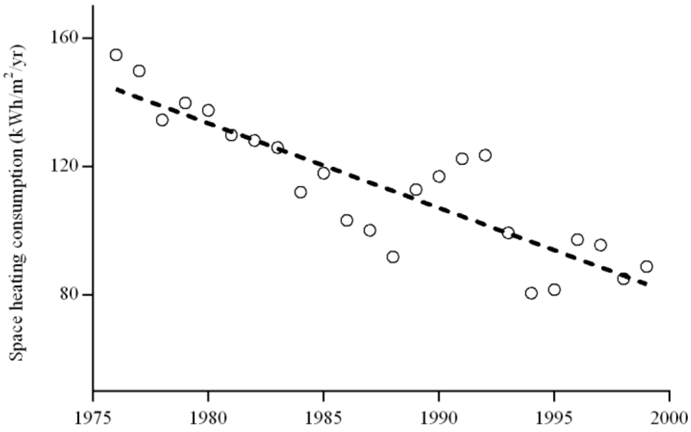
Table 2 The result of multiple regression analysis

	Independent variables	**SRC**	**Significance**
Space heating consumption (R^2=0.580)	The thermal conditions of building envelopes	-0.626	0.000
	Heating methods	-0.301	0.000
	The lengths of buildings	0.196	0.000
	The sizes of apartment clusters	-0.129	0.008
Electricity consumption (R^2=0.256)	The sizes of apartment units	0.300	0.000
	The sizes of apartment clusters	-0.202	0.002
	The types of building layouts	0.203	0.004
	The thermal conditions of building envelopes	-0.203	0.008

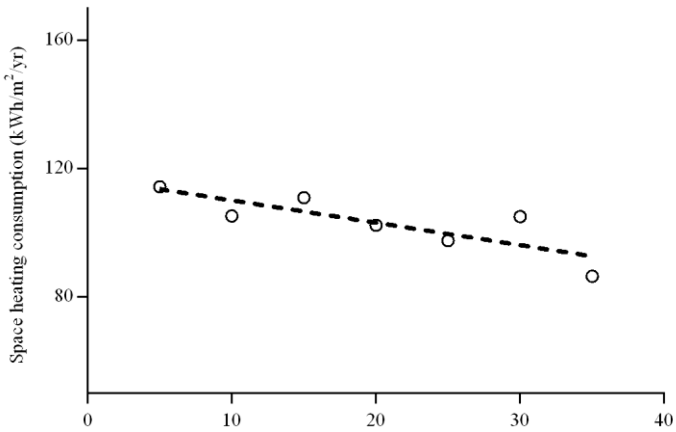
The standardised regression coefficients (SRC) of building features specify the effects of building features on energy consumption. The opposite trends of building features, as seen in the previous section, arefound by negative and positive values of the standardised coefficients (Figure 6 (a-d)). The negative values of coefficients, decreasing energy consumption, are attributed to the transformations of these three features: improving the conditions of building envelopes; changing heating methods from central gas to individual gas heating; reducing the sizes of clusters. On the contrary, the positive values of coefficients, increasing energy consumption, are found by the other three features: shortening the lengths of buildings; reducing the sizes of building units; changing the types of building layouts from linear to grid.

In space heating, four features were chosen as influential variables: the thermal condition of building envelopes, heating system methods, the lengths of buildings and the sizes of clusters (Table 2). Only the feature, the lengths of buildings, is with positive SRC while the other three features are with the negative SRCs. The means that space heating consumption was decreased by these four conditions: reducing the lengths of buildings; improving the conditions of building envelope; changing heating methods from central gas to district or individual gas heating; increasing the sizes of clusters. The former three conditions are typically found in apartment buildings constructed in late stage whilst the large sizes of clusters are identified in the early stage of apartment construction. The effects of the opposite tendencies on space heating are quantified by the values of SRC in Table 2. The former three features are relatively the higher values of SRC than the sizes of clusters with SRC 0.129. This interprets the reason why space heating in old apartment buildings could effectively reduce space heating consumption by transforming building features. Specially, improving the thermal conditions of building envelope played a significant role in this tendency with the most robust SRC 0.626 as seen in Table 2. This can be a strong criterion to determine a priority for refurbishment.

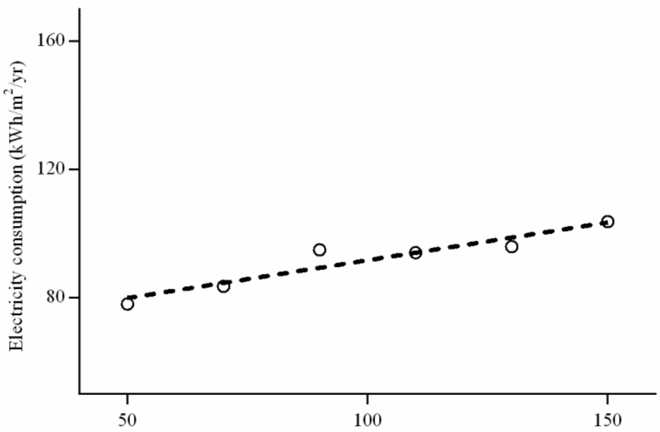
In electricity, the opposite tendencies are also identified. The sizes of units and the types of layouts show the positive SRC whereas the sizes of clusters and the thermal conditions of building envelopes indicate the negative SRC. In other words, electricity consumption was decreased by reducing the sizes of clusters and improving the thermal conditions of building envelope. However, the consumption was increased by the larger sizes of units and the changes of layout types from linear to grid. These four conditions are found in buildings built in late stage. The most significant feature is the sizes of units with SRC 0.300, but the significance is not as robust as the features affecting space heating. The other three features are approximately the very similar value of SRC with 0.202 or 0.203. These values of SRC reflect that both opposite tendencies have not significant differences each other. This interprets the reason why there was no significant change in electricity consumption in old apartment buildings.



(a) Condition of building envelope
(construction year)



(b) Sizes of clusters
(Number of buildings in a cluster)



(c) Sizes of building units (m²)

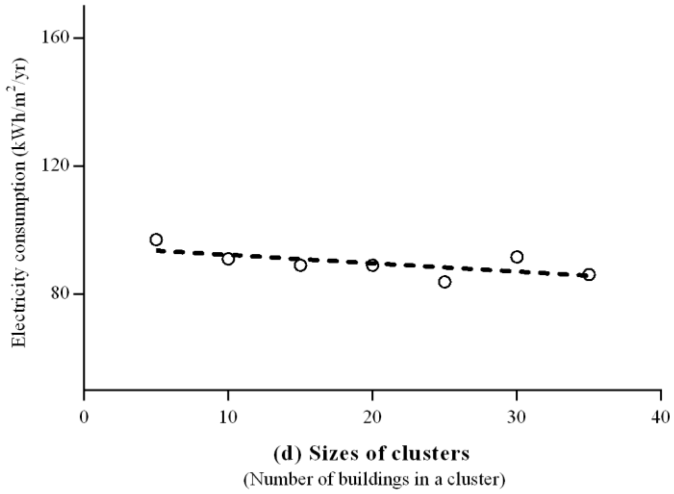


Figure 6) Regression curves of building features with energy consumption: space heating with (a) construction year and (b) sizes of clusters, and electricity with (c) sizes of building units and (d) sizes of clusters

3.3.2 Results of factor analysis

In the factor analysis, Bartlett's test of Sphericity was significant (186.557, ρ=0.000) and Kaiser-Meyer-Olkin was satisfactory (0.616); thus this factor analysis model is acceptable, but not marvellous due to the same reason of the multiple regression analysis. Despite it, 70.8% of the total variance is explained by the eight measured variables, which is statistically effective to account for the variance. Four factors are identified in this factor analysis as seen Table 3.

The first factor explains the most significant proportions of the total variance with 25.9%. The measured variables in this factor are associated with building form and fabric such as the sizes of building units, the types of building accesses, the conditions of building envelopes and the lengths of buildings. Apartment buildings in early stage need to be suitable to accommodate population increased in urban area; therefore, the building form was longer length, smaller unit sizes and corridor type, as identified in Figure 1. The conditions of building envelopes were similarly improved with these factors.In this reason, the four variables are in the same factor, and they are statistically correlated with overall correlation coefficients (R=0.4). The second and third factorsaccount for 18.0% and 15.5% of total variance, respectively. The second factor is comprised by as the types of layouts, the sizes of clusters while the third has total cluster area. Although the three variables are associated with apartment clusters, the difference between them is that the two variables in the second factor is associated with specifically the characteristic of buildings in clusters whilst total cluster area is more likely the sizes of site. However, the variables are statistically correlated withoverall correlation coefficients (R= 0.3). The last factor contains heating system method accounting for 11.4% of total variance.

Table 3 Pattern matrix in factor analysis

Category		**Factors**			
		Factor 1	**Factor 2**	**Factor 3**	**Factor 4**
Structure Matrix	Sizes of building units	0.663			
	Types of building access	0.584			
	Conditions of building envelopes	-0.584			
	Lengths of buildings	0.370			
	Types of building layouts		0.675		
	Sizes of clusters		-0.591		
	Total cluster area			-0.608	
	Heating methods				-0.342
Total Variance Explained (70.866 %)	% of Variance	25.900	18.082	15.445	11.440

4. Discussion

The results based on empirical data in this study demonstrated four distinctive aspects, compared to findings in other countries. Firstly, energy consumption for space heating in old apartment building is not extremely high by regarding the climate zone of Seoul in South Korea (Heating Degree Days (HDDs) 2800-3200) [52]. Compared to European countries, Denmark (HDDs 3000-3400) [53] showed 144.1 kWh/m^2 of heating consumption in apartment buildings [54]. United Kingdom (HDDs 2800-3100) and Germany (HDDs 2700-3200) [53],which have similar HDDs from South Korea, showed higher energy consumption in dwelling constructed in the 1980sand 1990s: 268.2 kWh/m^2 in detached houses in the UK and 159 kWh/m^2 in Germany; 102.8 kWh/m^2 in post 2002 mid-terrace housing in the UK, and 94kWh/m^2 in Germany in 1995 [55]. In our study, apartment buildings indicated 116.7 kWh/m^2/year in the 1980s and 94.4 kWh/m^2/year in the 1990s although the maximum consumption in the samples was 173.9 kWh/m^2/year in the 1980s and 158.8 kWh/m^2/year in the 1990s. The space heating consumption in old apartment buildings in South Korea is found the generally consumed in the climate zone. However, the consumption needs to be reduced like how European countries have been trying to achieve.

Secondly, the eight building features of apartment buildings in South Korea indicated the significantly higher percentage of the variation explained in energy use which is 70.9% (R^2=0.580 for space heating, R^2=0. 256 for electricity). 42% (R^2=0.379 for space heating) of the variation explained was reported in analyzing building characteristics with 15,000 houses in Netherlands [56]. Sonderegger [57] reported 54% of total variation were explained by physical building features with 205 houses in USA. Schuler et al [58] found relatively low R^2value, 0.144, with building characteristics in West-German households. Pachauri [59] found 61.4 % of total explained variance by including socio-economic characteristics in dwelling in India. Consequently, the effects of physical conditions in old apartment buildings in South Korea are much more significant than buildings in other countries. In other words, the energy consumption of these old apartment buildings in South Korea can be effectively reduced by improving their physical conditions.

Thirdly, the building features affecting energy consumption in old apartment buildings in South Korea are more prominent with higher SRC values although the lists of efficient building features are similar from buildings in other countries. Three building features have been identified in common as efficient factors reducing energy consumption: thermal conditions of building envelope (insulations and the glazing of windows); the volume of areas (heated areas, housing sizes and the number of rooms); construction years (vintages). In West-Germany, construction years and the sizes of housing were found as the relatively effective factors with SRC 0.225 and -0.221 [58]. In Netherlands, the sizes of heated area (useful living area), construction years and the insulations of building facades showed relatively higher SRC values, 0.321, -0.082 and 0-0.087 [56]. According to Balaras et al [54], the thermal insulation of the building envelopes and building system in European apartment buildings, such as Denmark, France, Poland and Switzerland, were the main factors influencing space heating. In our study, there is a dominant determinant affecting space heating consumption, the thermal conditions of building envelope with SRC -0.626 in space heating. This result clearly showed how the building refurbishment for old apartment buildings in South Korea to approach in order to reduce energy consumption efficiently.

Fourthly, the effects of building features related to building clusters are important factors. Unlike European countries, apartment buildings in South Korea were built as clusters including several buildings up to thirties. Therefore, the relations among individual buildings are also important factors that must be considered in energy consumption. In our study, the features related to building clusters explained 33.4% of total variations in energy use. Moreover, the undeniable contribution of these features was identified in the results of the multiple regression analysis for space heating and electricity although the SRC values were not decisively high.

5. Conclusions

This study aims to identify old apartment buildings in South Korea that need to be refurbished in terms of energy efficiency and suggests how the refurbishment should be done to reduce their energy consumption. It reveals that old apartment buildings constructed between the 1980s and 1990s are those which need to be urgently refurbished. This is because they showed excessive energy consumption for space heating and cooling, compared with the consumption of apartment buildings built in the 2000s. However, maximum 43.65 kWh/m^2/year in space heating and 5.70 kWh/m^2/year in cooling were reduced in those old apartment buildings in terms of construction years. This reduction was attributed to the transformations of building features in the twenty-year period. The eight features in old apartment buildings successfully account for 70.9% of total variance in the factor analysis. The largest proportion, 25.9%, was explained by the factor related to building form and fabric. Multiple regression analysis indicatedthe three most influential parameters, the thermal conditions of building envelopes with SRC 0.626, heating methods with SRC 0.301 and the sizes of building units with SRC 0.300.

Hence, this study found that the priority of refurbishment should be given to these three features. Amongst them, the most significant determinant should be the thermal conditions of building envelopes with SRC0.626.The other two features will be subsidiary conditions in refurbishment strategies. In this respect, the most urgent target for refurbishment should be the buildings constructed before 1980 (with central gas heating and large sizes of building units), and the latest target can be those constructed after 1988 (with individual gas heating and small sizes of building units).

Applications of this approach to cases in the other countries may bring about different building features in prioritising old high-rise apartment buildings for energy-efficient refurbishment. Thus, the refurbishment strategies for each country should take specific features and conditions of the apartment buildings into account in order to suggest efficient policies and regulations for refurbishment in each country.

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