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Interior insulation – Characterisation of the historic, solid masonry building segment and analysis of the heat saving potential by 1d, 2d, and 3d simulation.

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Abstract

When considering interior insulation of historic, multi-story buildings with solid masonry walls, it is important to focus on two important factors: How big is the building segment to which it can be applied, and what is the significance of how the multi-dimensional geometry of these façade walls is considered in the assessment of the heat saving potential.

The findings show that a large proportion of Danish multi-storey dwellings with solid masonry walls, high energy consumption, and uniform characteristics were found to originate from the period 1851 – 1930. This segment accounts for 25 % of all multi-storey apartments in Denmark. It was investigated, which relative reduction of the average thermal transmittance could be obtained by interior insulation when simulated in different dimensions, degrees of insulation and thickness. The analysis showed that partial insulation of the spandrels below windows on the 2nd/3rd highest storeys accounted for up to 40 % of the average thermal transmittance reduction achievable by fully insulating inside walls, while covering 17 % of the space needed in the full insulation strategy. Furthermore, the analysis showed an underestimation of average thermal transmittance by 2-dimensional compared to 3-dimensional simulation by up to 57 %, indicating that 3-dimensional analysis is needed to obtain realistic results.

Keywords: multi-storey; segment; saving potential; historical; internal insulation; simulation; multi-dimensional.

Highlights:

- 60 % of Danish multi-storey buildings are historic with overall uniform traits.
- 1- and 2-dimensional simulation significantly overestimates heat saving potential.
- Historic multi-storey dwellings have limited surface area for interior insulation.
- A correlation exists between window width and apartment area/thermal envelope.
- Large heat savings can be obtained from only internally insulating spandrels.

1 Introduction

The Danish government has a vision of becoming fossil fuel free by year 2050. Numbers from the Danish Energy Agency [1] estimated that the climate adjusted energy consumption in multi-family households in Denmark in 2013 accounted for 13.87 TWh. Compared to a total energy consumption of 168.61 TWh in Denmark, multi-family housing accounted for 8.2 % of the total energy use. The distribution was the same when focusing on the energy used for heat consumption and domestic hot water, where multi-storey housing accounted for 8.3 % of the consumption with 11.35 TWh compared to a total of 137.40 TWh.

With today's focus on reducing energy consumption, Danish multi-storey buildings with solid masonry walls receive increasing attention due to their large potential for energy conservation and consequent reduction of CO_2 emissions [2,3]. Multi-storey buildings have previously been studied extensively [4,5], and it was found that a great part of the buildings with solid masonry walls were typically built in the period 1850-1930, and to some degree in the period 1930-1950. Multi-storey buildings from 1850-1930 and 1930-1950 have a high energy consumption for space heating and domestic hot water of approximately 155 kWh/m², which could potentially be reduced to approximately 60 kWh/m², which is almost the level required for rather new buildings built according to the Danish Building Regulations 2010 [3]. In a later work [2] the space heating and domestic hot water demands for buildings from the same period was calculated to be 150 kWh/m². Total energy consumption, for all multi-storey building from the periods 1851-1930 and 1931-1950, was calculated to be 4.35 TWh/year and 2.35 TWh/year respectively, corresponding to approximately 3.2 % and 1.7 % of the total energy used for space heating and domestic hot water in Denmark. When comparing with the specific energy used for space heating and domestic hot water in all multi-storey buildings, the energy use of buildings from these periods corresponds to 38.3 % and 20.7 % respectively.

Heat loss is one aspect accounting for a large part of the total energy consumption for multi-storey dwellings from the period 1850-1930. The heat loss can be simplified to a vertical component through roof and ground, and a horizontal component through the façade, including the gables, when exposed. There has previously been a focus on the façade, showing that considerable energy savings can be achieved by applying thermal insulation to the facades [6,7]. The best solution from a building physics point of view is to insulate the exterior surface of existing buildings [8,9]. Exterior insulation is, however, rarely suitable for buildings from the segment, as most are to some degree worthy of preservation. The lowest Danish preservation class is "worth-to-preserve", where the preservation of original architectural features of the exterior facade is mandatory. External insulation is therefore not included in the present paper. In the segment of "worth-to-preserve" buildings, occupants are able to obtain indoor climate and comfort levels that meet modern standards by means of interior insulation. However, interior insulation approaches have a range of disadvantages that must be acknowledged: 1) Thermal bridges cannot be eliminated; 2) Reduction of the indoor space; 3) Alteration of interior expression; 4) Risk of increased moisture content in the materials [10–13]; 5) The temperature in the original wall drops severely [12,14].

To support the intention of the government to reduce energy, and to obtain deeper knowledge on these building segments, the present paper identifies the number and distribution of multi-storey buildings and apartments in Denmark from the period 1850 to 1950 and describes the architectural and structural features they have in common. A minor study of typical building characteristics and country-wide segment size was performed in [15]. The aim of the present paper is to focus on a regional segment analysis in Denmark, and to perform a further clarification of building characteristics. This clarification of segment size and regional placement in Denmark can serve as a basis for development of general energy reduction strategies that could apply to buildings from the period, with possible large-scale application to reduce energy consumption.

Previous research has focused on how to install interior insulation in old masonry constructions [6,16–19], but it did not clarify the degree to which thermal bridges, such as floor structure and geometry around windows, would influence the resulting efficiency of the interior insulation. Thermal bridges do not influence the construction when it is considered from a 1-dimensional point of view, but will have an increasing influence when 2- and 3-dimensional aspects are taken into account. The present paper determines the influence of typical thermal bridges that are found in these segments on the efficiency of different interior insulation methods when modelled in 2 and 3 dimensions.

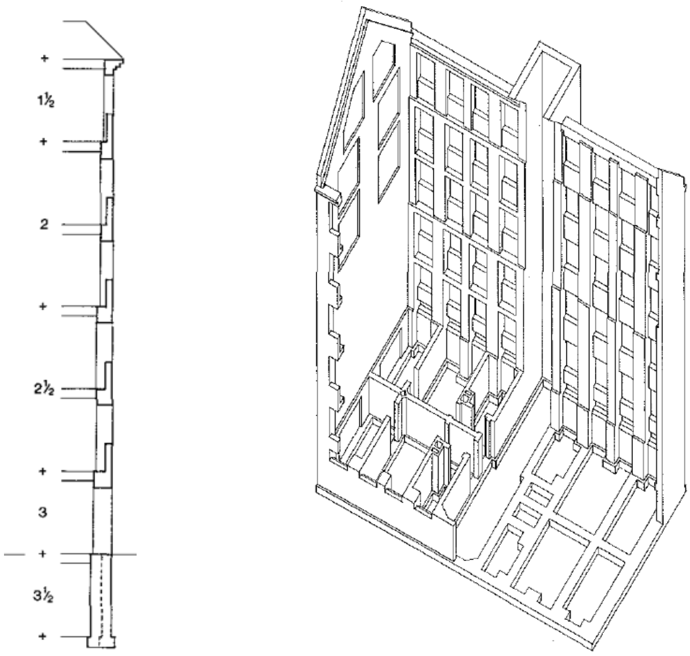
2 The traditional Danish multi-storey housing, year 1850-1930

The following section comprises a literature study into the compositions and characteristics of historical multi-storey buildings in Denmark built in the pre-war period before the Second World War. The building style of this building segment has been extensively researched and documented in Danish by J. Engelmark [4,5], who has provided detailed documentation about the composition of this type of buildings.

The first building code in Denmark took effect in 1856 [5,20]. This collection of regulations was ground breaking, due to clear formulations covering construction details and choice of materials and thought through in such a manner that the general dimensions and construction techniques did not change until the 1930's, when a new building code was passed. The buildings from the period 1850-1950 were generally built after the same strict principles because of this building legislation, gradually changing to more modern building methods through the last 20 years of the period. This change of methods that was introduced with the new building code in 1930, included the use of cavity walls, and concrete and steel as building materials [5]. The building geometries however generally followed the same principles as in the earlier period. Initially, the legislation applied to construction in Copenhagen, but the regional boroughs of Denmark quickly adopted the regulations.

The general working procedure in the period was that architects designed the multi-storey buildings, usually cutting margins to the limit permitted by the regulations, based on short handbooks. Engineers were rarely involved in the design of standard multi-storey building, and then only if special details were needed. Due to this custom, the majority of buildings from the period were constructed with the same general characteristics.

The buildings were typically made with facades of brick, with or without render, and with some wooden members, e.g. as supports of the floor beams. The floor decks were constructed with wooden beams between the façades, with wooden floorboards on top, clay pugging placed on wooden pugging boards between the beams and wooden furring strips below as underlay for a rendered ceiling. One important parameter, which was defined in the building code, was the composition of the façade, including the minimum thickness of load bearing wall columns and the dimensions of spandrels under windows. Danish masonry is constructed after modular dimensions revolving around brick dimensions (228 x 108 x 54) mm with mortar joints in the horizontal direction of 12 mm and in the vertical direction of (3 bricks + 3 mortar layers) = 200 mm. The thickness of the wall columns varied within the building and was defined as shown in Figure 1(a), with 1½ bricks' thickness (348mm) at the highest floor, increasing downwards as illustrated in the figure. Windows were placed between the wall columns, and spandrels completed the façade in the areas between the windows and the floor decks. The spandrels are of special interest in this study, since they were always 1 brick thick (228 mm) regardless of the floor number, and thus constitute the thinnest part of the façade. The wall above the window had a thickness corresponding to the column size at the given floor. The building code stated a maximum permissible degree of penetration of the facade for windows and doors to be 2/3's of the surface in the horizontal direction and 1/2 of the surface in the vertical direction. This maximum allowance was aimed for when designing buildings to yield the highest floor space and lowest material use, which thereby resulted in very perforated facades. Figure 1(b) shows the outer shell of a typical construction from the time, with the maximum allowed degree of penetration and minimum size of column and spandrel. The only place where large undisturbed wall areas were present was in the gables, but the gables were generally shared with the next building, and thus not exposed to the exterior. The heat loss of the gable wall was therefore negligible.



(b)

(a)

Figure 1 (a) Thickness of wall columns in bricks (~0.24 m per brick). (b) Maximum penetration of outer leaf. Both illustrated in courtesy of J. Engelmark, extracts from Danish literature [4].

3 Method, segment size, floorplans and heat flux models

The investigation took place in three parts. The amount and national distribution of relevant buildings and apartments were documented, using a major database managed by the Danish Government [21]. The previously described characteristic building design was investigated based on a range of randomly selected floor plans. A theoretical thermal simulation study was performed, which focused on the possible areas for application of interior insulation in single apartments, using assumptions based on the construction legislation that had been in force and validated in the floor plan analysis.

3.1 Investigation of segment size

To discover the segment size and nationwide distribution, data for this paper were collected from the national Danish Building and Dwelling Register, shortened "BBR". The register was administered at a governmental/ministry level, and contained information on all buildings in Denmark [21].

The BBR register was used to investigate the segment size of typical old multi-storey dwellings in Denmark. The raw data from the BBR were sorted according to different criteria to remove irrelevant apartment areas and to quantify the size of the segment at the national, regional and local scale. The data were initially prepared by:

- Including only buildings containing multi-storey apartments.
- Including only non-demolished buildings.
- In some buildings, the original attic and basement rooms have been converted into apartments. These areas have been removed from the dataset, as focus is on the original apartments.

The data were then further categorised as described in the following subsections.

3.1.1 Construction year

The data were sorted after three different ranges of construction year, where the first two were defined according to when shifts in prevailing building style/characteristics had taken place, shifts which have previously been identified in literature [2,3,5]. The third sorting mechanism included all construction years in the database, acting as a point of reference, for illustrating the size of the first two segments, compared to all current multi-storey dwellings in Denmark.

The definitions used in this paper are the following:

- 1851 to 1930: Solid walls.
- 1931 to 1950: Introduction of cavity walls and new materials: concrete and steel.
- $-\infty$ to January 25, 2017: Point of reference, all units in register.

3.1.2 Storeys in building

The definition of multi-story houses in the register were households split vertically. To exclude minor town houses, the investigation was limited to multi-storey buildings with a minimum of 3 storeys.

3.1.3 Regional location

Denmark was at the time of the analysis divided into 98 municipalities with unique municipality ID-numbers, distributed over 5 regions. Neither the municipalities nor the regions were equivalent in size or population. Municipalities with high density of multi-storey buildings in the period 1851-1930 were extracted from the regional summations and documented separately. An illustration of the regional division and separate municipality values can be seen in Figure 5.

3.1.4 Facade composition

For the 1851 – 1930 and 1931-1950 periods, only buildings with brick façade were included in the datasets. The point-of-reference dataset described in Section 3.1.1 comprises all registered units with all façade types.

3.1.5 Decomposition into individual apartments/buildings

In the dataset, all apartments and buildings had unique ID numbers. The data were decomposed by isolating unique apartment/building ID.

3.2 Investigation of actual façade composition from floorplans

A range of floorplans from different parts of Copenhagen were analysed to see if a correlation between different parameters existed. The following parameters were registered for each individual apartment: Amount of rooms, amount and width of windows, apartment area including walls, length of thermal envelope and length of gable.

43 apartments divided over 9 buildings were analysed. The buildings had the following construction years: 1874, 1886, 1886, 1880, 1890, 1892, 1897, 1904, 1914, 1920. One of the buildings included a mansion apartment.

There were two purposes of the floorplan investigation:

1. To validate the characteristics of the traditional Danish multi-storey housing.
2. To identify a possible correlation between the segment size investigation in Section 3.1 and the total amount/width of windows in the Danish multi-storey building stock from the relevant period.

3.3 Thermal heat flux models, based on Danish construction legislation and different insulation strategies

A 3-dimensional model [22], representing the characteristic geometry of a façade element from the 1850-1930 period, as illustrated in Figure 1(b), was set up in the simulation software COMSOL Multiphysics [23]. The model was used to perform a thermal investigation and to calculate the relative reduction in average thermal transmittance (U-value) for the masonry part of the model, achieved by applying interior insulation that varied in extent and thickness. The model consisted of a wall section, with vertical delimitation in the middle of columns on the left and right side of an spandrel. The horizontal delimitation was underneath the wooden pugging board in the floor structure.

The 1-dimensional model was defined as a point in the 1-brick spandrel consisting of bare brick towards the exterior and rendering on the interior side (total wall thickness 238 mm).

The 2-dimensional model was produced as a horizontal cross section of the 3-dimensional model to ensure cohesion. The model was created at the level of the spandrel. Examples of the model can be seen in Figure 3(a, b).

The 3-dimensional model was made as a parametric model as illustrated in Figure 2. Examples of model variations can be seen in Figure 3(c,d,e,f). The models in this study were based on a wall column depth of 2 bricks (478 mm), corresponding to the traditional construction at the second and third floor from the top. The model has a resulting exterior masonry area of 3.83 m^2 after subtracting the window area. The vertical composition of the model is based on the illustration on page 84 of [5]. This construction has a total height of 2.985 m, consisting of an interior surface height of 2.75 m. The window has a height of 1.70 m, with 0.70 m of spandrel below and 0.35 m of interior wall above. The horizontal composition of the model was based on conversations with J. Engelmark, on his thesis [4] and on the floorplan investigation described in Section 3.2. The width of the construction consist of two half wall columns of 0.30 m on each side of 4½ bricks (1.092 m) of spandrel or window structure, resulting in a total width for one window sections of 1.692 m.

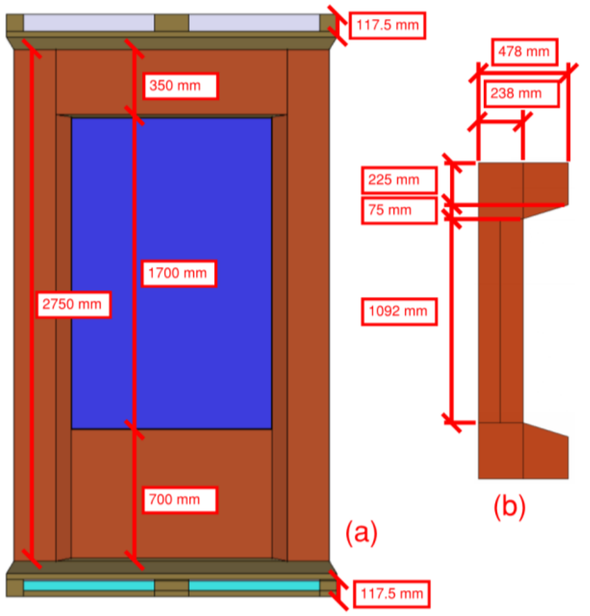


Figure 2 Dimensions of COMSOL model. (a) = vertical section of 3-dimensional model, (b) = 2-dimensional model. Horizontal dimensions of 2- and 3-dimensional model are identical.

The floor structure consisted of pugging, air, a 100 x 100 mm wooden beam in the middle and 2 50 x 100 mm wooden beams at right and left edge of the model. The beams embedded in masonry in the columns did not have any air surrounding them in the model as these areas have in practice become full of dust and dirt. The beam between the columns had air and pugging surrounding it, as the beam would be lying freely and not in direct contact with the wall.

1-, 2- and 3-dimensional models are abbreviated as “1d”, “2d” and “3d” in the graphs, tables and caption text in this paper.

The parametric 2- and 3-dimensional models include a wide range of different insulation strategies, as it can be seen in Figure 3. The models are abbreviated in graphs, tables and caption text with the following words: Spandrel, sides, front. The abbreviations have the following meaning:

- Spandrel: Insulation placed in front of the spandrel. Can be seen in Figure 3(a,b,c,f).
- Sides: Insulation placed on the slant side of the columns. Has a maximum thickness of 15 mm. Can be seen in Figure 3(b,d,f).
- Front: Insulation placed at the front of the column and at the wall area above the window. Can be seen in Figure 3(b,e,f).

The masonry area within the floor structure was left uninsulated in the models, as this area is rarely opened and insulated when performing refurbishment of multi-storey buildings in Denmark.

The thermal conductivity values of the materials in the model were mainly obtained from the Delphin material database [24,25]: Masonry (brick + mortar), λ=0.8 W/(m·K), shown in red in the models; Thermal insulation, λ=0.045 W/(m·K), shown in yellow in the models; Wood (longitudinal), λ=0.194 W/(m·K), shown in brown in the models; Sandy clay, used as pugging, λ=1.76 W/(m·K), shown in cyan in models.

The properties of air was defined in COMSOL Multiphysics [23]. The heat transfer through the air was thereby not limited to conduction, but also included radiation and convection, depending on the dimensions of the object. Air was coloured grey in models.

The window is shown in dark blue in the models, with a defined frame thickness of 115 mm. The resulting heat loss through the window was subtracted from the results, as focus was on the potential average reduction in thermal transmittance of the masonry part of the total external wall area.

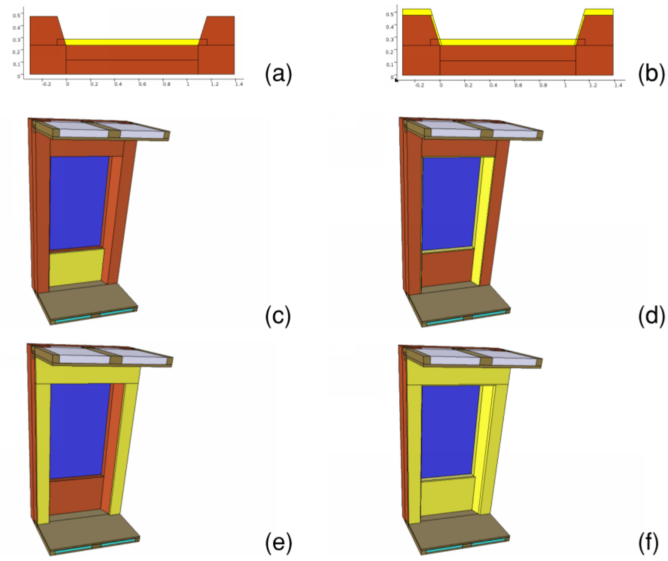


Figure 3 Examples of the models used in the simulations [22]. The text describes simulation dimension and placement of insulation as presented in Section 3.3: (a) 2d, spandrel. (b) 2d, spandrel, sides, front. (c) 3d, spandrel. (d) 3d, sides. (e) 3d, front. (f) 3d, spandrel, sides, front.

4 Results

4.1 Segment analysis through the Buildings and Dwellings Register

The Danish Building and Dwelling Register [21] was used to evaluate the number of multi-storey buildings in Denmark. All results have been based on data extracted on January 25, 2017.

A segmented illustration of the total number of apartment units in Denmark, not situated on basement or attic level, is shown in Figure 4, illustrating the large number of apartment units in Denmark with construction year in the period 1851-1930, and 1931-1950, compared to other periods. The apartment units are grouped according to construction year along the x-axis, storeys along the y-axis and the number of apartments within the respective groups on the z-axis.

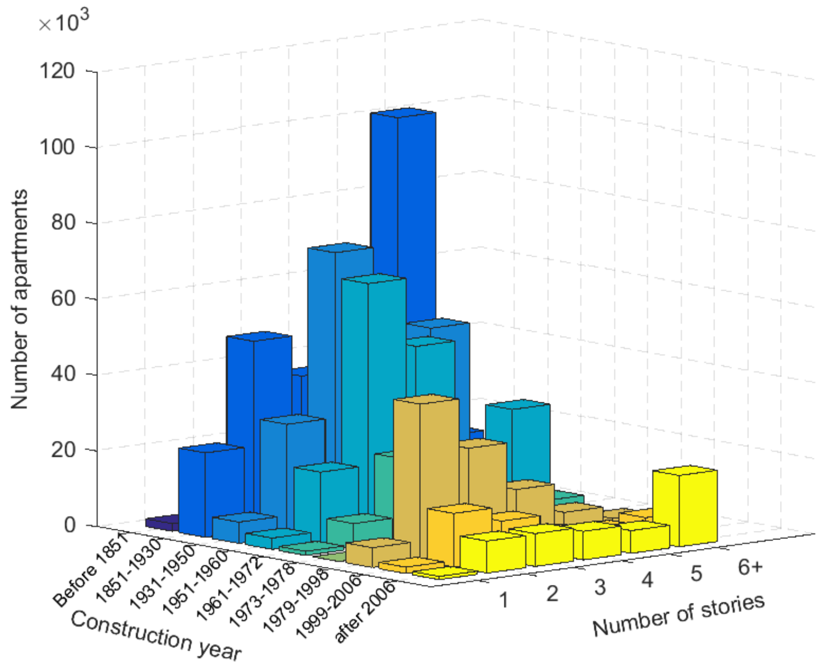


Figure 4 Apartment units, sorted after construction year and number of storeys. The time steps represent shifts in building style, inspired by Wittchen & Engelmark [2,5].

The data on which Figure 4 is based can be seen in Table 1 for the periods 1851-1930 and 1931-1950, with additional information regarding the number of individual buildings in the described periods. The numbers in the larger period -∞ until data extraction in Table 1 serve as a reference number, for illustrating the share of multi-storey buildings/apartments which origin from the earlier periods.

Sorting criteria	Period	Unique	3 storeys	4 storeys	5 storeys	6+ storeys	Sum
Brick façade	1851 to 1930	Buildings	5,962	2,994	5,381	640	14,977
		Apartments	38,961	31,118	103,414	18,004	191,497
Brick façade	1931 to 1950	Buildings	4,177	1,123	1,412	172	6,884
		Apartments	72,821	22,984	49,427	10,110	155,342
All façade types	- ∞ to	Buildings	18,836	7,534	8,044	2,004	36,418
	2016.11.28	Apartments	299,175	159,593	196,572	105,725	761,065

Table 1 Segment analysis, number of multi-storey buildings and apartments.

The number of apartments with construction period 1851-1930 in Table 1 were further analysed according to the regional location. This data were plotted on a map of Denmark in Figure 5(a). The map shows the regional borders with orange lines, including the number of apartment units in the regions outside the abstracted cities with orange text in unframed boxes. The number of apartment units in the abstracted cities are shown in red framed boxes connected to the red dot illustrating the location of the individual cities. A similar figure for the later period 1931-1950 can be seen in Figure 5(b).

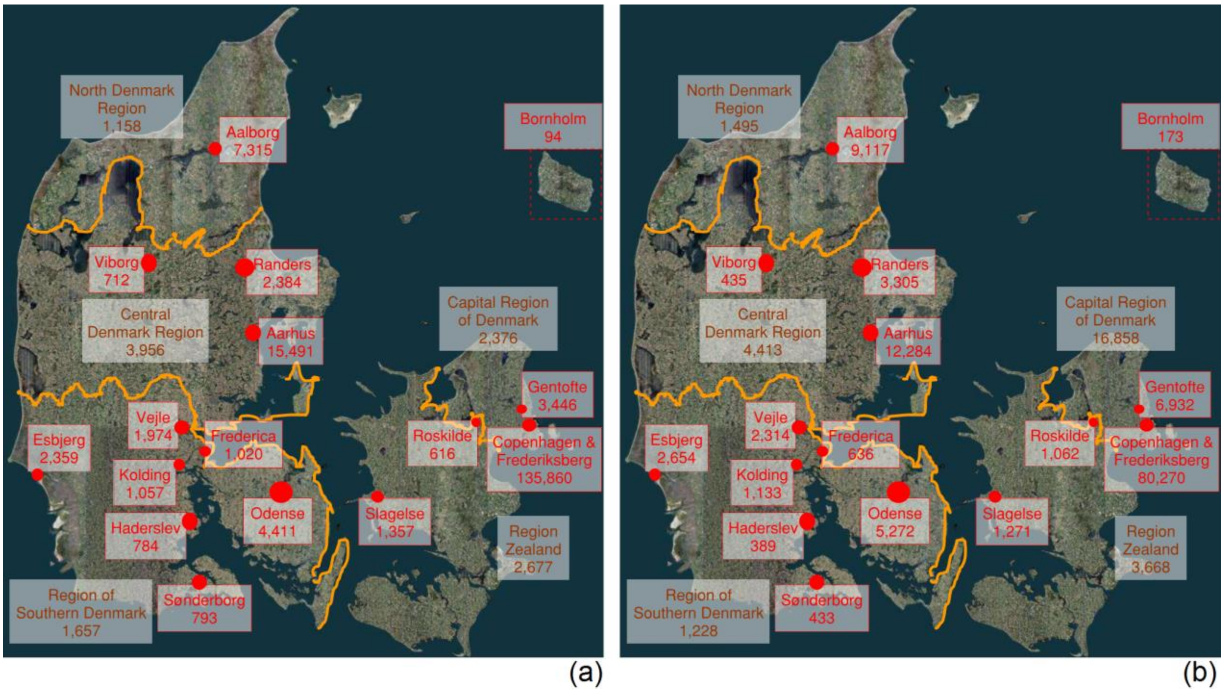


Figure 5 Brick facade, multi-storey apartments>2 storeys. Periods: (a) = 1851-1930, (b) = 1931-1950.

4.2 Façade investigation based on 43 floorplans

Each window was analysed and the results can be seen in Figure 6. In this figure, it can be seen that the most registered window width is 1.1 m, and that windows with widths of 1.0, 1.1 and 1.2 meter make up 50 % of all registered windows.

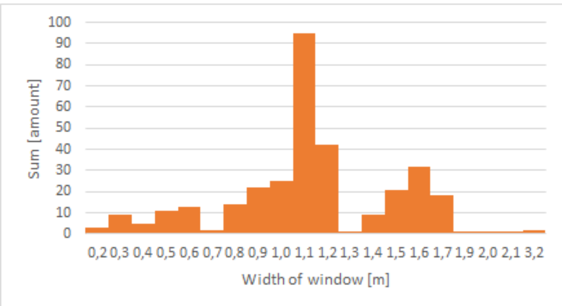


Figure 6 All registered window widths from floorplan investigation.

The window width is summed up for each apartment, with windows shared between apartments, e.g. due to shared staircases, being divided with 50 % width to each apartment. The apartment's total width of windows is then compared to the total width of thermal envelope, excluding gable walls, in Figure 7, and the apartment area, including walls, in Figure 8. The gable wall had to be removed from the apartment's thermal envelope in all cases. Amount of windows and amount of rooms showed no clear correlation with other registered parameters.

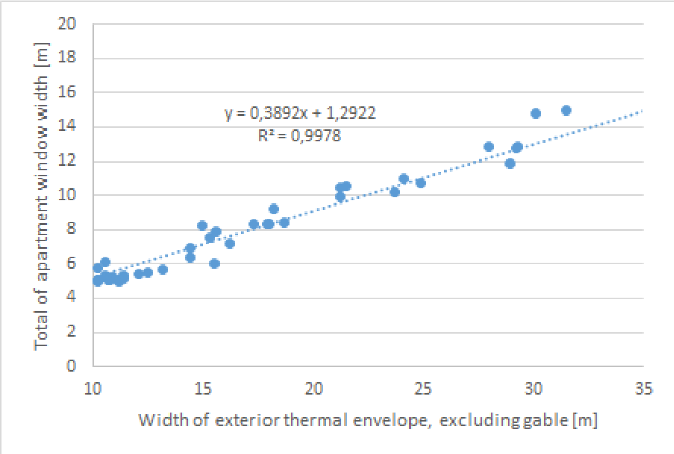


Figure 7 Total window width and width of exterior thermal envelope for apartments from floorplan investigation. One mansion apartment is situated outside the axis, with coordinates (241.2, 94.8).

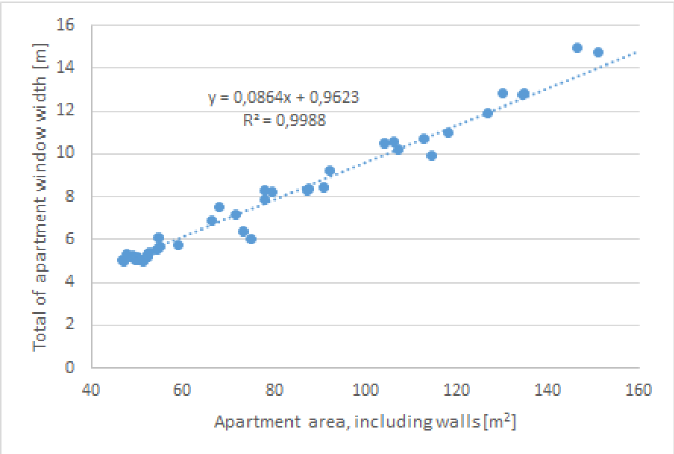


Figure 8 Sum of window width and apartment area from floorplan investigation. One mansion apartment is situated outside the axis, with coordinates (1089, 94.8).

4.3 Heat loss investigation of interior insulation of a typical façade

The output of the simulated 1-, 2- and 3-dimensional models presented in Section 3.3 resulted in a range of specific heat flow rates for each combination of insulation degree/thickness as can be seen in Figure 9. The influence of the window has been subtracted, and the result has been divided by the exterior masonry area to obtain the average thermal transmittance of the masonry part of the wall. The calculated relative reductions can be seen in Figure 10, defined as the difference between the average thermal transmittance of the uninsulated model, compared to the average thermal transmittance of the increasing insulation thickness. The output of the simulations in Figure 9 and Figure 10 show results with different geometrical dimension and degrees of insulation coverage.

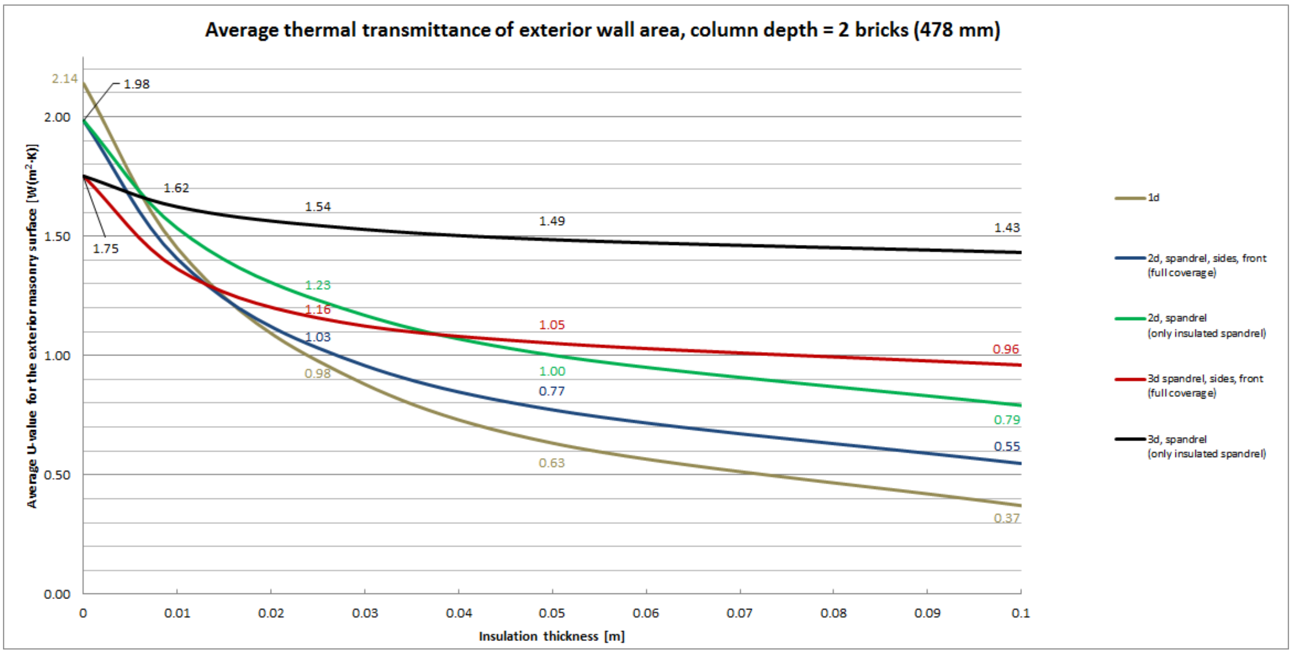


Figure 9 Exterior surface average thermal transmittance as a function of insulation thickness: 10, 25, 50 and 100 mm. Focus on geometrical dimensions and insulation coverage. Abbreviations have been described in depth in Section 3.3.

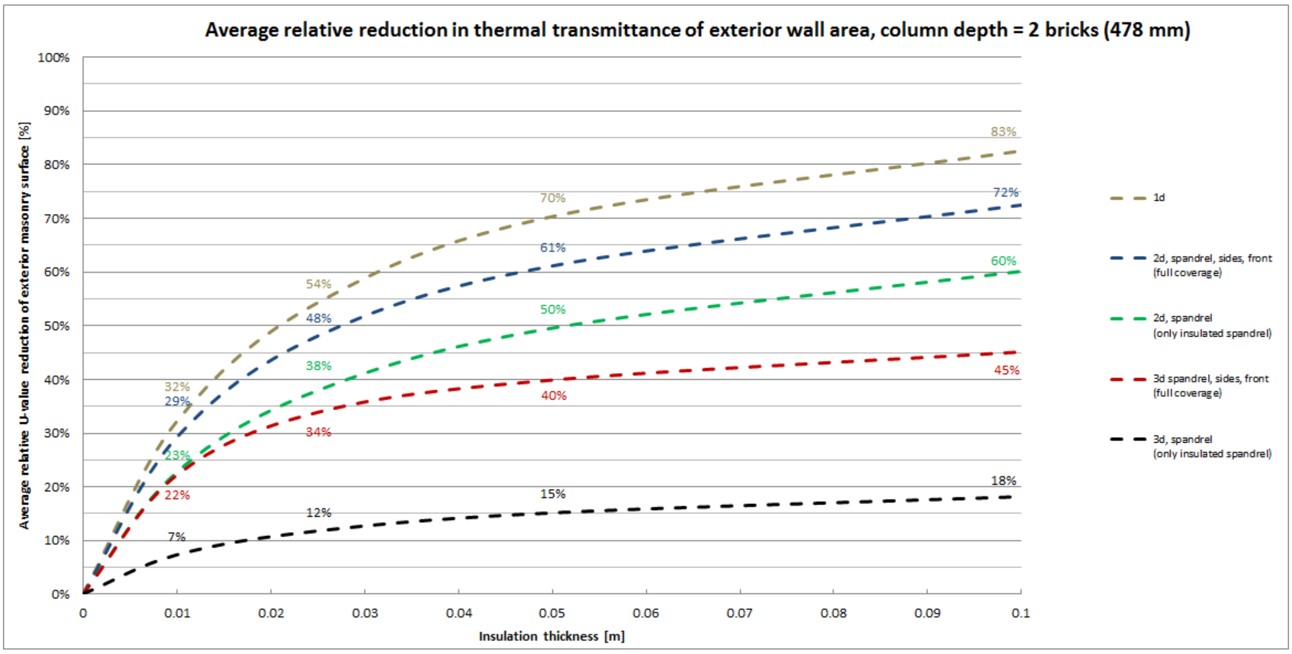


Figure 10 Relative reduction in thermal transmittance compared to the uninsulated wall as a function of insulation thickness: 10, 25, 50 and 100 mm. Focus on geometrical dimensions and insulation coverage. Abbreviations have been described in depth in Section 3.3.

5 Discussion

5.1 Segment size

As it can be seen graphically in Figure 4, a large proportion of the Danish multi-storey apartments were constructed in the period 1851-1930 and 1931-1950. Table 1 shows the specific numbers of multi-storey dwellings with more than 2 storeys constructed within these periods. The ratio of the number of apartments from the two periods, compared to all currently existing multi-storey apartments, was calculated to illustrate the significant relative size of these segments for the country of Denmark: 25 % of the current apartments in multi-storey buildings and 41 % of the multi-storey buildings were constructed in the period 1851-1930. For the period 1931-1950, the equivalent numbers were 20 % and 19 %, respectively. It can thereby be concluded that 46 % of the apartments and 60 % of the buildings in the current Danish multi-storey dwelling stock higher than 2 storeys consist of buildings constructed in the period 1851-1950 with brick facades and overall uniform characteristics.

It can be seen from Figure 5(a) that most of the dwellings constructed in the years 1851-1930 are situated in the larger cities of Denmark: Copenhagen & Frederiksberg; Aarhus; Aalborg; Odense; and Gentofte. The Danish capital, Copenhagen and Frederiksberg, accounted for the largest proportion of all, with 71 % of the apartment units accounted for in the figure.

The latter period, 1931-1950, was summarised in Figure 5(b). The numbers from this period had a distribution of apartments quite similar to the earlier and much longer period. The largest difference can be seen in the Capital Region of Denmark. In this region, it is clear that the smaller municipalities surrounding Copenhagen/Frederiksberg experienced a large increase in units constructed. While Copenhagen/Frederiksberg accounted for a lower proportion of the total amount of apartment units in the latter period (52 %), the large increase in the surrounding municipalities meant that the Capital Region of Denmark still contained 67 % of the total number of apartments in the period. The ratio in the earlier period was 74 %.

5.2 Actual façade composition

As it can be seen in Figure 7, there is an almost linear relationship between the width of the exterior thermal envelope of individual apartments, excluding gables, and the total of their window widths. The linear trend line has a coefficient of determination of R^2=0.9978, over the range from 10.2 to 241.2 ms of thermal envelope. The distribution between windows and masonry in the horizontal direction was further calculated and visualised in Figure 11. A box plot of the results including information on the quartiles can be seen in Figure 12.

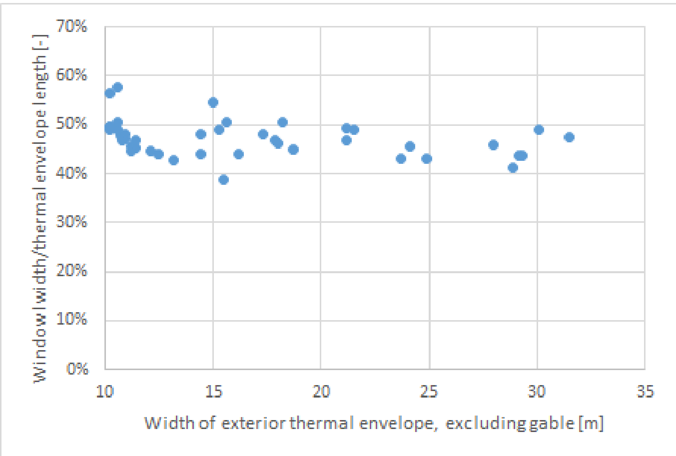


Figure 11 Scatter plot of window/thermal envelope ratio from floorplan investigation. One mansion apartment is situated outside the axis, with coordinates (241.2, 39.3).

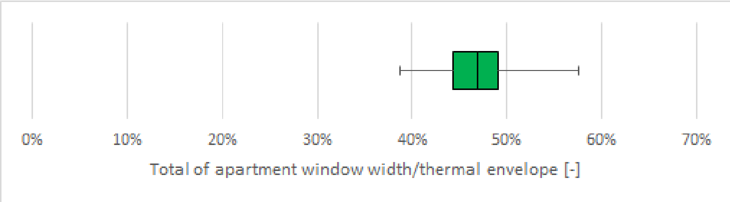


Figure 12 Box plot of window/thermal envelope ratio from floorplan investigation. *25 % quartile = 44.4 %, median = 46.9 %, 75 % quartile = 49.0 %.*

The found 25 % quartile of 44.4 % windows/thermal envelope in Figure 12 was used to locate a floorplan with similar window/thermal envelope distribution. One that had a window/thermal envelope ratio of 43.0 % was found, and details from the floorplan, where interior insulation was not directly applicable, were marked on a Google Street view picture of the façade. This picture can be seen in Figure 13. The yellow hatches mark windows, the red hatches show the position of solid interior walls separating fire cells from neighbouring apartments/staircases, the blue hatches show the position of interior walls, which could be either timber or solid masonry walls, and the green hatches indicate the position of the floor structure. The 43.0 % ratio were below the 25 % quartile of the box plot in Figure 12, illustrating that the possible areas for application of interior insulation are limited. The figure shows the same characteristics as Figure 1(b), illustrating the high degree of penetration of the façade and the very limited areas available for the application of interior insulation, with surrounding thermal bridges consisting of floor structure and occasional interior walls. It is possible to insulate the floor structure between the wooden beams and the ceiling/floor boards, but this is typically not done in Denmark as it greatly increases the cost of the refurbishment.

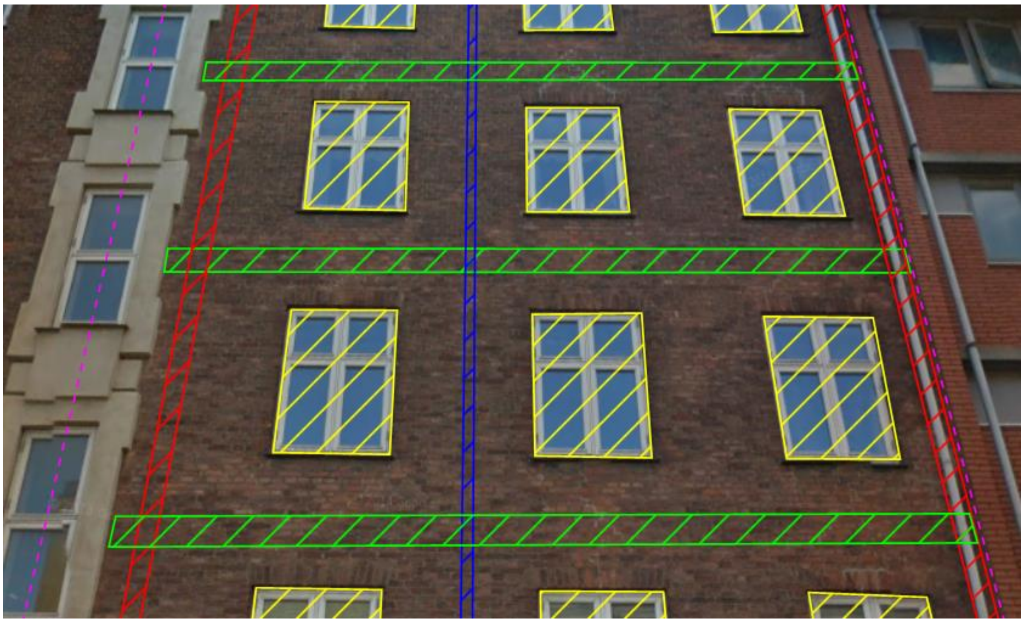


Figure 13 Exterior surface of a 1927 multi-storey building with a window/thermal envelope ratio of 43.0 % within the pink dashed lines. Hatches were defined as follows: Yellow = windows, blue = light interior walls, red = solid/fire walls, green = floor structure. Hatches were based on actual floorplan (Original photo by Google street view).

The floorplan investigation further showed an almost linear correlation between the summed window width and apartment areas in Figure 8. The linear trend tendency line had a coefficient of determination of R^2=0.9988, over the range from 46.7 to 1089.9 m² apartment area. The width of window per floor area was calculated and visualised in Figure 14. A box plot of the results including info on the quartiles may be seen in Figure 15.

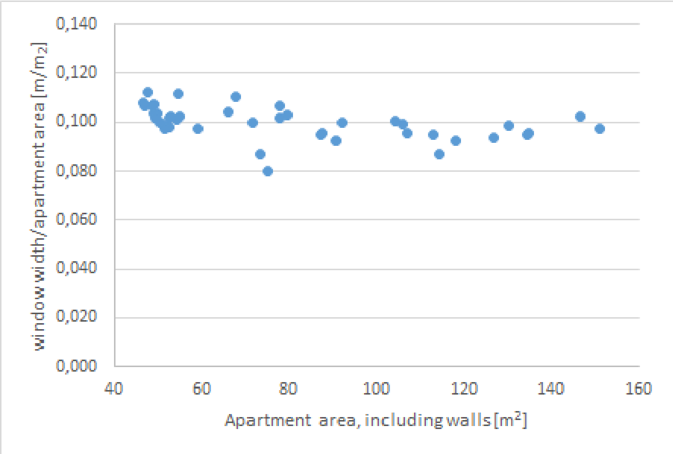


Figure 14 Scatter plot of window width/apartment area ratio. One mansion apartment is situated outside the axis, with coordinates (1089, 0.087).

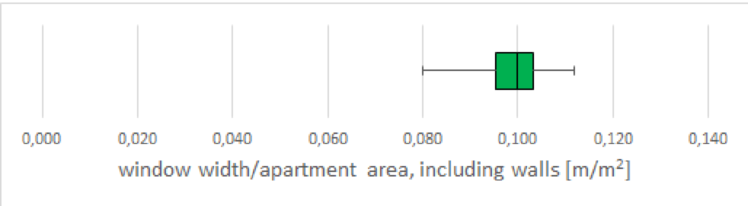


Figure 15 Box plot of window width/apartment area ratio. 25 % quartile = 9.5 %, median = 10.0 %, 75 % quartile = 10.3 %.

5.3 Average thermal transmittance and relative reduction potential for interior insulation applied to characteristic facades

The COMSOL models described in Section 3.3 were used to evaluate the resulting average thermal transmittance in Figure 9 and corresponding relative reduction in thermal transmittance in Figure 10 by application of different degrees of insulation. A 1-dimensional model, illustrating the theoretical reduction in thermal transmittance of the thin spandrel with increasing insulation, is shown as a reference in Figure 9 and Figure 10. As it can be seen Figure 1(b), the buildings from the period 1850-1930 has a high geometric complexity, and as a result thereof, 1-dimensional conditions for assessment of heat transmission through the walls are rarely present in practice.

The 2- and 3-dimensional models were evaluated based on different insulation strategies, presented in Section 4.2 and illustrated in Figure 3. As it can be seen in Figure 9 and Figure 10, there was a large difference between simulating the construction in 1d, 2d or 3d. While the 3d model with 100 mm with full insulation coverage of spandrels, sides and front resulted in a 45 % relative reduction in average thermal transmittance. The corresponding 2d and 1d model resulted in 72 % and 83 % respectively. The difference between the average thermal transmittances in 2d and 3d were calculated and may be seen in Table 2. This table indicated that 2d simulation overestimated the constructions average thermal transmittance in the un-insulated case, but underestimated the average thermal transmittance by 55-57 % with 100mm insulation.

	Insulation thickness [mm]				
	0	10	25	50	100
spandrel	113 %	94 %	80 %	67 %	55 %
spandrel, sides, front	113 %	103 %	89 %	73 %	57 %

Table 2 Difference in average thermal transmittance from simulating with 2d instead of 3d. Values under 100 % means higher average thermal transmittance for 3d.

Another result that could be seen from Figure 9 was the potential reduction from insulating only the spandrel, compared to full coverage of spandrel, sides and front. The reduction illustrated in Table 3, showed that for the 3d case, 33-40 % of the obtainable reduction in thermal transmittance through the fully covering insulation strategy could be obtained by the cheaper and less complex insulating strategy of only insulating the thin spandrel under the window. To illustrate why the reduced spandrel insulation is cheaper and less complex, a simple measurement of area was performed. In the model, the spandrel insulation has an extent of 0.77 m^2, while the fully covering spandrel, sides, front insulation strategy has an extent of 4.65 m^2. This means the extent of the spandrel insulation is 17 % of that of the fully covering spandrel, sides and front insulation strategy.

A similar calculation were done for the 2d simulation in Table 3, showing that 78-83 % of the relative reduction in thermal transmittance from a fully covering insulation strategy on spandrel, sides and front could be achieved by only insulating the spandrel. Even though the heat flow through the window was excluded from the results, the heat flow that was affected by the geometry of the wall around the window yielded a significant increase.

Based on the large variation between 1d, 2d and 3d simulation in Table 2 and Table 3, it was concluded that 3-dimensional analysis was needed to obtain realistic results.

	Physics/savings/extent of insulation system	Unit	Insulation thickness [mm] 0	10	25	50	100
2-dimensional model	U-value: Spandrel, sides, front	$\left[\frac{W}{m^2K}\right]$	1.98	1.40	1.03	0.77	0.55
	Reduction by ins.: Spandrel, sides, front	$\left[\frac{W}{m^2K}\right]$	-	0.58	0.95	1.21	1.44
	U-value: Spandrel	$\left[\frac{W}{m^2K}\right]$	1.98	1.53	1.23	1.00	0.79
	Reduction by ins.: Spandrel	$\left[\frac{W}{m^2K}\right]$	-	0.45	0.75	0.98	1.19
	Achieved by spandrel vs. full insulation		**-**	**78 %**	**79 %**	**81 %**	**83 %**
3-dimensional model	U-value: Spandrel, sides, front	$\left[\frac{W}{m^2K}\right]$	1.75	1.36	1.16	1.05	0.96
	Reduction by ins.: Spandrel, sides, front	$\left[\frac{W}{m^2K}\right]$	-	0.39	0.59	0.70	0.79
	U-value: Spandrel	$\left[\frac{W}{m^2K}\right]$	1.75	1.62	1.54	1.49	1.43
	Reduction by ins.: Spandrel	$\left[\frac{W}{m^2K}\right]$	-	0.13	0.21	0.27	0.32
	Achieved by spandrel vs. full insulation		**-**	**33 %**	**35 %**	**38 %**	**40 %**

Table 3 Thermal transmittance of the different COMSOL models, the reduction from insulation and the possible percentage achievable from insulating spandrel, compared to full coverage with spandrel, sides, front.

5.4 Recapitulation of segment size, floorplan investigation for façade composition and potential reduction in average thermal transmittance

The procedure of installing fully covering interior insulation has previously been shown to involve a high capital cost, technical problems due to the many fitting and fixtures, and occupational health problems due to disruption during the conversion [26]. Brannigan and Both deemed these problems, and the resulting reduced room size, prohibitive. A way to persuade occupants to install interior insulation could be the use of the less extensive and generally simpler partial insulation strategy, insulating only the spandrel. Installed on a large scale in the city of Copenhagen/Frederiksberg, where the segment have been shown in Section 4.1 & 5.1 to be large and to share many characteristics, the energy saving from this smaller intervention was found to offer a large potential energy saving for heating.

The following thermal conductance values for the masonry part of a window section were found by multiplying the found thermal transmittances in Figure 9 with the external masonry area of the model. The model of interest were a 3-dimensinal model with only spandrel insulation (illustrated in Figure 3(c)): uninsulated = 6.71 W/K, 100 mm of insulation = 5.49 W/K, savings = 1.22 W/K pr. window section. With 2726 mean degree days in a normal year in Denmark [27], this resulted in an energy saving of $3.33\,\frac{kWh}{windowsections \cdot year}$. The Danish method to calculate degree days is based on an indoor temperature of 17 °C, calculated when the mean outdoor temperature is below 10 °C in spring and 12 °C in autumn for 3 consecutive days. The BBR register was used to find the total floor space in multi-storey apartments over 2 storeys constructed in the period 1851-1930 in Copenhagen/Frederiksberg, being 11,400,000 m^2. The analysis of the 43 floorplans in Section 5.2 showed a median of 0.1 m window / m^2 apartment area, resulting in 1,140,000 m window. By adding the found distribution in Figure 6, the total amount of window sections in Copenhagen/Frederiksberg were calculated to be 1,206,000. The analysis yielded a final potential energy saving from insulating the spandrel in apartments constructed in 1851-1930 and located in Copenhagen/Frederiksberg:

$$Q_{save,parapet} = 3.33\,\frac{kWh}{windowsections \cdot year} \cdot 1{,}206{,}000\; windowsections = 4.02\,\frac{GWh}{year}.$$

This saving account for 0.1 % of the 4.35 TWh/year space heating and domestic hot water energy usage in all Danish multi-storey buildings from the period 1851-1930 [2].

The strategy of installing insulation on the spandrel could pose technical problems, as radiators are often placed in this location. An alternative could be the use of heat shields, which in earlier studies showed the ability to decrease the heat loss through the thin spandrel considerably [28].

6 Conclusion

The following bullets contain the main findings in present paper.

- The results of the segment analysis showed that 25 % apartments and 41 % buildings of the current Danish multi-storey building stock originates from the period 1851-1930. 71 % of those apartment units are situated in the Capital of Denmark.
- The results of the floorplan analysis showed a façade composition median of 47 % windows/thermal envelope ratio and a median of 0.1 m window width/m^2 apartment area.
- The thermal heat flow analysis showed:
    - 2 dimensional simulation underestimated the heat loss when applying interior insulation by up to 55-57 % with 100mm insulation, compared to 3 dimensional simulation.
        - 3-dimensional analysis is needed to obtain realistic results.
    - By only insulating the spandrels below the windows, 33-40 % of the effect from a full coverage insulation strategy could be achieved.
- Recapitulation of the three analyses showed an energy saving potential from insulating the spandrel of all multi-storey apartments over 2 storeys in Denmark of 4.02 GWh/year, correlating to 0.1 % of the space heating and domestic hot water energy usage in all Danish multi-storey buildings from the period 1851-1930.

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