Investigating the Impact of Renewing Floor Coverings on the Energy Performance of Dwellings with Suspended Timber Floors, Tested under Controlled Conditions

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Abstract: Dwellings with suspended timber floors are commonplace in the UK, making up almost a third of the overall housing stock. Floor coverings, such as carpets and vinyl, are often used in these types of dwellings to achieve thermal comfort, aesthetics and energy. Over time, due to general wear and tear, the quality and performance of floor coverings can deteriorate. This deterioration affects the overall performance of these coverings as a whole and so it becomes necessary to replace them. Developments in the production of floor coverings and underlay have resulted in the opportunity to replace floor coverings with more robust materials, which can demonstrate improved energy efficiency.

The Energy House at the University of Salford is a full-scale replica of a typical UK home (pre 1920's Victorian Terrace), contained within a controlled environment. This facility was originally fitted with a synthetic carpet and laminate on top of rubber-based underlay material. After 6 years of heavy use, all floor coverings within the house were replaced with new materials. Tests were conducted throughout the transition from old coverings to new, under steady state conditions; this included measurements of energy consumption, heat flux density, air tightness, and the global heat transfer coefficient.

The original floor coverings were found to improve the overall energy consumption by 2.7%, heat flux through the floor by 16.9%, air tightness by 3.3% and the global heat transfer coefficient by 3.0%.

By replacing the original coverings with new materials, the improvement to the overall energy consumption rose to 4.8%, heat flux rose to 27.1%, air tightness to 6.0% and the global heat transfer coefficient by 5.0%. Thus, it can be demonstrated that by replacing old floor coverings for this building type, the energy performance of those coverings can be almost doubled.

Keywords: Building Performance, Pre-1920 Housing, Thermal Performance, Suspended Timber Floors, Retrofit, Floor Coverings, and Controlled Environment

Introduction

The UK has made a formal commitment to reduce the level of CO_2 emissions by 80% when compared to 1990, by the year 2050 according to the Climate Change Act 2008 (DECC, 2008), a significant portion of the CO_2 emissions currently are generated from domestic energy usage currently around 30% (BEIS, 2017). This leaves the housing stock in the UK, the subject of many ambitions to reduce energy usage and this minimise CO_2 emissions.

Whilst many consider that fabric and services retrofitting combined with behaviour change are an important way of meeting these targets (Swan, Ruddock, Smith, & Fitton, 2013), there is another aspect of energy savings which has not been addressed thoroughly in the literature, in the area of soft furnishings which have been proven in the past to have a positive effect on the energy efficiency of a building, the author has recently proven this in a paper around curtains and blinds in domestic properties with reductions in energy loss in windows being reduced by between 5% and 29% (Fitton, Swan, Hughes, & Benjaber, 2017). These type of energy savings given their very nature can also have significant effects on not only the energy performance of a dwelling but the thermal comfort levels present (Baker, 2008; Fang, 2001; Mcneil, Bulletin, & Zealand, 2016).

This paper examines the energy savings offered by floor coverings and their installation technique under controlled conditions at a whole house scale. Existing floor covering materials – carpet and underlay in the majority of rooms and luxury vinyl tiles (LVT) with a timber base in the kitchen – were replaced with new carpets and underlay, and new LVT and a purpose made LVT underlay. Measurement under controlled conditions allowed for accurate measurements to be carried out with low uncertainty margins when compared to making these measurements in the field.

Mechanisms affected by carpets and underlays, conduction convection and radiation

The purpose of a floor covering can be many different things; to aid in thermal comfort (providing a barrier to a cold floor surface), to provide a comfortable surface for sitting and walking, and assist in the day to day cleaning of the property. This paper however is focussed entirely on the topic of the prevention of heat loss in a dwelling. Heat loss can happen through 3 mechanisms, conduction convection and radiation (Hens, 2012), we will examine only two aspects; thermal transmission through the floors (conduction) and infiltration related losses (convection).

Energy savings attributed to floor coverings are generally attributed to the following; Increase in the thermal resistance of the floor, any material added on the top of an unfinished floor will increase its resistance.

Increasing the airtightness of the dwelling itself will have the effect of minimising heat loss through warm air leaving the building though the floor structure and cold air entering. The process of re-fitting floor coverings to a high standard reduces the overall flow of warm air from the building by generating an air-tight seal around the boundary of the room. Figure 1 demonstrates such a fit using carpet grippers.

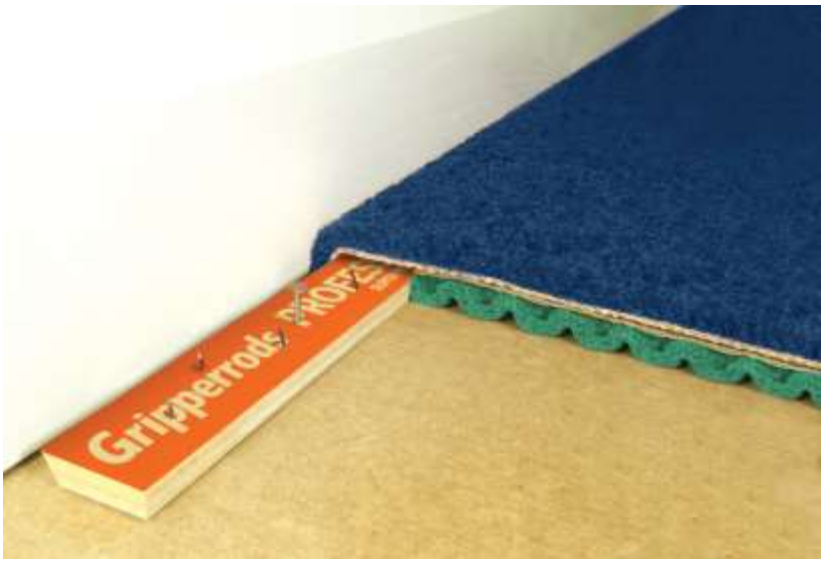

Figure 1. Underlay and carpet fitted using carpet grippers to form an air-tight seal around the edge of a room.

We will first examine the resistance of the element: The current way in the UK of defining the heat loss through a suspended timber floor is to use a U value, expressed in W/m^2K, this gives the rate of heat loss from the heated side of an element to the unheated side. This is calculated using U-value =1/Sum of total resistance.

This process can be found explored in much greater detail on papers related directly at measuring heat loss in floors (Pelsmakers et al., 2017), this paper takes simpler approach in the point values are measured for transmission performance rather than attempting to scale these results out across the entire floor. This is illustrated by Pelsmaker's findings which were the result of a very detailed measurement campaign also carried out on the floor in the Energy House (Pelsmakers et al., 2017). This revealed a large variance in U-values over the ground floor of the property, ranging from 0.56 to 1.18 W/m^{2}K, this is represented graphically in Figure 2 which shows the U values across the living room of the Energy House.

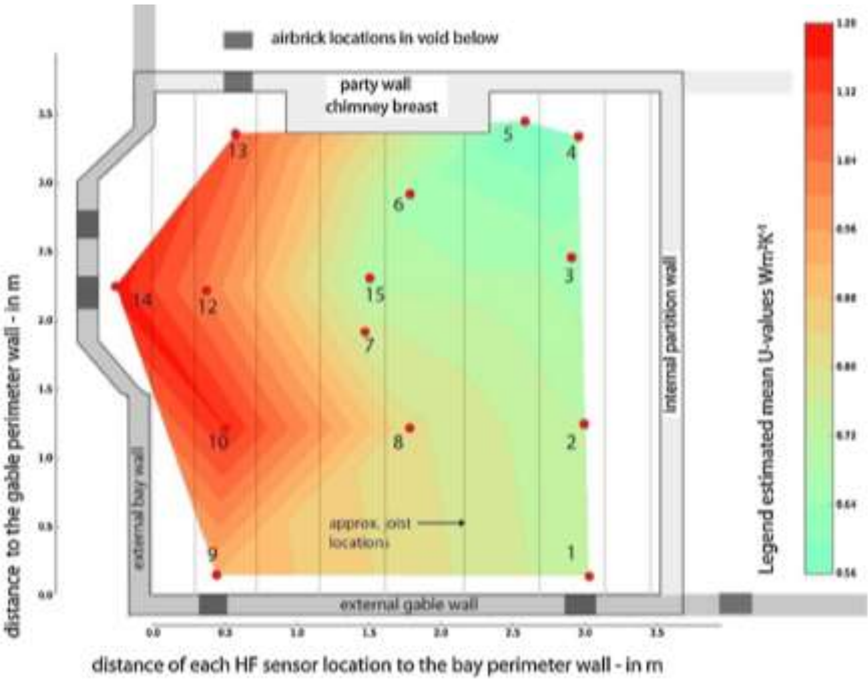

Figure 2. Linear interpolated U-values as a function of both bay (X-axis) and gable (Y-axis) wall distances. (Pelsmakers et al., 2017).

This is presented below in a theoretical calculation for a suspended floor with and without a floor covering:

U-value of floor construction:

Layer	d (mm)	λ layer	λ bridge	Fraction	R layer	R bridge	Description
					0.170		Rsi
1	19	0.130			0.146		Timber flooring
					0.170		Rs (underfloor)
					0.486		

This study looks to investigate the impact of not only floor covering replacement, but the high standard of installation of those floor coverings on the overall energy efficiency of a dwelling.

New carpets vs old

Carpets are subject to frequent wear and degrade over time. Any one of the following can be a cause to replace carpets (Gupta and Goswami, 2018):

- Loss of definition
- Fibre shedding
- Fuzzing / piling
- Shading / water marks
- Fading

- Soiling
- Stretching / rucking.

While these factors account for aesthetic defects in carpet material, the degradation of that material can also impact its thermal performance.

A compromise exists between fibre quantity and the space for static air between fibres (Bakker, 2018). Increased fibre quantity causes an increase in heat loss by conduction, while increased air space causes an increase in heat loss by convection and radiation, and so a balance between the two is necessary. As carpets degrade, this balance is disrupted, largely by the material's ability to retain its original definition. Figure 3 shows how carpets piles are subject to deformation over time.

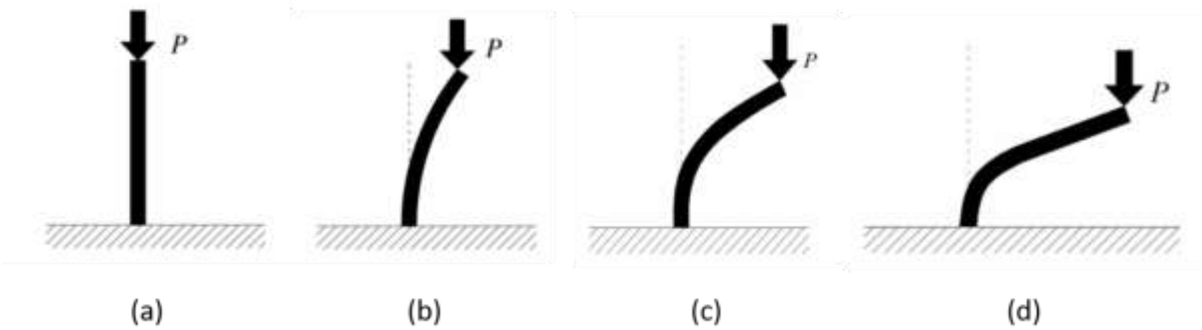

Figure 3. Deformation of carpet piles over time; (a) New carpets, <7 treads, (b) Used carpets, >7 treads, (c) Old carpets, (d) Older carpets. (Dayiary et al., 2009).

With time, as loads (P) are applied onto carpet piles, the bending of individual fibres moves gradually to the base as definition is lost. Eventually, fibres represent (d) in figure 3, reaching a stage called jamming. This is where deformation is at a maximum, spacing between fibres becomes a minimum, and heat loss through conduction peaks. The jamming process impacts material performance in three ways:

- Acoustic performance of the carpets is reduced.
- Thermal conduction through the floor is increased, reducing thermal performance.
- Perceived thermal comfort is reduced due to the increased heat loss through the floor.

Resiliency is the ability of a carpet and or underlay to return to its original upright position, retain its definition and in turn maintain its performance. It is considered one of the most important characteristics of carpets (Chaudhuri, 2018). Common materials used in carpet making, which demonstrate resiliency, are Nylon and wool. Other materials used in carpet making, but have a reduced resiliency are acrylic, polypropylene, polyester, cotton and silk. Given the different structural properties of these materials and the varying sub-structure of carpet (pile fibre content vs air spacing), the thermal properties of carpets can vary. As such, the time taken for the thermal and acoustic properties of carpets to degrade will also vary.

While aesthetics play a large part in determining when carpets and floor coverings are replaced, these three performance factors are often disregarded in the process of replacement. This work investigates the impact of replacing carpets on the overall energy performance of the dwelling as a whole, and asks the question as to whether these performance factors should be taken into consideration.

How are carpets currently dealt with in models and regulation?

There is some discrepancy about how floor coverings are dealt with regards to energy modelling in the UK. SAP (The Government's Standard Assessment Procedure for Energy Rating of Dwellings), the UK's regulatory energy modelling package of new and existing dwellings makes no mention of floor coverings within its documentation, so one may presume that often the resistance added by floor coverings is omitted by designers (BRE, 2011). BR443, which is the recognised guidance in the UK for calculation of U-values declares that "*floor coverings are not included in the calculation; but it is permissible to include them if their properties are adequately defined*" (Anderson, 2006). This gives the option but not the requirement to incorporate floor coverings into the U-value calculation.

Method

The Energy House test facility was used to conduct three key tests to determine the change in energy performance of a dwelling following the replacement of all floor coverings within the home. These three tests were:

- A whole house global heat loss test.
- Heat flux density measurements of the ground floor.
- Blower door tests to determine the air permeability of the building.

Each of the tests were carried out under controlled conditions, for each of the test scenarios: with old floor coverings, with no floor coverings (bare floorboards), and with new floor coverings. Energy consumption was also monitored during each of the test periods.

Description of facility and construction

The Energy House test facility at the University of Salford is a full scale replica of a pre-1919 UK Victorian end terrace house. The house was built inside a climate controlled chamber, where all environmental conditions inside and outside the building can be controlled. The facility is shown in figure 4.

Figure 4. The Energy House test facility at the University of Salford.

The majority of materials used to build this house were reclaimed, and the construction carried out in the typical tradition used at the time. This type of house is representative of a large proportion of the UK's existing housing stock (NIHE, 2009; ONS, 2010 & 2011), which is expected to make up around 80% of the total housing stock in the UK by 2050 (SDC, 2006). A more in depth description of the building can be seen in work by Marshall et al., (2018).

The core feature of this research facility is that the building exhibits extremely similar behaviour to those found in the field, and so modifications made to the fabric of the Energy House deliver realistic measurable changes to energy performance.

The tests discussed in this section benefit from steady state conditions and are a requirement for co-heating and heat flux density measurements for the accurate calculation of heat loss coefficient (HTC) and U-value. By controlling the environmental conditions in the house and chamber, it was possible to achieve quasi-steady state conditions to facilitate these tests.

Whole house global heat loss test

The electric co-heating method as described by Johnston et al. (2013) was used to determine the heat transfer coefficient (HTC) of the Energy House at three different stages of refitting the carpets within the house – with old carpets and underlay, with no carpets or underlay, and with new carpets and underlay. The HTC is a measure of the global heat loss from a building and consists of both fabric and ventilation losses.

Quasi-steady state conditions are required to carry out the test, with a significant temperature difference between internal and external spaces to ensure mono-directional heat flow through the building envelope. To achieve this, the external temperature in the chamber was held at a constant temperature of 4.3 ± 0.5 °C. Internal temperatures were artificially raised to 21 ± 0.5°C using electric fan heaters in each of the six thermal zones within the house. Additional fans were also used to circulate air around the building to reduce the effect of stratification.

The heat transfer coefficient can be calculated using:

$$HTC = \frac{Q_{avg}}{T_{i,avg} - T_{e,avg}},$$

Where Q_{avg} is the average power input from all heaters (W), $T_{i,avg}$ is the average internal temperature of the building (°C), and $T_{e,avg}$ is the average external temperature (°C). Note that solar input typically used in this equation is not used for this study.

The building was allowed to reach quasi-steady state conditions following the establishment of each test scenario (old coverings, no coverings, new coverings), following which data was collected for multiples of 24h. Data from the final 24h of each test period was used to calculate the HTC.

Heat flux density measurements

Heat flux plates were affixed to the bottom of the floorboards of the ground floor – in both the kitchen and the living room. Four Hukseflux HFP-01 plates were used per room, to give an indication of the heat flow through the ground floor of the building. Note that the ground floor of the Energy House is a suspended timber floor, with a 300mm air gap.
Data from these heat flux plates were collected during the same test period as the electric coheating test. The final 24h of heat flux data were used to calculate an average per room, for each of the test scenarios.

Blower door tests

Following each electric coheating test, blower door tests were performed on the Energy House. These tests were carried out to the standards of ATTMA Technical Standard L1 (ATTMA, 2010).
An external doorway was fitted with a specialised frame, which holds a fan capable of pressurising and depressurising the building to create a pressure difference across the building envelope. Each test considered depressurisation at 50Pa, to calculate an air permeability in $m^3/h/m^2$. To achieve this calculation, the flow of air out of the building was increased to raise the depressurisation pressure by increments of 5Pa to 75Pa.

As per the ATTMA Technical Standard, all mechanical vents were sealed to ensure only the building's natural permeability was captured during the tests. Results for each scenario were then compared.

Results

Four parameters were identified for each of the test scenarios; this included the Heat Transfer Coefficient for the whole building, the average heat flux through both kitchen and living room floors, the air permeability of the whole building, and the energy consumption over 24 hours.

Results from the Electric Coheating Test

Conditions within the house and within the chamber were maintained to facilitate this test, an example of this is shown in figure 5, which gives the temperatures for each room and the chamber during the test for the original floor coverings.

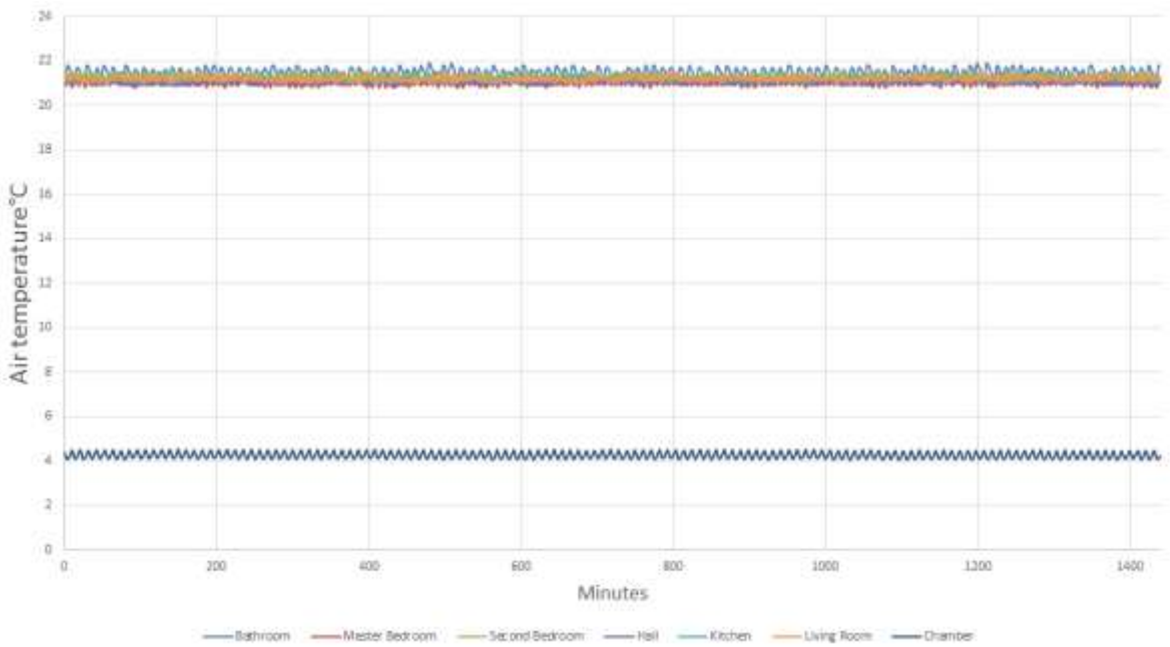

Figure 5. Air temperature measurements during the final 24h of an electric coheating test, carried out using original floor coverings.

Note that air temperature measurements were taken at the geometric centre of each room. Steady temperatures as shown in figure 5 were exhibited during all tests.

Average power input and average temperature differences over the 24h period were used to calculate the HTC using equation in section 3.2. Table 1 lists the HTCs calculated for each test scenario.

Test Scenario	Average Power Input (W)	Average Internal Temperature (^{o}C)	Average External Temperature (^{o}C)	HTC (W/K)
No Floor Coverings	3450.42	21.13	4.24	204.29
Old Floor Coverings	3350.42	21.19	4.27	197.98
New Floor Coverings	3278.75	21.22	4.33	194.15

Table 1. Calculated Heat Transfer Coefficient for old floor coverings, no floor coverings and new floor coverings.

Results demonstrate a reduction in the HTC of 1.94% when changing from old floor coverings to new floor coverings. Old floor coverings provided a reduction of 3.09% over bare floorboards, while new floor coverings provided a reduction of 5.0%.

The reduction in HTC is a combination of effects from improved fabric thermal performance and an improvement of the ground floor air tightness. The contributions for each are inferred from the following results of heat flux density measurements and blower door testing.

Results from Heat Flux Density Measurements

Heat flux measurements were consistent for both the living room and kitchen. Variations were observed between the data for each given the different type of floor covering used. Figure 6 shows an example of this in the 24h test period for the scenario with old floor coverings.

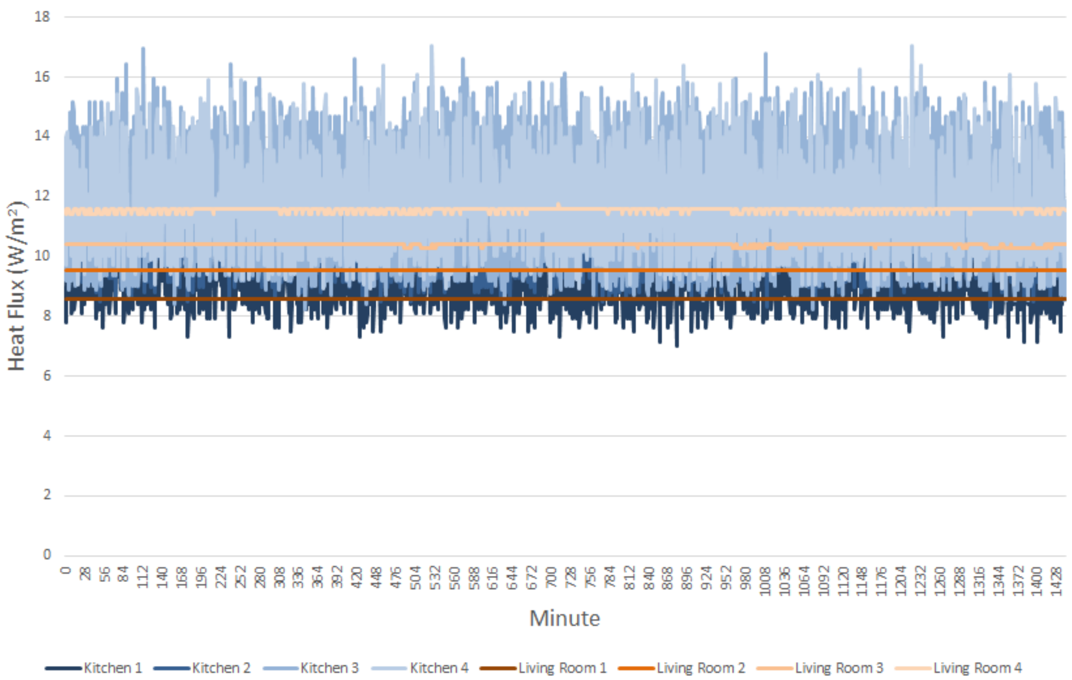

Figure 6. Heat flux density measurements of the ground floor in the kitchen and living room, with the old floor coverings.

The data in figure 6 show that heat flux through the kitchen floor exhibits far more fluctuations than the living room floor. This demonstrates the difference between heat flow through carpet, LVT and their respective underlays. Fluctuations appear in the heat flux measurements of both kitchen and living room without floor coverings (bare wooden floorboards) and disappear in the living room with the installation of the new carpet.

The average heat flux throughout each test is consolidated in table 2, with the difference due to changes in floor covering.

Test Scenario	Average Heat Flux Living Room (W/m^2)	Difference from No Covering	Average Heat Flux Kitchen (W/m^2)	Difference from No Covering
No Coverings	11.34	-	9.78	-
Old Coverings	8.56	24.51%	9.22	5.72%
New Coverings	8.12	28.39%	7.87	20.40%

Table 2. Average heat flux data for the kitchen and living room, for each test scenario.

Results from the heat flux density measurements reveal that floor coverings reduce heat flux through the ground floor significantly. In the case of living room carpets, the old and new carpets provided a similar reduction to heat flux, with the new carpet having a greater impact. The new installation of LVT and the LVT underlay composite in the kitchen however, demonstrated a much higher reduction in heat flux over the old installation of vinyl with a timber base.

Results from Blower Door Tests.

Each of the blower door tests gave an output value for air permeability in $m^3/h/m^2$, based on the depressurisation pressures achieved around 50Pa and the air flow into the building required to sustain them. Table 3 gives the air flow and pressure measurements during each blower door test, with the resulting air permeability value.

Scenario	Air Permeability ($m^3/h/m^2$)	Error	Difference from No Covering
No Covering	13.22	1.1%	-
Old Coverings	12.79	2.8%	3.25%
New Coverings	12.43	1.3%	5.98%

Table 3. Results from each blower door test.

Results from the blower door tests show that carpets, LVT and their underlays do impact on the air permeability of the building; not only the presence of floor coverings, but the quality of those fitted coverings. By replacing floor coverings within the Energy House, it was possible to reduce the air permeability by 2.82%, a reduction which almost certainly contributes to the overall HTC reduction of the building.

Results of 24h Energy Consumption

Throughout each of the tests, the energy consumption in the final 24h of data collection was measured. This was compared to give an indication as to the possible energy reduction due to the changing of floor coverings. Table 4 lists the energy consumption measurements, and differences for each scenario.

Scenario	Energy Consumption (kWh)	Difference to No Coverings
No Coverings	82.81	-
Old Coverings	80.41	3%
New Coverings	78.69	5%

Table 4. Results from 24h energy consumption measurements.

Results from these rests demonstrate how, by replacing old carpets and vinyls with new, the reduction in energy consumption due to those floor coverings can be almost doubled.

Conclusion

All floor coverings – carpets and vinyl – of a replica Victorian UK terraced house were removed and replaced with new floor coverings. This process was carried out to assess the change in performance at whole building, and at building element level. Environmental conditions were controlled and maintained to facilitate quasi-steady state conditions.

Three test scenarios were used for the study: no floor coverings, old floor coverings and new floor coverings. Four energy performance parameters were then measured or calculated to assess the impact of each test scenario on building performance. These were the heat transfer coefficient, heat flux through the ground floor, air permeability, and energy consumption over 24 hours. Data from the final 24 hours of each test period were used to evaluate each of the energy performance parameters – with the exception of air permeability.

In all cases, results indicated that floor coverings improve the overall energy performance of a dwelling. In addition to the benefits observed from the old coverings, the materials used in the installation of new floor coverings and the high standards of that installation saw a further increase in the benefits to energy performance.

By replacing the carpet, vinyl floor, and underlay coverings of a whole dwelling, using a high standard of installation, it was possible to reduce the global HTC by 1.94%, the heat flux through the floor by up to 14.60% (due to the replacement of vinyl and a timber base, with LVT and a purpose made LVT underlay), the air permeability of the building by 2.82%, and 24h of energy consumption by 2.14%.

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