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Energy efficiency: behavioural effects of occupants and the role of refurbishment for European office buildings

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ABSTRACT

Energy consumption in office buildings is determined partly by fixed building characteristics, but also by the behaviour of occupants. Within the European Union, office buildings have become subject to more stringent energy efficiency regulation for new construction or extensive refurbishment, with the aim to reduce energy consumption and carbon emissions. The study determines the influence of physical building characteristics and occupant behaviour on energy consumption, and in particular, the role of refurbishment in different intensities on energy consumption is investigated. The data-set of the Green Rating Alliance is tested to provide evidence, by applying multiple regression models for energy consumption. The results highlight considerably increased energy consumption of single-tenant compared to multi-tenant office buildings. Very large office buildings consume significantly more energy per square metre that their smaller peers. A building's modelled water consumption turns out to be a good indicator for the actual energy consumption, emphasising the importance of assessing further sustainability measures. Overall, buildings of higher age turn out to be of lower energy consumption, pointing to additional appliances and equipment in more recent buildings, to provide better services and more comfort. In general, extensive refurbishment measures account for significant higher energy use, since the overall quality of the buildings is improved with additional appliances and equipment. Testing for the interaction effect between building age and refurbishment, the results demonstrate significantly lower additional energy consumption for buildings with more recent extensive refurbishment, compared to those with refurbishment several years ago. However, the results need to be considered with precaution against deriving firm conclusions due to the small sample size and some drawbacks in the applied data-set.

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1. Introduction

In the European Union (EU), energy consumption by the building sector accounts for 40% of the total final energy use. Over the past decade, EU policy has required all member states

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to implement increased energy efficiency regulation for new construction. As a consequence, office buildings became subject to more stringent energy efficiency regulation for new construction or extensive refurbishment. The term "refurbishment" is used within this paper referring to other terms used in the real estate industry, such as retrofit, redevelopment or revitalisation, usually defining major construction works affecting the thermal, technical and further energy consuming characteristics within the existing building structure. In a theoretical framework, these measures are expected to save energy, provided the technical facilities and their operability, as well as the behaviour of occupants, do not undermine the potential positive effects, or additional services with further equipment and additional energy consumption is applied.

The energy consumption of office buildings is determined mainly by core operations, which refer to physical building characteristics (heating, cooling, lighting, ventilation and elevators) and consumption from applied technical equipment, depending on occupant behaviour in the buildings. That is, besides the fixed building characteristics such as location, size, building fabric and age, energy consumption in office buildings also depends substantially on the behaviour of their occupants.

While more stringent energy efficiency regulation is intended to reduce carbon emissions from the existing building stock, the question arises as to whether this can be achieved essentially by focusing on the physical building characteristics in the context of technological progress. The controversial debate about the existence of a latent "rebound effect", implying a negative behavioural response of occupants when confronted with a more energy-efficient building quality, pertains to the role of the occupants with their behaviour towards energy consumption. Since the rebound effect is attributed to occupant behaviour with additional use of the same services due to increased efficiency, it is rather difficult to identify this effect. For the existing building stock refurbishments are in many cases not realised in order to only increase the energy efficiency, but to increase or to provide further services, such as technical equipment that might be installed, in order to satisfy increased user requirements.

In this context, the study tries to investigate the relationship between actual energy consumption, physical building characteristics and behavioural attributes of occupants, subject to attempts to control for outdoor weather conditions and spatial heterogeneity.

The results provide evidence that refurbishments are associated with higher consumption in the tested office building portfolio, due to additional appliances and equipment. Testing a small sub-sample with refurbishment dedicated to energy efficiency and thermal building characteristics, no indication of a potential rebound or significant energy savings from these refurbishment measures are found. Although newer buildings are subject to more stringent energy efficiency regulation, our study reveals that newer office buildings do not necessarily consume less energy. This is found to be true only for most recently refurbished observations in the tested portfolio.

The remainder of this paper is as organised as follows. Section 2 provides the background to our study and considers some related research. In Section 3, we explain the characteristics of the used data-set and discuss the econometric methodology. Section 4 presents the results of the regression model, while Section 5 highlights some major conclusions and recommendations for further research.

2. Background and empirical framework

2.1. Background

Due to a significant greenhouse gas externality associated with energy consumption, the building sector has considerable potential in reducing global carbon emissions from the existing building stock. In the absence of any carbon pricing, an increment in energy consumption of commercial buildings has a negative impact on climate change.

Within the EU, the European Performance of Buildings Directive (EPBD) obliged all member states to implement increased energy efficiency regulation for new construction. In the course of the EPBD, Energy Performance Certificates (EPC) were introduced in 2002 and became mandatory by the year 2008. The regulation was implemented, based on a theoretical framework requiring the application of stricter building codes for new construction, and for existing structures undergoing complete or major refurbishment. This applies also for office buildings. The targeted reduction in energy consumption is based mostly on the potential offered by the physical building. However, little attention has been paid to the success factors of refurbishment in the context of energy savings.

Over the past decade, research insights into energy consumption and potential carbon emission savings in the commercial building sector of Europe have remained limited. This corresponds to experiences in the US, where Kahn, Kok, and Quigley (2014) found that research on commercial building energy consumption is still limited and most of it has been provided by engineers rather than economists. Research on the engineering dimension of energy efficiency of office buildings exhibits an extensive body of literature from the past decades, for example, in the related research projects of the Association of European Renewable Energy Research Centres (2016), Fraunhofer ISE (2015), Fraunhofer IBP (2009) or Post-occupancy Review of Buildings and their Engineering (1997). However, a study by Guerra Santin, Itard, and Visscher (2009) argues that empirical results, especially on occupants' influence in the commercial or office building sector of Europe, remain unsatisfactory.

The energy consumption of office buildings is determined by the combination and interaction of multiple factors. The physical building characteristics include location, building envelope (referring to building size, fabric and age) and technical equipment, such as heating, cooling, ventilation, lighting, elevators and IT equipment. The most relevant factors influencing energy consumption for heating and cooling are the thermal characteristics and related technical systems, the building type with regard to the surface to cubic volume ratio, occupant behaviour and the outdoor weather conditions. Since the largest energy consumption in office buildings is determined by heating, ventilation and air-conditions (HVAC), a significant intensification in the energy consumption, due to the expansion of HVAC systems in new buildings, was observed over the past decades. With the further expansion of new office space build, a growing trend of energy consumption is expected for the future (see Lombard et al., 2008).

Based on UK office buildings, Jenkins, Liu, and Peacock (2008) investigate that the energy consumption is primarily dominated by heating energy consumption. Their study assumes a more efficient office equipment and lighting in the future with lower levels of surplus heat production, but an increasing demand in heating energy for substitution. This will be mitigated to some extent by the temperature increase coming along with climate change.

Due to economies of scale in heating and cooling of office buildings, very large structures might behave differently to their smaller peers. Kahn et al. (2014) prove for significant higher energy consumption with increase in building size. They assume that heating and cooling of large buildings requires additional equipment and energy loads to bridge large vertical distances in office towers, offsetting otherwise beneficial economies of scale.

The difference between actual energy consumption and engineering-predicted intrinsic energy consumption depends on the final construction with its installed technical systems and also on the utilisation of such systems, for example, in response to the indoor temperature set by occupants. However, the predicted intrinsic energy consumption is estimated on the basis of several determinants included in a modelled code baseline building, to indicate potential cost savings. Thus, the intrinsic assessment does not necessarily predict the future actual consumption since the prediction is applied as an engineering benchmark for relative energy performance, to allow for comparisons between buildings or implement stricter energy efficiency regulation in building codes (see New Buildings Institute, 2008). Torcellini et al. (2004) suggest that the deviation between actual consumption and predicted savings from intrinsic assessment is caused by higher than expected loads form occupants' behaviour and systems which do not perform together as designed.

The comparison between intrinsic predictions and actual consumption is even more difficult, since the intrinsic energy assessment might not predict all issues and variation in operational factors of energy consumption, such as "plug loads". These plug loads represent not the "regulated loads" for basic building comfort, such as HVAC and lighting, but the "unregulated" or process-related energy consumption, which is primarily driven by building equipment (elevators, computers, video-screens) and activity of building occupants. In the modelling of intrinsic energy for certification of Leadership in Energy and Environmental Design (LEED), a default of 25% of total "baseline energy" was included. More importantly, previously completed LEED projects were not able to attempt any energy savings in the unregulated plug load category with a widely varying percentage of plug loads (see New Buildings Institute, 2008) and Scofield (2009) argues that evidence for lower energy from LEED-certification of office buildings has not been provided in a previous study.

Further key factors account for differences between the predicted intrinsic and actual energy consumption, such as differing occupancy hours and intensities, experimental – especially energy saving – technology does not perform as expected or a lack of knowledge, how to run the building most energy efficiently by facility managers and/or occupants (see Newsham, Mancini, & Birt, 2009). To sum it up, it remains reasonable that actual energy consumption is affected by multiple factors, whereas intrinsic energy assessment has limits in the applied determinants to predict actual energy consumption.

2.2. Behavioural effect of office occupants

Among the research of occupant behaviour and related effects on energy consumption exists only a small body of literature and the most of it is dedicated to modelling tools to simulate the influence of occupant behaviour and how occupants interact with building equipment and plug loads.

Besides the fixed influence of applied technical equipment in buildings, occupant behaviour concerning HVAC is highly dynamic and depends not only on outdoor climatic conditions, but also on the type of HVAC equipment and occupant experiences with them. Individual heating or cooling systems, instead of a centralised control system, allow for a varying usage between different (parts in) office buildings.

Technical equipment and plug loads in office buildings are prone to be significantly influenced by the behaviour of occupants in different appliances and intensities. Another influence factor is whether the building is rented out to a single tenant or to several. The allocated office space per occupant implies an important effect as well as the overall occupancy rate, indicating business cycle effects. Kahn et al. (2014) found that a 1% higher occupancy rate increases electricity consumption by 2.6% in office buildings. Depending on the specific industry and the related technical equipment, such as IT, occupants' activities and behavioural patterns result in a different intensity of energy consumption.

Moreover, the individual awareness and behavioural attitude of occupants towards energy consumption and potential energy (cost) savings is assumed, to play an overall important role in the dynamic dimension of energy consumption (see Bloom, Genakos, Martin, & Sadun, 2011). Experience from the US demonstrates that the presence of a building engineer significantly lowers consumption, compared to buildings without an engineer (see Kahn et al., 2014). For Australian office properties, Gabe (2014) found that a frequent site energy consumption auditing is a potential strategy to reduce energy consumption and mitigate greenhouse gas emissions. As part of a so-called green management strategy, the repetitive auditing experiences to be a successful approach for motivating owners to invest in energy efficiency technologies. For a European portfolio of corporate real estate assets from the wholesale and hypermarket sector, Surmann, Brunauer, and Bienert (2016) found evidence that a centralised corporate energy management contributes to recurring energy consumption reductions and thus energy measures for corporate assets provide leverage towards a more efficient corporate environmental performance.

Research work of Kavulya and Becerik-Gerber (2012) analysed occupant behaviour in an office environment and interaction of occupants with energy consuming equipment in visual observations with tracking of daily activities on commonly used office appliances. The results estimate an energy saving potential of up to 38%, if occupants switch of appliances not in use, due to higher awareness between consumption and occupant usage data. The study argues that energy awareness plays a key role to modify the behaviour of occupants towards reduced energy consumption.

2.3. Refurbishment and rebound effect

The term rebound effect refers to a situation in which the actual energy savings from an innovation are lower than those expected from improved efficiency, due to more extensive – rebound – consumption by users, either in the form of more hours of use or a higher quality of energy service (see Herring & Roy, 2007). Experience from the automobile industry shows that a reduction in fuel consumption was achieved, while the safety and comfort attributes of cars had been enhanced remarkably (see Knittel, 2012). With regard to cars, the term rebound effect means that a more fuel efficient car will lead to more kilometres travelled (see Gillingham, Kotchen, Rapson, & Wagner, 2013).

Similar observations were expected from the commercial building sector in the past, offsetting increased energy efficiency to some extent. The effect has been investigated and described in an early study for commercial buildings by Greening, Greene, and Difiglio (2000). They conclude that the range of estimates for the size of the rebound effect is very low to moderate. Based on a review of studies for gasoline and electricity consumption, Gillingham et al. (2013), Gillingham, Rapson, and Wagner (2016) argue that the behavioural response of users offsets between 5% and up to 30% of intended energy savings. They conclude that the rebound effect is rather small and therefore no excuse for inaction in the economy.

For commercial real estate, it is difficult to distinguish between the rebound effect and the "principle of additionality", in which higher energy efficiency is realised with the provision of increased or additional services and comfort, provided with less energy consumption than they would otherwise have. This principle of additionality usually comes along in the course of refurbishments or in the development of new buildings, when additional or new technical equipment is installed, in order to satisfy increased user requirements. The principle is observed for commercial buildings of lower age or recent refurbishment with higher energy consumption compared to their older peers. Recent research results from the US reveal that both younger office buildings and those of higher quality are in fact responsible for higher electricity consumption (see Kahn et al., 2014).

Kahn et al. (2014) state that energy consumption and building quality are complements – not substitutes. Even when technological progress reduces the theoretical energy demand from HVAC and lighting, the increase in quality attributes, such as a more attractive lobby and office space, more elevators and individual adaption of comfort temperature by occupants, may actually increase energy consumption. Hence, the replacement of older structures by new buildings or at least extensive refurbishment is likely to increase the energy consumption of the durable building stock.

Results for a refurbishment variable included in the work of Kahn et al. (2014) have documented that refurbished buildings feature a higher energy consumption of 19%, compared to similar-sized buildings without refurbishment. Besides a potential, but expected to be small, rebound effect when improved building quality provides better HVAC and lighting systems which may induce greater energy use, the additional services employed in the course of refurbishment account for the increase in consumption for the most part.

Furthermore, refurbishment is not associated only with energy-saving measures of the technical equipment in a building, but often involves a replacement or enlargement of the technical infrastructure, especially lighting, HVAC and IT, which might be associated with additional energy consumption. A survey by Kok, Miller, and Morris (2012) found only 14% of refurbishments with improvements solely dedicated to sustainability, whereas refurbishment was carried out to improve the overall quality of the buildings. In the context of the necessity to update otherwise obsolete buildings (see Baum & McElhinney, 1997; Baum & Turner, 2004) also energy efficiency improvements were considered for the technical equipment replaced, but moreover the building quality standard as a whole is enhanced. This corresponds to the observation of Chegut, Eichholtz, and Kok (2015) that although sustainable construction is gaining market share, new construction and building refurbishments are still mostly conventional.

With regard to the discussed empirical findings, our study is intended to investigate the relationship between actual energy consumption, physical building characteristics and occupant attributes. With increasing building size up to a certain point, we expect lower energy consumption by trend for office buildings, due to economies of scale in heating and cooling. For very large office buildings (office towers), we expect higher energy consumption while economies of scale are offset by higher energy loads to bridge large vertical distances in office towers. Since energy efficiency regulation within the EU has become more rigorous for new construction or extensive refurbishment, we test whether higher energy efficiency is achieved for younger office buildings. The effect of refurbishment is of special interest in this study. On the one hand, major refurbishment is expected to consider higher energy efficiency standards, thus allowing for improvements of the thermo-physical quality of the buildings and potential energy savings. On the other hand, research results prove for additional energy consumption in the course of refurbishment, due to the provision of additional services and new technical equipment employed.

3. Data-set

In order to answer our research questions, we use the data-set of the Green Rating Alliance (GRA), which provides physical office building characteristics and occupant attributes in detail at the building level. The data-set includes two main sources of energy consumption; first, the actual metered energy consumption and second, the intrinsic energy consumption as result of the Green Rating auditing. However, the data-set of GRA contains actual energy consumption and intrinsic assessment metered only once at a certain point of time in the years from 2008 to 2012 for issuing the Green Rating audit. Therefore, the data-set is not covering a panel of observations over time, which is a drawback for the analysis.

The intrinsic energy measure of GRA is based on an individual assessment of the physical building characteristics, with an estimation of the thermal qualities of different construction and fit-out elements, inherent in each single building. The calculation of intrinsic consumption is modelled under standard – optimised – conditions of the building use with assumptions of occupant behaviour concerning schedules and temperature set points. While this fixed standard model is equal for each building in the assessment, the intrinsic energy should be seen as a measure of potential energy consumption, without taking into account the impact of occupant behaviour differing among buildings. Since GRA's intrinsic benchmark is modelling under optimised conditions of the building use and does not account for plug loads from the occupants, we expect much lower intrinsic figures than actual metered consumption.

The data-set also contains actual and intrinsic measures concerning the buildings' annual water consumption. Parallel as for energy consumption, actual measures are derived from metered consumption and intrinsic measures from modelling based on standard assumptions. In regard to the relationship between energy and water consumption, office buildings designed with higher energy efficiency standards or stricter building codes might also have higher standards in water efficiency for lower actual consumption. Investors committed for investment in sustainable real estate consider metered water consumption besides energy consumption. Among other institutional investors, Bouwfonds Investment Management (2013) states commitment, to contribute to a reduction in water intensity of the real estate they manage. We hypothesise a correlation between energy and water consumption, due to a more efficient building design and higher efficiency requirements from increased regulation, as well as from the social responsible investment strategies of institutional investors (see Cajias & Bienert, 2011; Cajias, Fuerst, McAllister, & Nanda, 2011; Kerscher & Schaefers, 2015).

Therefore, we use intrinsic water consumption measures from GRA to estimate actual energy consumption, because the intrinsic consumption is based directly on building characteristics and not influenced by occupant behaviour, thereby avoiding potential bias.

To control for the attributes of outdoor weather conditions and temperature, the heating degree days (HDD) and cooling degree days (CDD) of the respective auditing year were used. The heating and CDD were calculated on a basis of 65 °F (18.3 °C), obtained from the

Table 1. Descriptive statistics of applied metric attributes.

Descriptive statistics	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Actual energy consumption in kWh/sqm/a	73.5	175.7	235.2	254.8	317.2	696.5
Intrinsic energy consumption in kWh/sqm/a	46.2	104.3	129.0	138.2	162.1	368.7
No. of heating degree days in year of Green Rating Audit	1,317	2,429	2,652	2,757	3,009	3,941
No. of cooling degree days in year of Green Rating Audit	0	123	163	179	183	734
Intrinsic water consumption in cbm/sqm/a	.094	.266	.333	.352	.432	1.060
Actual energy consumption heating in kWh/sqm/a	6.1	49.1	75.5	83.5	101.6	365.7
Actual energy consumption cooling in kWh/sqm/a	.0	12.1	24.5	34.6	41.6	205.0
Actual energy consumption lighting in kWh/sqm/a	1.0	17.5	24.2	27.5	35.3	115.6
Actual energy consumption IT in kWh/sqm/a	1.1	8.3	12.8	15.9	20.7	77.1
Actual energy consumption ventilation in kWh/sqm/a	.0	8.4	14.6	19.8	25.1	144.7
Actual energy consumption elevator in kWh/sqm/a	.0	2.3	3.9	5.3	6.3	61.1
Actual energy consumption other in kWh/sqm/a	.0	24.5	50.2	68.7	93.1	503.0
Building age (economic)	.0	3.0	9.0	11.7	19.0	50.0
Building area in sqm	1,340	5,596	10,040	13,960	17,979	108,070
Building area in sqm per occupant	5.2	17.0	21.8	26.2	30.7	147.1
Ceiling height in metres	2.3	2.6	2.7	2.8	2.9	4.3

database of Weather underground (2015). While the auditing process of GRA with actual measurement is assessed over a time period of at least 8 months (normally 12), we applied the HDD and CDD with respect to the year in which more than 4 months of the auditing period were carried out. Our total sample comprises 288 observations, combining the GRA sample with the HDD and CDD in a period from 2008 to 2012.

In the context of our theoretical considerations on the role of physical building characteristics, building age and size, as well as ceiling height and heating production type and the intensity of refurbishment are of a major research interest. To investigate the influence of occupants, we focus on the attributes of building area per office occupant, and differentiate between single and multi-tenant-occupied buildings. We expect a significant difference between buildings rented on single-tenant basis, compared to those on a multi-tenant basis. Our supposition is that multi-tenant buildings face more decisions regarding the heating, cooling and lighting of the office space in question, thus resulting to higher consumption.

The sub-categories of the total actual energy consumption applicable from the data-set, enable distinguishing between each energy-consuming sub-category. Table 1 includes some descriptive statistics of the applied metric response and explanatory variables:

Comparing the actual with the intrinsic energy consumption, a large gap is obvious at first glance. Since the intrinsic consumption is a measure in relation to the physical building characteristics and a standard factor for occupant influence, modelling under optimised conditions of the building use, the large gap meets our expectations.

When looking at the share of sub-categories to the total energy consumption in Figure 1, it is evident that heating, cooling and ventilation account for more than 55% of the total actual consumption. The sub-category "other" accounts for a share of 24% of the total consumption, including consumption e.g. from (underground) car park, canteen and outside lighting. However, the share of these categories summarised under "other" was not applicable from the GRA data-set, what points to a limitation when explaining actual energy consumption.

The economic building age was derived from the (historical) construction year under consideration of complete or extensive (full/major/general) refurbishment in the past and yields an average of 12 years. This result demonstrates the importance of the information from the data-set regarding refurbishment.

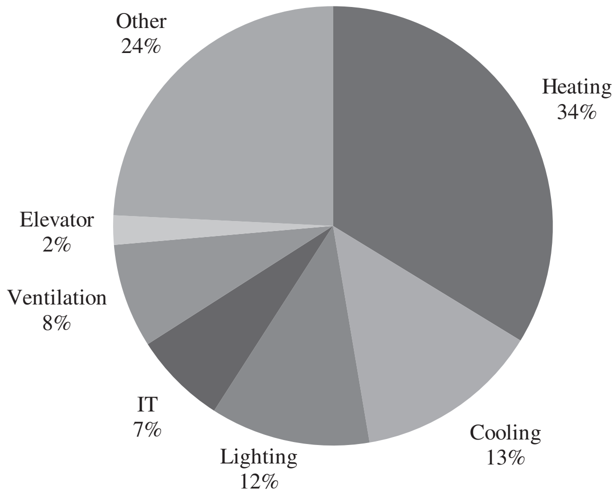

Figure 1. Sub-categories' share of total actual energy consumption.

Table 2. Actual energy consumption and refurbishment sub-samples.

Refurbishment and Actual energy consumption [kWh/sqm/a]	Min.	1st Qu.	Median	Mean	3rd Qu.	Max
Total Sample ($n = 288$)	73.4	175.7	235.2	254.8	317.2	696.5
Refurbishment = no ($n = 115$)	86.3	169.6	223.2	240.4	296.1	696.5
Refurbishment = yes ($n = 173$)	73.4	181.6	243.1	264.4	328.5	685.5
Refurbishment <= 5 years ($n = 109$)	73.5	175.9	238.4	262.4	328.5	685.5
Refurbishment > 5 years & <= 15 years ($n = 50$)	111.6	188.7	240.4	256.1	294.3	615.2
Refurbishment > 15 years ($n = 14$)	134.4	190.2	251.2	310.2	444.8	503.3
Full, major, general refurbishment ($n = 45$)	104.0	223.2	269.6	276.1	328.5	478.6
Façade, windows, roof, insulation ($n = 23$)	91.8	163.8	220.7	243.9	299.4	538.8
HVAC ($n = 42$)	108.6	185.8	239.3	261.6	315.2	609.7
Other refurbishments ($n = 62$)	104.0	179.3	206.4	263.7	331.5	685.5

At first glance, we find no verification that refurbishment has a positive impact on energy efficiency in such a way, as to decrease actual energy consumption of the tested office buildings (see Table 2). Mean and median values of actual consumption of refurbished buildings are slightly above the levels of non-refurbished buildings. In comparison to the total sample, the observations attributed to having undergone a refurbishment in the past ($n = 173$) suggest a 3.6% higher energy consumption on average which points to the principle of additionality. The sub-sample for buildings refurbished more than 15 years ago indicates significantly higher actual energy consumption, especially concerning the mean and 75%-percentile, when compared with more recently refurbished buildings (see Figure 2). It can be concluded that refurbishments in the last 15 years came with a stronger focus on energy efficiency. Actually, the share of refurbishments with a focus on façade, windows, roof, insulation or HVAC is much higher for recently refurbished buildings (≤15 years: 23.2%) than for other buildings (>15 years: 4.5%).

A small sub-sample of 23 observations attributed with energy efficiency refurbishment concerning façade/windows/roof/insulation, which is expected to reduce energy consumption, shows the lowest actual energy consumption, as regards first, second and third quartile and the mean value as well as compared to the total sample. The result indicates a conservation potential of around 4.5% on average and approximately 6.6% for the median value, due

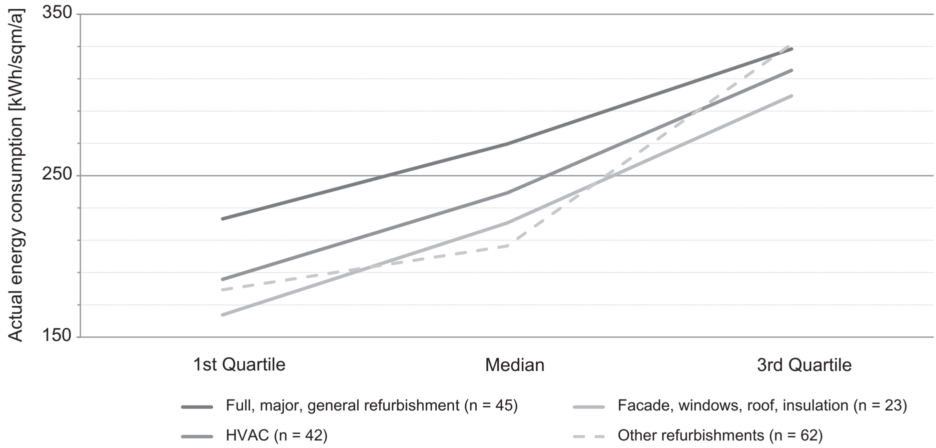

Figure 2. Actual energy consumption and type of refurbishment.

to the refurbishment of thermal building characteristics. In contrast to the slight decrease in actual consumption in relation to the refurbishment of only thermal building characteristics, we found the actual consumption of 45 observations attributed with full/major/general refurbishment with a 13.2% higher consumption on average. This sub-sample even exceeds the average per square metre consumption of the total sample by 7.7%. Buildings with extensive (full/major/general) refurbishment also show higher energy consumption than buildings with refurbishments concerning HVAC-equipment. We assume that for extensive refurbishments, the potential positive effects of renewing thermal building characteristics or HVAC equipment might be counteracted by other changes in the building resulting into higher energy consumption. At first glance, the result proves for the principle of additionality as effect of extensive refurbishment measures.

To verify these preliminary results while accounting for other effects, we include refurbishment details as explanatory variables in our regression analysis.

The correlation matrix for metric attributes in Table 3 shows an orthogonal linear relationship between the response and explanatory variables. Corresponding to our expectations, a positive bivariate relationship between intrinsic and actual energy consumption is observable. HDD (CDD) demonstrate a positive (negative) bidirectional relationship with actual and intrinsic consumption. Somewhat surprisingly, the energy consumption decreases with an increase in CDD. Anyway, this result is only based on correlation and needs to be further examined by a regression analysis, taking into account all other possible explanatory factors. The intrinsic water consumption shows a positive bivariate correlation with actual energy consumption.

The negative relationship between building age and actual consumption is at first glance interesting, when observations of older buildings turn out to be less energy consuming. The building size is expected to be inversely related to energy consumption (per square metre), due to economies of scale in larger buildings. However, this does not appear to be true for actual consumption. The building area allocated per occupant has been calculated from the building area and the total number of occupants, both obtained from GRA data. The

Table 3. Correlation matrix of metric attributes.

Correlation matrix		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
LN (actual energy consumption in kWh/sqm/a)	(1)	1								
LN (intrinsic energy consumption in kWh/sqm/a)	(2)	.544	1							
No. of heating degree days in year of Green Rating audit (HDD)	(3)	.084	.225	1						
No. of cooling degree days in year of Green Rating audit (CDD)	(4)	−.200	−.254	−.556	1					
Intrinsic water consumption in cbm/sqm/a	(5)	.233	.306	.004	−.072	1				
Building age (economic)	(6)	−.056	.020	−.089	.089	.057	1			
LN (building area in sqm)	(7)	.126	−.043	.073	−.044	−.118	−.054	1		
LN (building area in sqm per occupant)	(8)	−.143	−.019	.039	−.061	.127	−.029	.023	1	
Ceiling height in metres	(9)	.076	.125	.112	−.047	−.012	−.174	.033	.082	1

negative bivariate correlation between the building area allocated per occupant might be the result of missing information about vacancy as more space per occupant can mean: (a) a higher vacancy rate and (b) larger offices or common spaces. The two possible explanations cannot be distinguished from one another with the given GRA data.

4. Econometric approach

The energy consumption of office buildings can be explained with a function of the consumption from core operations (HVAC) in relation to the physical building and additional consumption from appliances with installed equipment and plug loads both used by the occupants. In order to determine these effects on the response variable, we have to control for all other factors affecting energy consumption. To address this issue within a multiple regression model, the dependent variable is decomposed into the implicit contribution of the available building characteristics and occupant attributes, while controlling for the outdoor weather conditions and effects from spatial heterogeneity.

The general regression model via ordinary least squares is described in Equation 1, with Y as the response variable, X as a vector containing the explanatory variables, β as unknown parameters and ε as error term.

$$Y_i = \alpha_i + \beta X_i + \varepsilon_i \quad (1)$$

In our approach, the regression model is used for actual energy consumption metered in kWh/sqm/a. The vector containing the explanatory variables includes the physical building and occupant attributes, as well as the HDD and CDD controlling for the local outdoor climate weather conditions and effects from spatial heterogeneity.

For the regression of actual energy consumption, the response variable is transformed logarithmically (see Malpezzi, 2003). This procedure allows for the interpretation of the estimated effects as elasticities if both sides are logarithmically transformed, or semi-elasticities if the explanatory variable enters the equation in absolute values. Furthermore, strictly positive metric variables are transformed logarithmically when estimating a log-linear function in Equation (2):

$$[\text{LN}(\text{actual E cons.})_i] = \alpha + \beta_1\,\text{HDD}_i + \beta_2\,\text{CDD}_i + \beta_3 \begin{bmatrix} \text{building age class}_i \\ \text{building area class}_i \\ \text{LN}(\text{area/occupant})_i \\ \text{intrinsic water cons.}_i \end{bmatrix} + \beta_4\,\text{single tenant binary}_i + \beta_5\,\text{electric heating binary}_i + \beta_6\,\text{refurb. binary}_i + [\text{country}'_i\kappa] + \varepsilon_i \qquad (2)$$

where (actual E cons.)$_i$: represents the actual energy consumption of building *i*, (area/occupant)$_i$: represents the allocated area per occupant, intrinsic water cons.$_i$ represents the intrinsic water consumption; single tenant binary$_i$: represents single or multi-tenant use, electric heating binary$_i$: represents electric heat production, refurb. binary$_i$: represents full/major/general refurbishment, country$_i$: represents location (country) and ε_i: represents an iid error term.

The explanatory variables *HDD* and *CDD* control for the local outdoor weather conditions in the relevant year of the Green Rating audit of the observations (building *i*).

The *building age* is included to test for differences between newer and older buildings. This was considered under economic considerations, reflecting total or major refurbishment with improved physical characteristics of the buildings, thus expressing a proxy for depreciation. This economic building age was classified in three groups (0–10, 11–20, >20). The *building area* is introduced to the regression model in terms of dummy variables representing the building's belonging to one of five quantiles. The building area allocated per occupant in square metres is entered logarithmically into the model with *LN (area/occupant)*.

The Green Rating audit data also contain information about the buildings' sustainability characteristics besides energy consumption, e.g. *Water consumption*, waste and carbon emissions, metrically scaled in units per square metre and year. Carbon emissions are highly correlated with energy consumption and therefore omitted for the regression. If one of the non-energetic sustainability ratings has significant explanatory power for a building's energy consumption, sustainability characteristics might become more relevant for investors, because they can help to identify energy-efficient buildings. In this regard, we use the intrinsic values for water consumption, to assess the influence on energy consumption. The actual values are not considered, due to expected bias by the specific occupant behaviour. Furthermore, a dummy variable for *electric heating* enters the equation to control for energy consumption related to different technical systems in the buildings.

With regard to the occupant attributes, the *single tenant binary* distinguishes between a single or multi-tenant use of the building premises.

In order to provide evidence for the effect of refurbishment on energy consumption, another dummy variable is introduced, to estimate the effect of a *full, major or general refurbishment*. Since we have few observations in the data-set with refurbishment dedicated to energy efficiency and thermal building characteristics, we use the attributes *façade/windows/roof/insulation* instead of the binary for extensive refurbishment in a second specification of the regression model. For the small sub-sample of 23 observations, a positive effect in the regression of energy consumption might point to a potential rebound effect with no energy savings resulting from the refurbishment. A negative coefficient could indicate energy savings due to the refurbishment measures.

A matrix of *country* dummies was considered to control for spatial heterogeneity, e.g. energy efficiency regulation with regard to local building codes and different pricing of energy between the 14 European countries. Due to the introduced HDD and CDD with reference to the location-based outdoor weather conditions, we do not append additional location dummies, to control for spatial heterogeneity, so as to avoid any selection bias.

Since the assumption of linearity in the effects of regression models often seems to be too restrictive in a real estate context (see e.g. Brunauer, Feilmayr, & Wagner, 2012; Brunauer, Lang, Wechselberger, & Bienert, 2010; Mason & Quigley, 1996; Pace, 1998; Parmeter, Henderson, & Kumbhakar, 2007), it seems appropriate to use more flexible non- and semi-parametric regression models. For example, the effect of building age is known to be nonlinear (for instance, Fahrmeir & Tutz, 2001). We consider generalised additive models (GAM), as described in Wood (2006), to discover nonlinear effects for the continuous covariates. Applying GAM provides the advantage, to express the nonlinear effects in the relationship between response and explanatory variables in visualised nonlinear regression splines.

To control for nonlinearity in the effects of our regression model, we replace the linear effects $\beta_j x_{ij}$ of the continuous covariates with possibly nonlinear functions $f_j\left(x_{ij}\right)$ in Equation (3):

$$
\begin{aligned}
\left[\text{LN(actual E cons.)}_i\right] = \alpha + \beta_1 \text{HDD}_i + f_1(\text{CDD}_i) + f_2(\text{building age}_i) \\
+ f_3(\text{building area}_i) + f_4(\text{LN}\left(\text{area/occupant}\right)_i) + f_5(\text{intrinsic water cons.}_i) \\
+ f_6(\text{refurb. binary}_i * \text{building age}_i) + \beta_2 \text{ single tenant binary}_i \\
+ \beta_3 \text{ electric heating binary} \\
+ \beta_4 \text{ refurb. binary}_i + \left[\text{country}_i' \kappa\right] + \varepsilon_i
\end{aligned}
\tag{3}
$$

The linear effect for HDD is not replaced with a nonlinear function for technical reasons. It is common practice in regression modelling to introduce combined variables for important effects to estimate the interaction between the both variables. To further investigate the effect of refurbishment on energy consumption, the *building age* of those observations attributed *with refurbishment* from the past is introduced with a nonlinear function. Besides the separate main effect of full/major/general refurbishment, the interaction effect of building age for observations with a refurbishment in the past is included in the regression. This procedure allows to estimate and display the effect, to be interpreted as the additional energy consumption of observations undergone a refurbishment by trend.

5. Research results

5.1. Results for actual energy consumption from Equation (2)

The results of our log-linear regression model for actual energy consumption are summarised in Table 4. The results for the regression with extensive refurbishment attributes full/major/general as explanatory variable are shown in column 1. The model specification in column 2 adds the observations for refurbishment dedicated to energy efficiency and thermal characteristics with façade/windows/roof/insulation instead of the extensive regression observations. In regard to the data-set employed, the adjusted R^2-value of both models appears to be low. Therefore, the results are to be considered with precaution.

Table 4. Regression results of log-linear model on actual energy consumption as response variable from Equation (2).

Response variable: LN (actual energy consumption in kWh/sqm/a)		
Explanatory variables coefficient (*t*-values)	1	2
Intercept	5.700 (17.069)***	5.702 (17.141)***
Number of HDD in audit year/100	−.011 (−1.534)	−.008 (−1.202)
Number of CDD in audit year/100	−.055 (−1.674)	−.060 (−1.761)
Economic building age 11–20 years	.063 (1.273)	.053 (1.077)
Economic building age > 20 years	−.101 (−1.654)	−.128 (−2.141)*
Building area second quantile	.010 (.189)	.008 (.143)
Building area third quantile	−.015 (−.206)	−.030 (−.435)
Building area fourth quantile	.060 (.887)	.035 (.530)
Building area fifth quantile	.154 (2.365)*	.141 (2.165)*
Single tenant	.142 (2.909)**	.147 (2.959)**
LN (sqm building area/occupant)	−.127 (−2.409)*	−.122 (−2.307)*
Intrinsic water consumption (cbm/sqm/a)	.482 (2.882)**	.483 (2.789)**
Electric heating	−.192 (−3.665)***	−.200 (−3.791)***
Full/major/general refurbishment	.139 (2.344)*	
Façade/windows/roof/insulation refurbishment		−.014 (−.228)
Countries (*n*)	14	14
R^2	32.47	31.78
Adjusted R^2	25.64	24.88

Significance: ***1%, **5%, *10%.

For the tested portfolio, the influence of outdoor weather conditions on actual energy consumptions seems to be very low, while the coefficients of HDD and CDD are not of any significance.

Turning to further explanatory variables measuring the influence of physical building characteristics, we found the classified economic building age to have virtually no explanatory power and lacking greater significance. Only in the model specification including refurbishment with regard to energy efficiency and thermal characteristics in column (2) displays a low significant effect of those buildings with the highest economic building age (21–50 years). The actual energy consumption per square metre is 12% lower than in the group of youngest buildings (0–10 years). For the interpretation of the coefficients for binary variables in a semi-logarithmic regression, the percentage effect is calculated as anti-logarithm of the estimated coefficients with $((\exp(\beta_x) - 1) \times 100)$ with regard to the omitted reference variable (see Halvorsen & Palmquist, 1980; see Hardy, 1993).

While the economic building age was derived under consideration of the (historic) construction year and the applicable refurbishment year, as well as the intensity of refurbishment, we also run the regression model with the (historic) construction year and found no significant effect, again. This is a remarkable finding, due to the overall expectation of an impact from the increased energy efficiency regulation in EU-member states over the past decade. Subject to potential limitations in the data-set with only 288 observations, this result would suggest that stricter building codes and construction standards seem to emerge without exerting a significant impact on the conservation of actual energy consumption.

Regarding the building area, the expectation of less consumption in heating and cooling does not appear for the tested portfolio. On the contrary, the quantile with the largest buildings even shows a significant increase in energy consumption between 15 and 16%, compared to the quantile with the smallest buildings. The data-set might include some high-rise office towers, contained in the quantile with the largest buildings and attributed with much higher consumption per square metre.

The building area allocated per office occupant has a significant effect on energy consumption, indicating a decreased consumption for an increasing area per occupant. At first, this points to the relationship of higher vacancy in office buildings being associated with lower per square metre consumption. Furthermore, the evidence suggests that occupants with more space allocated, but constant equipment and plug loads (*ceteris paribus*) consume less per square metre. In other words: More occupants on the same office area will increase energy use per square metre, which is in line with the literature review in Section 2. Further explanatory power is expected from the regression with nonlinear effects and illustration in regression splines following Equation (3).

The single tenant binary provides significant results. The coefficients demonstrate that single-tenant office buildings have significantly higher energy consumption than multi-tenant-occupied ones. With regard to the omitted multi-tenant reference category, the dummy variable explains a higher actual consumption of 15% (both column 1 and 2). Our expectation was that multi-tenant buildings would have higher energy consumption, because of somewhat contradictory decisions when running the building. A conclusion might be that a single tenant intends more to heat, cool, ventilate and light a building centrally as a whole, not differentiating (even when possible) between single building parts or floors, e.g. cooling of upper floors only. According to this interpretation, within a multi-tenant building, each tenant might behave in a more decentralised manner specifically for the smaller occupied part of the building. The more, a large single tenant might potentially consider energy prices with minor importance when referred to business turnover and allocated headcount cost.

The variable for intrinsic water consumption per square metre and year shows significance as explanatory variable for energy consumption. An increase in water consumption of 100 litres per square metre and year comes along with an approx. 6% increase in actual energy consumption. A water-efficient building infrastructure seems to be an indicator for a better energy performance by trend.

The electric production for heating has a highly significant negative effect on energy consumption. Under control of all other factors, energy consumption per square metre is more than 20% lower for electric heating in comparison to district heating network or boilers, thus indicating higher energy efficiency.

Turning to the refurbishment details introduced in our econometric approach, we obtain a significant coefficient for the aggregated dummy, containing full/major/general refurbishment, with reference to omitted observations without any refurbishment. The result reveals a positive impact on actual energy consumption for observations attributed with an extensive refurbishment. Compared to buildings without refurbishment, extensive refurbishment is attributed to have a higher energy consumption of 15%. The result proves for the principle of additionality being associated with refurbishment for the tested portfolio. This suggests that refurbishment was carried out to provide increased or additional services and comfort from appliances with additional or new equipment to satisfy user requirements.

Turning to the model specification with the small sub-sample for refurbishment dedicated to energy efficiency and thermal building characteristics, we find no significant impact of refurbishment associated with thermal qualities, contained in façade/windows/roof/insulation. The coefficient is estimated with a negative value, which is intuitive to our expectation, but insignificant.

5.2 Results for actual energy consumption from Equation (3)

The introduction of GAM and visualisation with smoothed curves in regression splines is considered to control for nonlinearity in the effects of the regression. Table 5 provides the parametric coefficients for the linear effects following Equation (3).

While lacking any significance, the continuous covariate for HDD was not visualised with a regression spline for technical reasons. For the single tenant binary, the results show again significantly higher energy consumption for single-tenant-occupied buildings. The coefficient for electric heating proves for significantly higher energy efficiency, again.

Interestingly, the introduced dummy variable for full/major/general refurbishment shows a positive coefficient, but is lacking significance. When this separate main effect is remaining without significance, we expect the interaction effect of building age for observations with a refurbishment in the past to explain the additional energy consumption of buildings with refurbishment in relation to their age.

The model with application of GAM in Equation (3) reveals a higher explanatory power with adjusted R^2 above 35%, compared to the linear model specification from Equation (2). However, the unexplained variation in the models remains of a considerable level.

The further covariate effects from Equation (3) are illustrated in the regression splines of Figure 3. In each graph, the y-axes can be approximately analysed as the percentage effect on energy consumption. The value for the estimated degrees of freedom (edf) higher than 1.0 displays a nonlinear function in the relationship. Within the splines, the continuous black lines are the expected effects and the grey areas are point-wise 95% confidence intervals.

The regression spline for CDD indicates only limited observations for the small data-set and only few observations with a higher annual number of CDD, thus indicating instability in the effect. However, the effect is significant for very low number of CDD (between values 0 and 2 on the x-axes), indicating slightly higher energy consumption when CDD are increasing due to higher air-condition loads.

The regression spline for building age shows high volatility in the effect. The highest energy consumption is estimated for office buildings around 15 years of age, whereas the most recent buildings consume slightly less energy, potentially with reference to higher energy efficiency. Older buildings with more than 20 years of age are attributed with significant lower energy consumption. The effect is significant up to the age of 30 years, followed by instability with limited number of observations. At first glance, this suggests that observations of building age lower than 15 years indicate higher consumption in regard to additional appliances and equipment. Older buildings are assumed to provide less services and comfort, therefore associated with lower consumption, since we cannot distinguish between refurbished and non-refurbished observations in this spline.

The regression spline for the building size is supportive to our interpretation of the linear effect. Up to a building size of approx. 12,000 square metres, the effect is almost indifferent for smaller observations. For buildings of more than 12,000 square metres, a strong and significant increase in energy consumption is observable with further increase in the building area. The effect might result from high-rise office towers in the database with higher levels of energy consumption, due to large vertical distances. The results prove not for any potential economies of scale in energy consumption in reference to the building size.

Higher intrinsic water consumption assessment corresponds to significantly higher actual energy consumption up to a certain level, indicated in the spline. Energy and water efficiency are correlated to each other. This could reflect the stricter efficiency regulation and building codes, indeed affecting the physical building. Further explanation could be that for most recent constructed buildings, rated in the Green Rating audit, the modelled intrinsic water consumption is set low when new buildings in fact consume lower energy.

The regression spline for office area allocated per occupant proves for a linear relationship (edf = 1.0) in the effect, corresponding to the significant effect found before in the linear specification of the regression model. More space per occupant allocated is attributed with lower energy consumption per square metre. We found this corresponding to the results of Kahn et al. (2014), who observed that an increase in the occupancy rate increases the electricity consumption of office buildings.

The regression spline for the interaction effect between building age refurbishment illustrates also a linear relationship with highest energy efficiency for the most recent refurbished buildings. Since this effect is to be interpreted as the additional energy consumption of refurbished observations in relation to the building age and besides the main effect of refurbishment, introduced with a dummy for full/major/general refurbishment, it turns out that with higher age (as a proxy for the time when full/major/general refurbishment was carried out), the additional energy consumption of the buildings is significantly increasing. In general, younger observations have significantly lower energy consumption than older buildings. For the younger peers, although assumed with additional services and equipment introduced upon refurbishment, it seems that they are more energy efficient than their older

Table 5. Parametric coefficients of log-linear model on actual energy consumption as response variable from Equation (3).

Response variable: LN (actual energy consumption in kWh/sqm/a)	
Explanatory variables coefficient (*t*-values)	
Intercept	5.120 (15.881)***
Number of HDD in audit year/100	−.006 (−.828)
Single tenant	.100 (2.050)*
Electric heating	−.219 (−4.009)***
Full/major/general refurbishment	.091 (1.443)
Countries (*n*)	14
R^2	44.50
Adjusted R^2	36.01

Significance: ***1%, **5%, *10%.

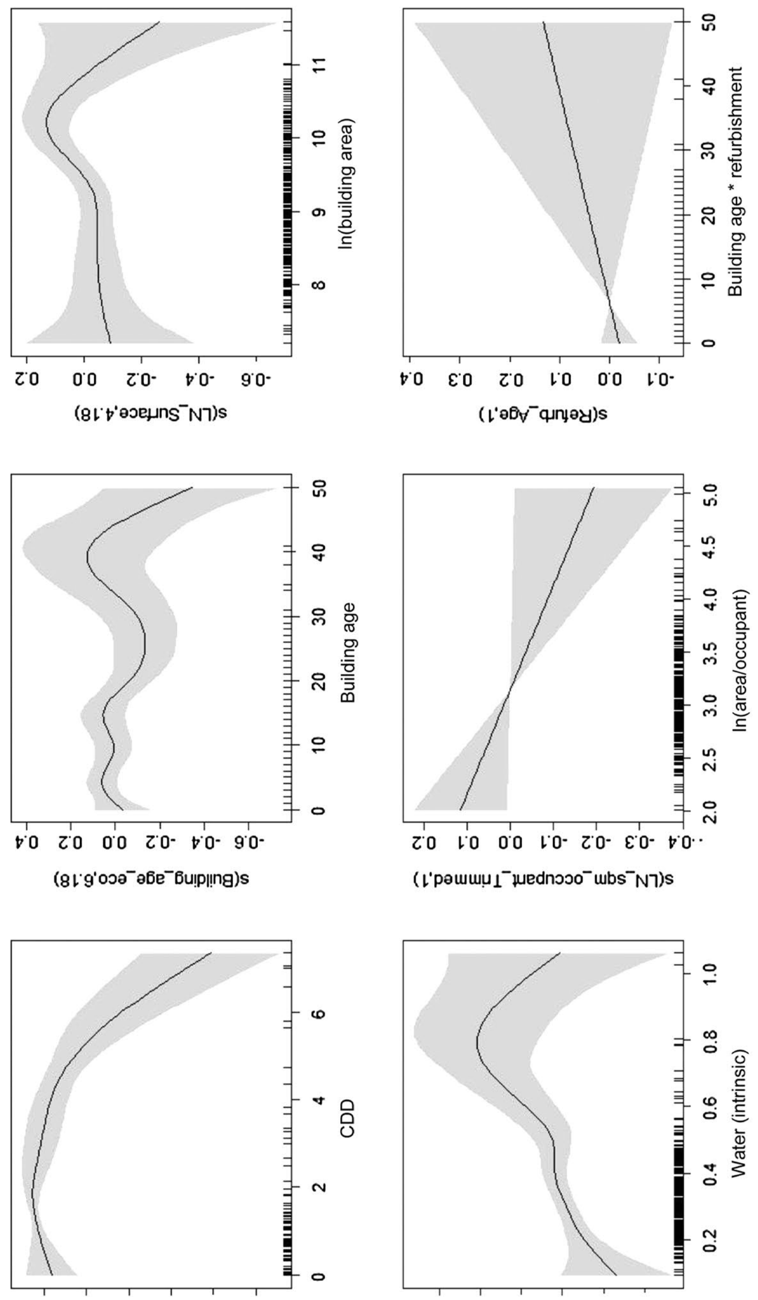

Figure 3. Regression Splines of log-linear model on actual energy consumption as response variable from Equation (3).

peers. This indicates a less energy-efficient refurbishment for older buildings carried out in the past, but with limited observations for a building age of more than 25 years and a rather board confidence cone. The repression spline suggests that refurbishment from the past (more than 10 years ago) was less dedicated to energy-efficient appliances and equipment, compared to most recent refurbishment efforts, all else equal. This result for lower additional energy consumption in relation to refurbishment and lower building age might reflect the influence of stricter building codes and more efficient design of office buildings, implemented over the last years.

To sum it up, the introduced GAM visualised with regression splines provides a more precise understanding of the effects for the tested portfolio from GRA.

6. Conclusion

The objective of this study was to determine the influence of physical building characteristics and of occupant attributes on the actual energy consumption of European office buildings contained in the database of the GRA with 288 observations. Furthermore, we analysed the role of refurbishment on energy consumption with the effects of an extensive refurbishment and refurbishment solely dedicated to energy efficiency and thermal building characteristics.

Besides the application of a regression model to estimate linear effects on actual energy consumption, the study introduces GAM and visualisation with smoothed curves in regression splines to control for expected nonlinearity in the effects of the regression.

The assumed impact of occupant attributes on energy savings was shown to apply for the distinction between single and multi-tenant buildings. Single tenant buildings have a higher actual energy consumption between 12 and 15% compared to multi-tenant buildings (depending on the applied model specification). The result indicates a less energy-efficient behaviour of single tenants responsible for one building as a whole.

The electric production of heating is estimated with significantly lower energy consumption per square metre of up to more than 20%. It could be the case that highly efficient technology for heating production is employed in office buildings which are overall attributed with a relatively high energy efficiency standard in the tested portfolio. Given the fact that the data-set has almost 200 observations located in France, of which more than 50% are equipped with electric heating production, this result might point to higher energy efficiency employed with electric production of heating, compared to omitted reference production types gas, fuel or a district heating network.

In the regression model with linear effects, significantly lower energy consumption is found for observations with more than 20 years of building age. The introduced specification with GAM allows a more detailed interpretation of the effect with highest energy consumption for office buildings around 15 years of age. For more recent buildings, slightly lower energy consumption is observed, potentially indicating higher energy efficiency in regard to increased energy efficiency regulation in EU-member states over the past decade. However, these attempts do not seem to reveal a significant impact on the conservation of actual energy consumption, based on the observations of the GRA portfolio. Corresponding to the principle of additionality with more and new appliances and equipment in more recent office buildings, we found older buildings of more than 20 years up to 30 years of age associated with significant lower energy consumption. These buildings are assumed to provide less services and comfort, which seems to correspond to observations for US office buildings.

Besides the linear coefficients introduced to control for the classified building size, the regression spline is of much higher explanatory quality for the nonlinear effect. The energy consumption of office buildings up to size of approx. 12,000 square metres is identified with a zone of almost indifference, followed by significantly higher energy consumption with increasing building area. For observations around 30,000 square metres, the highest consumption is observable. We find this in line with results of Kahn et al. (2014) when arguing that higher consumption is achieved in office towers, to bridge large vertical distances than in more compact building structures – rejecting the assumption of economies of scale.

Regarding actual energy consumption, the high explanatory power of the intrinsic water consumption is an interesting result of the study. Since this intrinsic measure is modelled according to the technical building characteristics and is independent of actual building use, it provides a potential indicator for high energy efficiency. This could reflect stricter efficiency regulation and building codes, indeed affecting the physical building. From an investor's point of view, this underlines the importance of measuring further sustainable characteristics besides energy, when high water efficiency is identified to be an indicator of high energy efficiency from the GRA data-set.

The linear coefficient but even more the regression spline for the allocated office space per occupant proves for a significant relationship with lower energy consumption per square metre when more office space is allocated per occupant. The regression spline indicates a linear effect in the relationship. Besides the effect of higher vacancy in office buildings associated with lower consumption, this also suggests that more occupants on the same office area will increase energy use per square metre from applied equipment and plug loads (especially if the building is heated or cooled centrally).

Since the role of refurbishment is of major research interest in this study, the attributes for extensive refurbishment (full/major/general) proved for significantly higher energy consumption of 15% as a linear covariate effect, compared to buildings without any refurbishment measures. For the tested portfolio, we find the principle of additionality being associated with refurbishment that provides increased or additional services and comfort from appliances with additional or new equipment. Since the extensive refurbishment was dedicated to improve the overall quality of the buildings, the measures might include those of higher energy efficiency, but from the additional appliances and equipment, the overall energy consumption is higher compared to peers without refurbishment.

Refurbishment dedicated solely to energy efficiency and thermo-physical building characteristics remains insignificant in the second specification of the regression model. The coefficient is estimated with a negative value, corresponding to potential energy savings, but insignificant, most probably because of only 23 observations. Since the effect is not estimated with a positive coefficient, there is no indication of a potential rebound effect inherent in the portfolio at all.

Finally, the regression spline for the interaction effect between building age and refurbishment, to be interpreted as additional energy consumption of refurbished buildings, shows the highest energy efficiency for the most recent refurbished buildings, although assumed with additional services and equipment introduced upon refurbishment. While the regression spline indicates a less energy efficient refurbishment for older buildings carried out in the past, this suggests that refurbishment from the past was less dedicated to energy-efficient appliances and equipment, compared to most recent refurbishment efforts, all else equal. This result for lower additional energy consumption in relation to refurbishment with lower building age might reflect stricter building codes and more efficient design of office buildings, implemented over the last years.

In the discussion and conclusion of our study results, we repeatedly referred to the small database from GRA of only 288 office buildings in 14 European countries as a major drawback.

As of now, there is no extensive research framework for energy consumption of commercial, especially office buildings, based on empirical evidence from Europe. This study aims to contribute to a better understanding of energy consumption in office buildings, in particular, when it comes to the role of refurbishment with differing intensity. However, there are limitations remaining from the small data-set, which lacks higher explanatory power. A reason for the very moderate fit of the regression models, indicated in the relatively low R^2 values and rather weak significance of the attributes might be due to omitted variables in our models or defaults in the used data.

Since the used data-set contains the actual metered energy consumption and the intrinsic assessment only assessed once for issuing the Green Rating audit, the results of the study should be interpreted with precaution. According to the limited nature of the data-set, we cannot exclude the possibility that any potential bias due to omitted variables is included in the outcomes. Besides the rather small number of observations from different years between 2008 and 2012, we do not have further information in regard to the building quality and maintenance or the equipment and appliances, differing among the observations. Furthermore, the missing information in regard to the sub-category “other” in the data-set is a limiting factor that could reduce explanatory power and introduce omitted variable bias. Moreover, we do not know the vacancy rate in the buildings or unemployment rates for the relevant time frame. Also, the business industries of the office occupants might be associated with potential differences in energy consumption, compared to each other. Another limitation is that we do not know and control for the relevant energy cost in the buildings. However, as an advantage, the used data-set contains detailed information to differentiate among the intensity of refurbishment measures, which is a precondition to investigate the role of refurbishment on energy consumption.

We tried to mitigate the problem of nonlinearity in the effects of the estimated regression coefficients with the introduction of GAM. The obtained regression splines provide a more precise understanding of the effects for the observed portfolio. However, a dynamic analysis of a panel with more observations over time – controlling the effects before and after refurbishment – is recommended.

Beyond the recommendation to consolidate our research results on a more extensive database, we believe that fostering the awareness of actual energy consumption in the direction of potential savings by occupants is furthermore an issue. Apart from technological progress and a more extensive and stricter energy efficiency regulation, the design of an effective (incentive) mechanism to shift office occupant behaviour towards energy conservation might achieve higher energy savings in practice. How this mechanism could be designed is a subject for further research, especially in the field of behavioural real estate research.

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