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An Inventory of Buildings in Dublin City for Energy Management

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Abstract: Globally, about one-third of final energy use and associated carbon dioxide emissions are sourced from buildings, the great majority of which are located in urban areas. Not surprisingly, managing building energy demand is a focus of city-based climate change policies while simultaneously tackling issues of fuel poverty. Assessing the potential for mitigation and evaluating the efficacy of energy policies relies on knowledge of the urban building stock, which varies geographically based on the age of building and retrofits that may have taken place. However, building data at a detailed scale are rarely available for these purposes. In this research, we present a geographic building database for Dublin city centre using a typology approach. The resulting data consists of material and energy attributes of over 25,000 buildings that have been constructed over a 200-year period. These data are used to estimate the energy ratings of households and to evaluate historic and potential retrofitting. In addition to energy studies, they provide a fundamental dataset on buildings that can be used to evaluate official sources and to support a wide range of urban research topics. The methodology used here is sufficiently general in nature that it can be expanded to other cities in Ireland and Europe.

Keywords: *building inventory, Geographic Information Systems (GIS), energy ratings*

Introduction

The Intergovernmental Panel on Climate Change (IPCC) estimates that the building sector was responsible for 8.8 $GtCO_2$ emissions in 2010 and this would increase by 50-150% by mid-century due to increased wealth, changes in lifestyle, access to energy networks, improved housing and urbanisation (IPCC, 2014). This sector is of particular concern as buildings and associated infrastructure have long lifespans leading to 'lock-in risks' (World Bank, 2010). In the EU, for example, about one-third of buildings are more than 50 years old and although three-quarters are considered energy efficient, only 0.4-1.2% of the building stock is renovated each year.

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[1]Not surprisingly then, energy management at the building scale forms a core part of global climate change and energy policies that attempt to improve efficiency and reduce fuel poverty. Again, in the EU, two directives (the 2018 Energy Performance of Buildings Directive[2] and the 2012 Energy Efficiency Directive[3], since updated) have an ambitious 2030 goal of 40% reduction in energy consumption compared to the 1990 level, 3% annual building renovation and de-carbonising the building sector by 2050.

In Ireland, energy regulations for buildings have been in place since 1978 and have become more stringent over time. Most recently, a renovation strategy (DCCAE, 2017) has been prepared to meet the requirements of the EU Energy Efficiency Directive; this includes a requirement that all new buildings be Near Zero Energy Buildings by 2021 and that renovation policy should be 'fabric first then fuel-switching', that is, the focus should be on the building envelope. Currently, estimating urban-scale building energy demand and evaluating retrofit opportunities relies on the decadal household census coupled with Building Energy Rating (BER) data. The former gathers demographic and socioeconomic data in addition to some dwelling information (age of housing, energy source etc.), which are aggregated to areas of varying size; the finest resolution is the Small Area scale, which consists of 80 to 120 dwellings. The BER assigns an energy value (kWh/m^2/yr) and rating category (A-G) to dwellings based on average occupancy and accounts for the age of construction, the material properties of the building envelope and heating/cooling systems present (Table 1). A BER is required for buildings sold or rented since 2007 and, as of 2016, 39% of the residential housing stock has been assessed (SEAI, 2018). Until recently, the BER information was available publicly at a postcode level, which is spatially coarse. Morris Cadogan (2017) used these data to examine the energy efficiency of the national building stock and the impact of policies. More detailed links to the household census data at the Small Area level have been used on estimates based on the age of housing. Cachia (2018) used this approach to generate a baseline map of energy use across the city of Dublin, as part of a climate change strategy; it was estimated that total energy use in the city in 2016 was 9,771 GWh of which nearly 70% was driven by residential and commercial demand. This work provides insights into the aggregate energy demand across urban neighbourhoods, but its precision is limited by both the scope of the BER data and nature of the household Census data.

Table 1. Building Energy Ratings (BER) and equivalent annual energy demand per sq. m. The estimated annual CO2 emissions (kg/m²/yr) and fuel costs are based on a typical occupancy and heating to a comfortable level

BER	Energy	2 Bed Apt 75 sq.m		3 Bed Semi-D 100 sq.m		Detached house 200 sq.m		Large house 300 sq.m	
	kWh/m²/yr	CO_2 kg/m²/yr	Cost (€)	CO_2 kg/m²/yr	Cost (€)	CO_2 kg/m²/yr	Cost (€)	CO_2 kg/m²/yr	Cost (€)
A1	<25	0.4	140	0.5	190	1.1	400	1.6	600
A2	>25	0.8	280	1.1	380	2.2	800	3.2	1,100
A3	>50	1	350	1.4	470	2.7	900	4.1	1,400
B1	>75	1.3	440	1.7	590	3.4	1,200	5	1,800
B2	>100	1.6	570	2.2	800	4.3	1,500	6.5	2,300
B3	>125	2	700	2.7	900	5.3	1,900	8	2,800
C1	>150	2.4	800	3.1	1,100	6.3	2,200	9.4	3,300
C2	>175	2.8	1,000	3.7	1,300	7.4	2,600	11	3,900
C3	>200	3.2	1,100	4.2	1,500	8.4	2,900	12.7	4,400
D1	>225	3.7	1,300	5	1,700	10	3,500	14.9	5,200
D2	>260	4.4	1,500	5.8	2,000	11.7	4,100	17.5	6,100
E1	>300	5	1,800	6.7	2,300	13.4	4,700	20.1	7,000
E2	>340	5.7	2,000	7.6	2,600	15.1	5,300	22.7	7,900
F	>380	6.8	2,400	9.1	3,200	18.2	6,300	27.2	9,500
G	>450	8.5	3,000	11.3	4,000	22.7	7,900	34	11,900

Source: https://www.seai.ie/energy-ratings/building-energy-rating-ber/

This paper presents a methodology to create a detailed geographic database of buildings in Dublin to support energy assessment and modelling. The case-study area is Dublin city centre, which encloses an area of 15km² in the historic core of the city (Figure 1); according to the 2016 Census, this area is home to over 100,000 residents and the daytime working population is twice as large (Table 2). The objectives of this paper are to:

1. Create and apply a methodology to develop a detailed building database for use in an urban building energy model (UBEM) using an example of Dublin city centre;
2. Demonstrate the value of the building database for assessing the energy status.

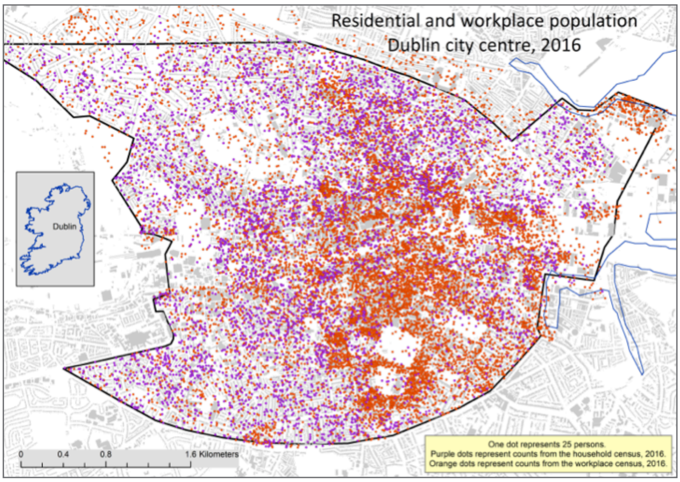

Figure 1. Dot-density map showing the distribution of population within the study area based on the 2016 household and workplace censuses. The outline represents the limit of the study area.

2016 Census	Dublin City	Study Area
Residential census		
Population	525,229	115,770
Density (per sq.km)	4,567	7,718
Households		
House	133,709	17,932
Apartment	72,526	32,010
Total	206,235	49,942
Age of construction (percent of households)		
<1919	12.94	21.15
1920-1969	36.28	20.18
1970-1999	23.4	21.64
2000-2009	13.31	15.01
>2010	1.2	1.4
Workplace census		
Workers	373,153	215,366
Density (per sq.km)	3,245	14,358
Population	702,159	319,705
Density (per sq.km)	6,106	21,314

Table 2. The results of the 2016 Census based on residence and workplace areas. The information is presented for Dublin City (115km^2) and for the city centre study area (15km^2).

Literature Review

In the international literature there are broadly two methods used to estimate building energy use, to derive energy profiles for neighbourhoods, design efficiency policies and evaluate future energy demand. The first is described as ‘top-down’ as it uses average energy consumption obtained for large areas and statistically decomposes these data by building types, occupation patterns, etc. The second is described as ‘bottom-up’ as it uses information for individual buildings, often generated using building energy models (BEMs); this method allows a detailed cost-benefit of retrofit options and behaviour changes but the required data is very difficult to obtain and upscaling individual building simulations is computationally expensive (Swan and Ugursal, 2009). As a result, it is the top-down approach that has been employed most often to evaluate energy use at urban scales. However, a new generation of models capable of simulating energy use (and evaluating policy) at neighbourhood scales has emerged. These Urban Building Energy Models (UBEMs) apply 'physical models of heat and mass flows in and around buildings to predict operational energy use as well as indoor and outdoor environmental conditions for groups of buildings' (Reinhart and Davila, 2016, p. 197). Davila *et al.* (2016) used a UBEM to model energy demand across Boston (US) using a geographic database of building properties (materials, heating/cooling systems and occupation patterns) over a 24-hour period. The potential for these models to simulate energy demand and evaluate policy options at the scale of streets and neighbourhoods is considerable but acquiring information on the building stock is a major challenge (Monteiro *et al.,* 2018).

One way of simplifying the database creation task is to employ a typology that links building types to a range of energy-relevant properties, including dimensions, materials and energy systems (e.g., Salat, 2009). In Europe, the Typology Approach for Building Stock Energy Assessment (Tabula) project has developed a database of residential building types for 21 countries[4]. This database identifies common building types with attributes on age of construction, building (wall, window, floor and roof) materials, insulation properties and HVAC systems. The information sheets for each archetype also include estimated energy consumption (kWh/m^2/yr) and retrofit options. A number of studies have used these data in conjunction with census data to estimate potential reductions in carbon emissions based on retrofits (Tabula, 2014; Ballarini *et al.,* 2014; Dascalaki *et al.,* 2011). More recently, Florio and Teissier (2015) merged national building stock data in France with Tabula archetypes to assess the energy performance of building stock over large areas.

In Ireland, studies have used BER data in combination with household census data on population characteristics and age of housing to evaluate building energy demand and efficiency. Curtis *et al.* (2015) created occupant energy profiles using census data to assess poor performing building types while Ali *et al.* (2018) and Dineen *et al.* (2015) created building archetypes to generate neighbourhood-scale building energy profiles. Others have simulated building energy at a neighbourhood scale. Beagon *et al.* (2018) and Egan *et al.* (2018) used Irish residential building examples to model building energy more efficiently at large scale. While the former study focused on one building archetype to model energy at a neighbourhood scale, the latter used several national archetypes to validate building energy model results using minimal inputs to reduce computational time. Others have used available data to evaluate the impact of energy renovation policies on the national and local building stocks. Hanratty *et al.* (2016) conducted a detailed study of the housing stock in north Dublin, where much of the housing stock is old, using the Tabula scheme alongside BER data; they found that much of the energy improvements were not captured by the BER system. Ahern and Norton (2019) used the household census data in combination with the BER data to show that average energy efficiency of Irish housing had improved by over 34% between 1995 and 2011.

Urban Building Energy Models (UBEM) provide an opportunity to overcome many of the issues associated with existing methods of examining building energy use at different scales. Currently, policy relies on information complied by matching readily available data (on age of build, for example) that is often crude in detail or by focussing on extremely detailed individual building information. In contrasts, UBEMs require 'sufficient' building scale data (on location, dimensions, materials and energy systems) to perform simulations (on retrofits, renewables and community heating schemes, as examples) at building group scales. The basic data in itself is a valuable resource for decision-making at neighbourhood scales on appropriate strategies for improving the building stock. The sections that follow outline the methods for creating the geographic data needed to support a UBEM and describes and analyses the results.

Methodology

The methodology for creating a geographic building inventory for Dublin Building Database (DUBLD) relies on a digital base map of building footprints and heights; Census data that record household characteristics for areas; the Tabula classification of building types; available imagery from Google Earth Pro (GEP) and Street View (GSV). These data were supplemented by information from An Post's GeoDirectory, which provides geocoded addresses. The compiled information is managed within Quantum GIS (QGIS), an open-source geographic information system. In the following section, we outline the building characteristics of the Dublin case study area using available data, outline the building typology used and the methods for creating the building database (Figure 2).

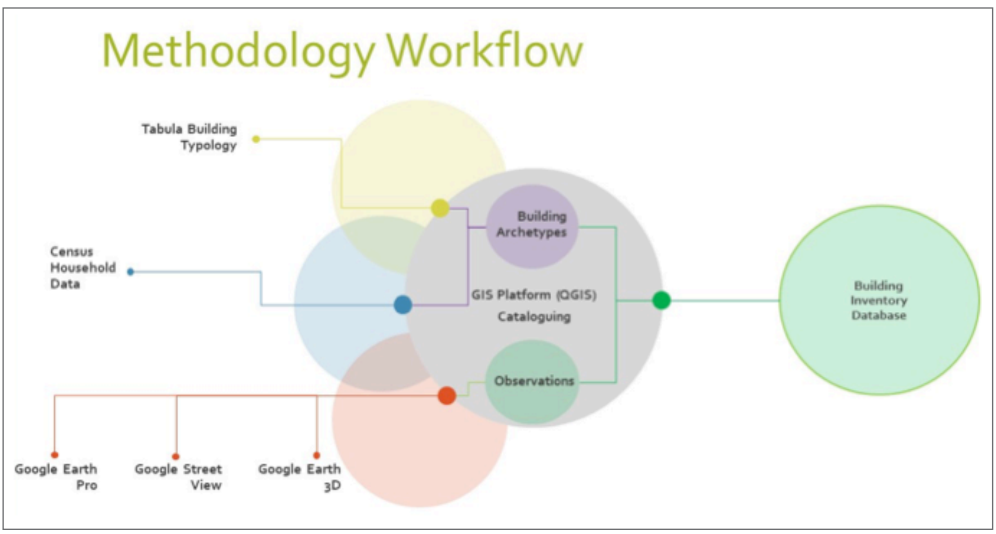

Figure 2. Workflow illustrating the key components, process and information flows involved in creating DUBLD.

Figure 3 Representative photographs of the nine common Tabula types, identified by number (see also Table 3).

Some basic information on the housing stock is available from the household Census, the most recent of which was conducted on 24 April 2016 (see www.cso.ie). In addition to population data, the Census also gathers information on housing; specifically, the type of accommodation (e.g., house or apartment), age of dwelling and the main fuel used for central heating (CSO, 2018). The information collected from individual households is compiled into tables and aggregated at different spatial scales. The Small Area Population Statistics (SAPS) are available for areas that comprise of between 80 to 120 dwellings and there are over 500 SAPS areas within the study area. Table 2 provides summary information for the study area and the city generally. There are nearly 50,000 households (>100,000 residents) in the study area, most of whom live in apartments which have been built in the last two decades. About 16% of households live in buildings constructed before 1919 and nearly all are heated using gas (40%) or electricity (45%). The working population in the study area is nearly three times higher than the resident population; the dominant occupations are in the financial, service and educational sectors. The study area is distinguished from Dublin City as a whole by population density, the percentage of the housing stock in multi-dwelling units and the age of buildings. Finally, it is worth stating that there are over 3,500 protected structures in the study area, many of which form streetscapes; as a result, much of the physical form of parts of the city cannot change quickly.

Type	Construction period	Wall	Roof	Windows	Energy Rating
(3) Terraced house	Pre-1900	Uninsulated brick 325/225mm thick.	Front pitched with 100mm of mineral wool in ceiling joists/ Rear pitched roof no insulation.	Single glazed, wooden frames.	352 (O) 95 (R)
N=5435		**U = 1.64/1.41**	**U = 0.4/2.3**	**Glazed fraction 6% U = 4.8**	
(5) Bungalow	1900-1929	Uninsulated brick, 325mm thick.	Pitched roof with 50mm of mineral wool in ceiling joists.	Single glazed, wooden/steel frame	624 (O) 178 (R)
N=2627		**U = 1.64**	**U = 0.68**	**Glazed fraction 10% U= 4.8/5.7**	
(6) End of terrace	1900-1929	Brick façade/ block to the side and rear. 225mm thick.	Pitched roof with 50mm of mineral wool in ceiling joists.	Single glazed, wooden/steel frame	458 (O) 123 (R)
N=1411		**U = 2.1/1.38**	**U = 0.68**	**Glazed fraction 9% U= 4.8/5.7**	
(7) Terraced house	1900-1929.	Uninsulated brick walls 325mm thick.	Pitched roof with 50mm of mineral wool in ceiling joists.	Single glazed, wooden/steel frame	624 (O) 178 (R)
N=5365		**U = 1.64**	**U = 0.68**	**Glazed fraction 6% U= 4.8/5.7**	
(9) Terraced house	1930-1949	Solid mass concrete	Pitched, insulation between the joists	Single gazed, metal frame	392 (O) 106 (R)
N=2760		**U = 2.2**	**U = 0.68**	**Glazed fraction 6% U= 5.7**	
(17) Terraced house	1978-1982	300mm walls, partially filled	Pitched, insulated between the joists	Double-glazed, metal frame, 6mm gap	311 (O) 117 (R)
N=1235		**U = 1.1**	**U = 0.4**	**Glazed fraction 9% U= 3.7**	
(25) Terraced house	1994-2004	Cavity walls, partially filled	Pitched, insulated between the joists	Double glazed, PVC/ wood, 12mm gap	177 (O) 119 (R)
N=869		**U= 0.55**	**U= 0.36**	**Glazed fraction 10% U= 2.8**	
(38) Apartment block	1994-2004	Block with part filled cavity walls 300mm thick.	Flat roof with insulation.	Double-glazed, air-filled windows with 12mm gap, wood/ PVC frames.	175 (O) 63 (R)
N=1109		**U = 0.55**	**U = 0.35**	**Glazed fraction 10% U= 2.8**	
(39) Apartment block	2005-2010	Solid reinforced concrete externally insulated.	Flat roof with insulation.	Double-glazed, air-filled windows with 16mm gap, wood/ PVC frames.	145 (O) 6 (R)
N=458		**U = 0.27**	**U = 0.22**	**Glazed fraction 40% U= 2.0**	

Table 3. The properties of the nine most common Tabula building types in the study area. The number (N) of buildings according to type are listed; there are 23,732 buildings classified into Tabula types in the study area and this group represents 21,269 of these. The energy ratings (kWh/m²/yr) represent the typical energy use (assuming standard occupancy rates) as originally built (O) and following a standard retrofit (R).

The Tabula project created 39 building types for the Irish residential housing stock. The attributes associated with each type includes descriptive information on roof, wall, floor and window materials. In addition, it provides insulation values and HVAC system present based on age of the structure, architectural characteristics and likely refurbishments. The attribute database for each type is organised into three categories (original, standard and advanced refurbishment), which quantify the energy-saving potential of refurbishment in terms of kWh/m^2 per annum (and CO_2). There is no equivalent typology for non-residential buildings that is based on their physical properties. Instead, typologies for commercial buildings are usually based on the functions present (CIBSE, 2012). In Dublin, as in other cities, many of the commercial functions are situated within residential building types (Figure 3) and there are relatively few buildings that are designed specifically for commercial use. Here, we focus on the residential building stock using the Tabula scheme and identify buildings that are non-domestic (institutional, commercial, industrial, etc.) separately.

Each building in the study area was categorised into a Tabula type or 'Other', using a split-screen view of the study area. On one screen, building footprints and SAPS census data were opened within QGIS, while the same information was opened within GEP with GSV on the other screen. The QGIS and GEP views were used in tandem to classify each building within a SAPS area in sequence; StreetView was used to confirm categorisation decisions. While this is a time-consuming process, the decision-making is aided by the use of SAPS housing data, which indicates the age of construction. In addition, as much of Dublin was built as distinctive neighbourhoods where there was a limited variation in house type, large numbers of buildings could be classified simultaneously. Once each building footprint was associated with a type, all of the associated Tabula attributes (Table 3) were then attached to that building, resulting in a first iteration of DUBLD.

Results

There were 28,078 building footprints in total within the study area, of which 85% (23,732) could be classified using the Tabula scheme; the Other group consisted of warehouses, commercial buildings, institutions, industry, etc. Of the 39 'national' types, 29 were identified in the study area but nine (seven single dwelling types and two multi-dwelling types) dominated, accounting for 89% of those categorised and 75% of all buildings. Figure 3 shows examples of the most common building types from the study area and Table 3 shows their attributes.

The oldest Tabula buildings were constructed before the 20th century, using solid brick walls, uninsulated timber roofs and single-pane glazing. These Georgian and Victorian buildings usually form terraces and would have been heated using fireplaces. They have an energy rating of >350 kWh/m^2/yr (based on the original construction), are between 1-4 storeys high and may have basements. Although most were built as single dwellings, many have been divided into multi-dwelling units or are wholly or in part used for commercial functions. Since the 1900s, there have been distinctive phases of building in the city. Between 1900 and 1939, most single dwellings were constructed as terraced housing with solid brick walls, pitched roofs and very poor energy ratings; most are categorised as G in the BER scheme (>450 kWh/m^2/yr).

During the period from 1940 until the 1990s there were few new houses built in the city centre as population growth took place in the suburbs and a large proportion of inner-city inhabitants were relocated. During this period, concrete and cavity block walls were used and roof insulation was used. The year 1978 is an important benchmark year as it marks the beginning of statutory building energy regulations. Since 1990, rapid population growth in the city centre is reflected in more construction and a shift from single to multi-dwelling units (see Table 2); the recent period of construction all but ended during the international financial crisis (2007) which resulted in a great many vacant dwellings. Economic recovery since 2011 has reduced the vacancy rate and construction has resumed, especially of apartment buildings. Since 1978, the improved energy standards has seen marked changes to the energy ratings of dwellings; whereas terraced, cavity wall buildings from the 1970s (type 25) had BER ratings of E1 (300-340 kWh/m^2/yr) a modern apartment typically has a rating of B3 (125-150 kWh/m^2/yr).

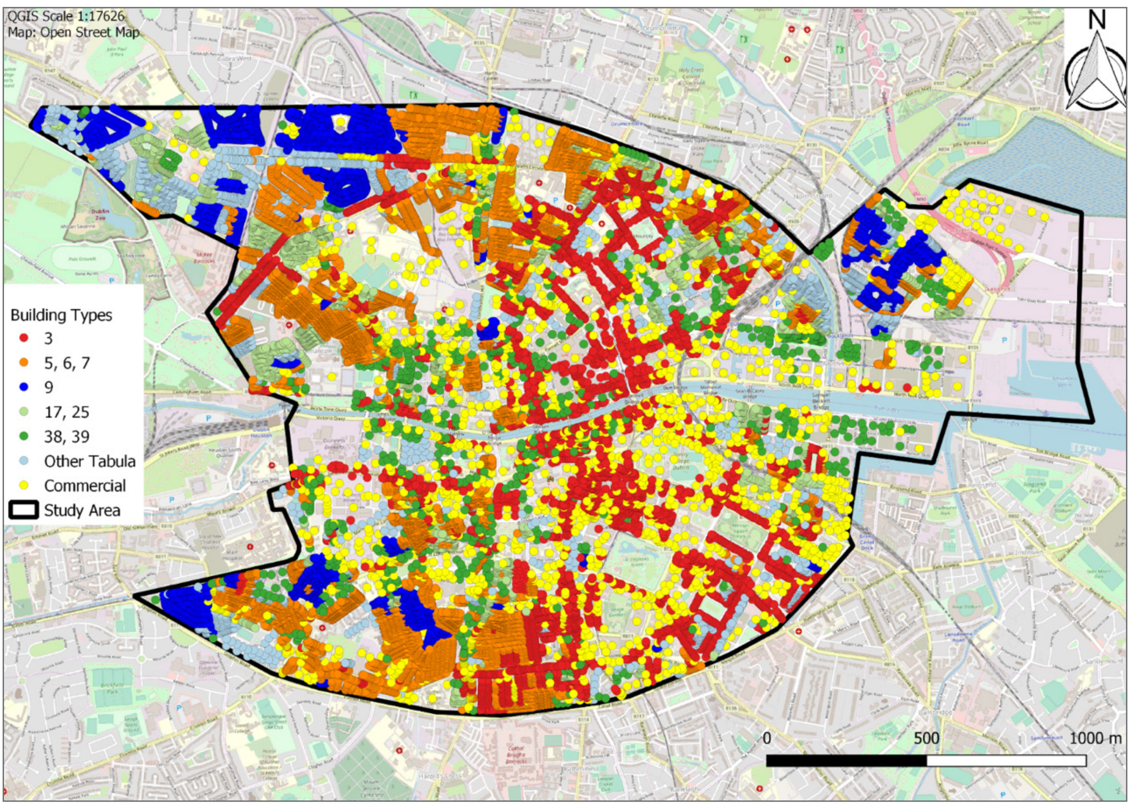

Figure 4. The geographical distribution of Tabula building types across the study area (see also Figure 3).

Each phase of building has resulted in distinctive neighbourhoods as shown in Figure 4. The oldest buildings are concentrated in the eastern half of the city centre, forming rows of houses along major roads and squares. The 20th-century houses are found in clusters in the western part of the city, away from the river Liffey. Modern apartments (types 38 and 39) are found close to the city centre in the west and along the river and some roads but are most common in the docklands area to the east of the city centre. As a generalisation, these patterns fit the historic development of the study area: the oldest extant buildings in the central core of the city, where much of the residential building stock has been repurposed (see Figure 1); the building of single (and multi-) dwelling housing for workers throughout the 20th century; and the redevelopment of Dublin Port in the east (and derelict city centre sites) to accommodate new workers in multi-dwelling units. The pattern of building illustrates the potential for neighbourhood-based schemes to improve energy efficiency.

Evaluation

The DUBLD database was evaluated against the 2016 Census, which is based on household responses and asks questions on housing such as age of dwelling and type of occupancy (e.g., house and apartment). This information is aggregated to the level of Small Areas; there are 569 Small Areas within the study area. To make the comparison, DUBLD building data was modified to account for the number of dwellings present in each footprint. This was done using An Post's GeoDirectory, a database that contains the geographic coordinates of individual addresses, identified as commercial business, residential properties or both. First, QGIS was used to spatially attach each residential address to its DUBLD building footprint. Second, all DUBLD buildings with one or more residential addresses were spatially matched to the Small Area units.

According to the 2016 Census, there were 58,107 households in this area, 19,489 were in single dwelling (SD) buildings (detached, semi-detached and terraced) and 38,618 were in multi-dwelling (MD) buildings (purpose-built apartments, converted houses and bed-sits); 1,498 of the houses and 5,266 of the MD units were recorded as vacant. By comparison, the Tabula-Geodirectory data estimates that there are 60,358 dwellings, 18,365 are in SD buildings and 41,993 are in MD buildings. The differences between the Census households and DUBLD dwellings is very small overall +3.87% (-5.77% and 8.74% for single and multi-dwelling buildings, respectively) and can be explained by three sources of error:

1. Census: missing or duplicated households,
2. DUBLD: incorrect GeoDirectory address locations (about 500 addresses fell outside building footprints and could not be allocated), and errors in the footprint geography,
3. Mismatch in the dates of data acquisition. The household census was taken in 2016 while the DUBLD data is from 2019. In the intervening period, there has been added residential stock; for example, in 2018, Dublin City (which extends well beyond the

city centre) had nearly 1,000 planning permits approved and in the first quarter of 2019, over 500 new dwellings completed.

Figure 5 shows the relationship between Small Area counts for single (top) and multi (bottom) dwelling buildings. The SD relationship is very close, with little scatter around the 1:1 line and a R^2 value of 0.91. For MD units the results are weaker but still strong (R^2 = 0.76). Additional errors in the Small Area comparison accrue when a large building footprint is divided by the Small Area boundary, but the dwellings are allocated to one area – this is more likely to affect large purpose-built apartment blocks. Overall, these results show that DUBLD is a good representation of the city centre building stock and can be used to explore aspects of Dublin's urban geography as it relates to housing and energy.

Figure 5. Scattergrams of the number of households in non-shared (top) and shared (bottom) accommodation from the 2016 Census against the number of dwellings estimated from Tabula-GeoDirectory.

Discussion

The DUBLD database has intrinsic value as a very detailed (and independent) benchmark geographic dataset against which progress in building energy management can be assessed. Previous work (e.g., Cachia, 2018) has evaluated the quality of the building stock by linking Census household information with Building Energy Rating (BER) data maintained by the Sustainable Energy Authority of Ireland (SEAI). The BER information includes the dwelling type, year of construction and geography postcode which can be used to link with Census data on age of dwelling; however, it is worth bearing in mind that 20% of households respondents did not provide a construction date and that vacant properties are not included. DUBLD should allow a more detailed analysis of the state of the housing stock as it is based on individual building types and their construction properties (Table 3).

Figure 6 shows the number of dwellings associated with each Tabula building type. Note that a large number of dwellings are found in purpose-built apartment building types (Tabula template ID 15, 34-39) but nearly 12,500 are in pre-1900 buildings. Tabula Type 3 buildings were constructed as large single-family dwellings (often with servants) but most (90%) of these have been partitioned into smaller spaces. A smaller number of older dwelling types (such as the terraced housing built between 1900 and 1929, see Table 3, Type 7) are also now divided into MD units. These results show the rapid change in housing patterns in Dublin as just 10% of the buildings in the city centre were built post-1994 but these accounted for over half of the MD units in the study area. The second-largest concentration of MD units are found in the oldest building stock (Table 3, Type 3) constructed before 1900. Less than one-third of dwellings in the study area are SD units and most (62%) are in buildings constructed before 1978, the date of the first building energy regulations for Ireland. Based on the Tabula original energy ratings, 80% of buildings and 54% of dwellings had F or G energy ratings (Table 1).

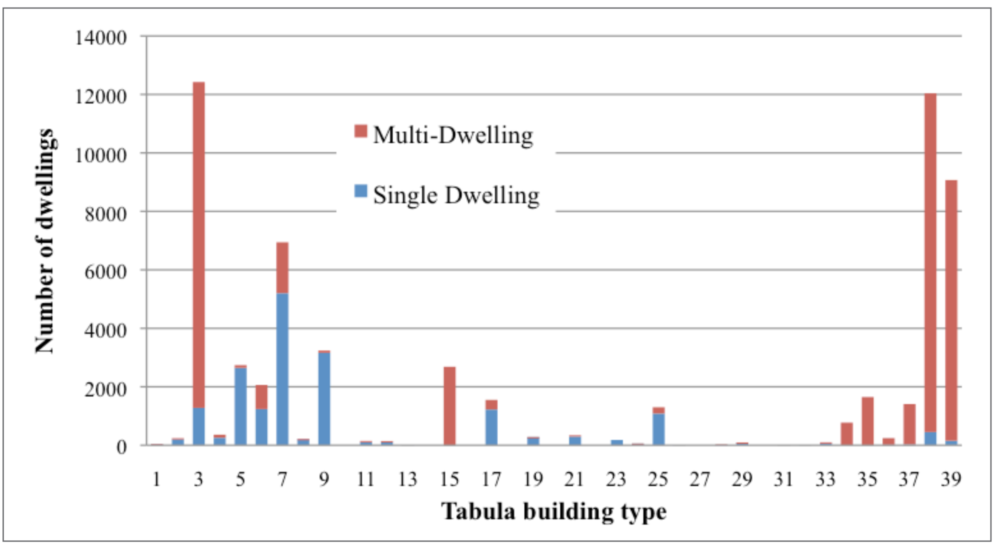

Figure 6. The number of dwellings in each Tabula category.

The SEAI database provides up-to-date energy assessments for dwellings bought or sold since 2007; it also includes dwellings that have received SEAI grants for retrofits. Here, we examined the BER data for all dwellings in four postcodes (Dublin 1, 2, 4, and 7) that incorporates the study area and surrounding area. Table 4 shows the frequency of dwellings by age and energy ratings based on Tabula (original build) and SEAI (current) energy ratings. The effect of building regulations since 1978 is clear in the improved ratings over time and the BER data on earlier buildings shows evidence of some upgrades. This is clearest for the single dwellings (SD), which show consistent improvements compared to original build values; the only exception is for the period 1994-2004, which may reflect poor construction practices. These results support Hanratty *et al.* (2016) who examined the rates of refurbishment for buildings with BER ratings in city centre Dublin and supplemented this information with a detailed survey of 100 dwellings. While the SEAI data showed that a significant proportion needed upgrades to walls (21%), to roofs (27%) and windows (45%), the field survey found higher rates of refurbishment, which were not reflected in the data. The data for MD units indicate poorer ratings when compared to SD units, apart from the 1930-1978 period; the difference is especially large for the oldest housing stock. Overall, however, the BER data suggest that the great majority of the building stock remains poor from an energy standpoint.

Table 4. DUBLD and SEAI information compiled by age of building and single (SD) and multi-dwelling (MD) units. The DUBLD data include the number of buildings, the estimated number of SD and MD followed by the Tabula energy rating based on original construction. The SEAI data includes the number of SD and MD units and the respective energy ratings. The last row shows totals and averages.

	DUBLD				SEAI			
Age	Buildings	SD	MD	Tabula kWh/m²/yr	SD	BER kWh/m²/yr	MD	BER kWh/m²/yr
1800-1899	6,257	1,763	11,301	425	1,208	403	983	453
1900-1929	9,930	9,085	2,660	569	2,940	395	1,640	505
1930-1949	3,452	3,365	88	521	1,898	346	1,113	284
1950-1977	456	214	4,406	481	1,495	339	1,517	298
1978-1993	2,223	2,018	1,986	258	1,964	218	2,022	303
1994-2004	1,937	1,594	11,803	205	885	238	9,092	263
2005-2010	452	263	8,934	153	184	168	5,744	179
2011-	131	63	815	55	134	65	538	64
Totals and averages	24,838	18,365	41,993	344	10,708	266	22,649	295

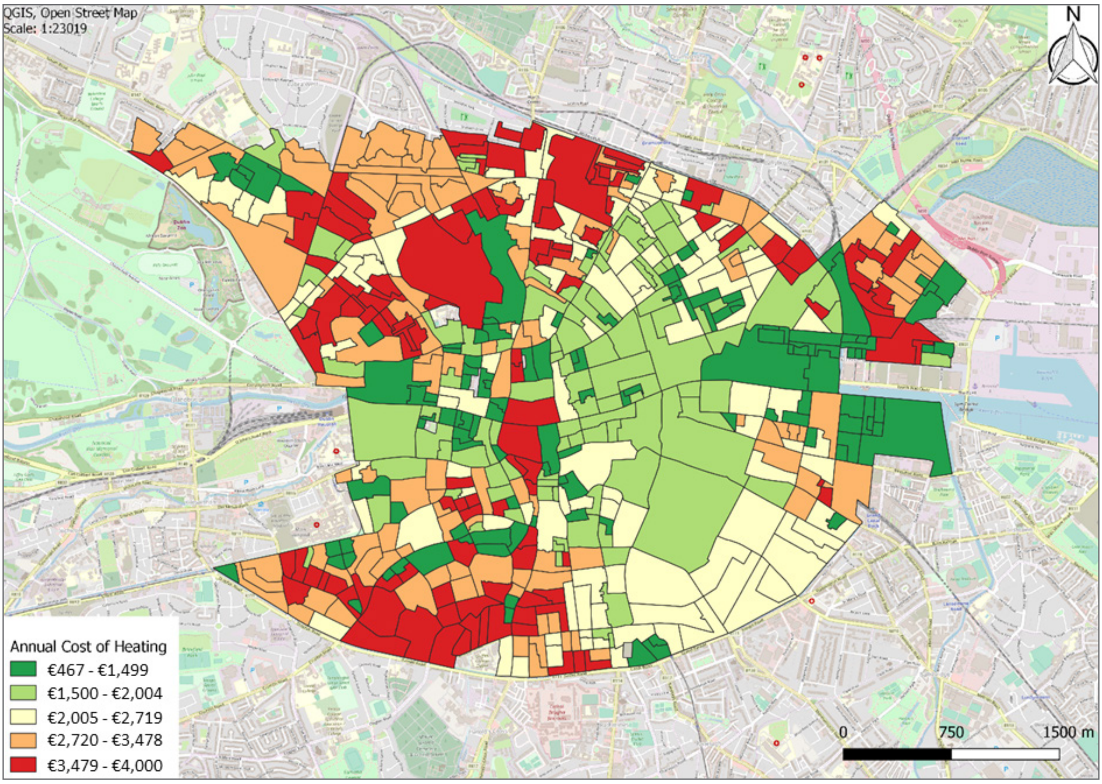

Figure 7. The estimated average energy cost per dwelling based on typical occupancy and heating to a comfortable level, based on Table 1.

The value of DUBLD for energy assessment can be explored using the BER data. In doing so, some caution should be exercised as the BER data is not a representative sample of the dwellings. For example, there are relatively few dwellings from before 1978. Moreover, until 1940, traditional construction methods included solid masonry walls, single-glazed windows and timber-framed uninsulated roofs. Unlike newer buildings constructed using cavity walls, wall retrofits for these buildings are expensive and complicated; a key feature of their walls is that they allow moisture transfer but are sufficiently thick to ensure the internal face remains dry (Purcell, 2018). The lack of data on these buildings affects the overall evaluation of the stock. For example, the BER data suggests an overall rating of 288 kWh/m²/yr but the values for SD (326) are higher than those for MD (270) and the overall value reflects the newer building stock, much of which is located in apartment blocks. However, if we estimate the overall energy rating using the BER data weighted by the DUBLD dwelling count, we get a value of 324 kWh/m²/yr (349 and 313 for SD and MD units, respectively); that is E2 rather than D2 (Table 1).

We can estimate the cost of energy and CO_2 emissions crudely using the information in Table 1 if we assume that SD corresponds to a 3-bed Semi-D (100m²) and MD to a 2-bed Apartment (75m²). Using the BER weighted DUBLD data, the estimated associated CO_2

emissions are 378kt and it would cost €131,735,000, in the study area, based on typical occupancy and heating to a comfortable level. The equivalent values using BER data alone are 87kt and €32,015,500. If we apply this approach to map the average cost per Small Area (Figure 7), the pattern illustrates the dominance of new apartment buildings in the eastern half of the city and of older single dwelling buildings in the western half of the city. The differences in estimated costs per dwelling are significant (>2,000) and have major implications for the designing neighbourhood scale energy policies.

Conclusion and next steps

This research has created a geographic database on the make-up of residential buildings in Dublin city centre. Using Tabula archetypes alongside other geographic databases, we have attached a range of properties (age, materials, heating systems, etc.) to a diverse and spatially heterogeneous building stock across the city. These data contribute to a knowledge gap in the field as previous studies (Ahern and Norton, 2019; Ali *et al.,* 2018; Curtis *et al*., 2015; Dineen *et al.,* 2015; and Hanratty, 2015) depended on BER and Census data which lack coverage and accuracy respectively. The results correspond closely with Census data, where a comparison is possible and illustrates the geographical variation in energy costs across the city centre. These data can be used to evaluate energy poverty and assess neighbourhood-scale policies to manage energy use and CO_2 emissions. Moreover, the resulting database provides the information needed to run an Urban Building Energy Model (Davilla *et al.,* 2016) that can be used to simulate the cost-benefits of different area-based interventions such as district heating schemes, neighbourhood retrofits and using renewable technologies. Moreover, the approach taken here of visual classification of housing stock into types could be modified to allow automatic classification based on computer recognition techniques. This would allow rapid assessment of the building stock where Tabula-like schemes have been developed.

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Endnotes

1 https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

2 https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-performance-of-buildings

3 https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive

4 www.episcope.eu