Using real occupancy in retrofit decision-making: Reducing the performance gap in low utilisation higher education buildings

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Abstract

The retrofit analysis relies on intuition and faith in the simulations that lead the decision-making process. However, intuition is built upon belief systems which become increasingly unjustifiable as building operation deviates from design whether in utilisation, occupant behaviours or climate. Higher education facilities are known for persistently low but well-recorded occupant presence and density. The low utilisation makes them susceptible to counterintuitive behaviours however, their registration data provides a means of identifying where intuition fails. When operation has little correlation with design it is possible for performance issues to appear to be symptoms of design considerations rather than root cause. Using a discrete space modelled in both EnergyPlus and SBEM as virtual case study g and class registration data, this paper explores how lighting retrofit simulation alludes to heating load concerns resulting from poor envelope and HVAC performance rather than heating management. This is achieved through utilisation of a new approach to scheduling utilisation and BMS systems for higher education facilities in EnergyPlus. The paper concludes suggesting the utilisation modelling method could replace the current heating efficiency credits approach approved for Part L2. Results include discussion on cost-benefit, legislative compliance and implications for retrofit decision-making

Keywords: Retrofit analysis, occupancy, compliance, low utilisation

1. Introduction

Janda (2011) stated "buildings don't use energy: people do" which is not entirely accurate. Building energy is in part consumed to meet the needs of people, but it is also attributable to the beliefs of the designer, building manager and occupants. Whether it is the designers' assumption that operational utilisation will be comparable to design or occupants' subjective perceptions, energy consumption can partially be attributed to assumptions rather than needs. In the case of design assumptions, higher education facilities' utilisation of teaching spaces in the UK is recorded is typically around 27% (Space Management Group, 2008) which is neither represented in compliance models nor meaningfully accommodated by existing utilities, despite utilisation being considered a primary cause of the building performance gap (Hong *et al.*, 2016; Kneifel *et al.*, 2016; Ridley *et al.*, 2014). Occupant behaviours inherently have a significant impact on net energy demand and the occupants' collective comfort (Guerra-Santin *et al.*, 2016; Liisberg *et al.*, 2016; Tagliabue *et al.*, 2016; Yousefi *et al.*, 2017). Their behaviours themselves are likewise bound to beliefs. s. Personality traits (Schweiker *et al.*, 2016), internal rendering colours (Wang *et al.*, 2018), perception of environmental control (Schweiker and Wagner, 2016; Yun, 2018) and even hearing other occupants describe comfort properties (Wang *et al.*, 2018) citing (Höppe, 2002) can affect occupants' beliefs about the ecosystem they reside.

Nondomestic buildings with poor thermal performance represent 66% of all building stock in the US and 75% in the (Lee *et al.*, 2019) which 60% are expected to still exist in 2050 (Pomponi *et al.*, 2015). Heating contributes 46% of UK energy demand with 86% of heating delivered by gas-fired systems (Chaudry *et al.*, 2015). Heating is an ecosystem-sensitive consumer in a sense changing the operational state of any discrete space within a building affects the heating of the remaining spaces. Given energy performance policy and plans to decarbonise the grid, heating perhaps deserves special attention despite compliance currently focusing on carbon emissions. Intuition suggests envelope thermal performance and heating, ventilation and air conditioning (HVAC) upgrades should be given precedence in the decision-making process, however; the former is not suitable for discrete spaces, and both are based upon the assumption that high heating demand is a system performance rather than system mismanagement problem.

Previous works identify sensitivity to occupant behaviours (Corgnati *et al.*, 2017), climate (Rastogi, 2016) and underutilisation (Gupta and Gregg, 2016). These highlight that retrofit decision-making is possibly better thought of as an exercise in risk aversion rather than identification of optimum. Rastogi offers a methodology for generating synthetic weather data for assessing retrofits and designs under probable climates. Lee *et al.* (2018) discuss a complementary Monte Carlo-based risk aversion method which mitigates some superstitions. Both are innovative approaches to decision-making but are susceptible to critical failures attributable to misguided assumptions. Gupta and Gregg (2016)identified a similar mismanagement hypothesis as discussed in this paper suggesting manual intervention from staff or some level of local smart radiator controls though they were not able to test the hypothesis. In a similar theme, this paper simulates lighting retrofits using explicitly known utilisation and two climates to demonstrate how heating management strategy for low utilisation spaces affects energy performance. The results are used to demonstrate that in the high heating demand is primarily a symptom of poor heating strategy management rather than envelope thermal performance or HVAC system efficiencies.

2. Methodology

Using a bespoke building model interfacing library, this paper demonstrates the necessity of using class registration data during retrofit analysis. This is achieved through a discussion of how lighting contributes to net energy demand when utilisation deviates from design occupancy. The results of 100 EnergyPlus and 19 Simplified Building Energy Model (SBEM) lighting and heating management retrofit simulations are used to explore the implications for decision-making, building operation, legislative compliance and energy scheduling and climate manipulations are exclusively incorporated to EnergyPlus simulations due to SBEM's limited flexibility. The tool used for scheduling both utilisation and building management systems (BMS) is described along with the cost methods used to for cost-benefit analyses.

2.1. Virtual case study

The seventh floor of the University of Strathclyde's Graham Hills Building was used for the study. The building was constructed between 1957 and 1959 which is two years prior to the introduction of the Building (Scotland) Act 1959 and six years prior to the Building Standards (Scotland) Regulations 1963. Therefore, the building's design was not bound to any meaningful performance regulations. However, it underwent staged building services retrofitting between 2000 and 2009 where HVAC, domestic hot water (DHW) and lighting were upgraded to be compliant with the Part L2B minimum standards at the time of installation. The floor is 2869m² with 13 teaching spaces of which 6 are utilised and1 is reserved with zero density presence.. The remainder of the space consists of43 offices and 23 secondary spaces. The floor below and partial floors above are retained for heat transfer calculations only. Opaque envelopes have a U-value of 1.7W/m²K and glazing a U-value of 5.68/W/m²K. Lighting efficacies are based on the National Calculation Method (NCM) lamp templates which best represent the fixtures as would be the case for any L2B survey. The floor is naturally ventilated with heating served by a low-temperature hot water boiler (LTHW) with a SCoP of 0.738 and delivered via a wet radiator. The two toilets have local extract fans with a specific fan power of 0.8W/l/s. There is no HMS present. The base model was created in DesigBuilder 5.4 and exported into SBEM 5.4.b and EnergyPlus 8.6.0. The disparity between lighting definitions in the models was resolved through standardised injection of efficacies and units from the NCM activity database including design illuminance levels.

2.2. Scheduling

Three standards and two complementary HMS-supported schedule scenarios were created for none-NCM spaces which represent the building's registered real world. Presence and density are taken from the class registration system.

NCM: A collection of standard schedules used for design and compliance modelling. These assume consistent presence across every standard weekday with separate near-zero utilisation schedules for weekends and holidays. In SBEM, these schedules are ignorant of both the real world and calendar whereas under normal circumstances outwith this paper, in EnergyPlus they are only ignorant of real-world utilisation. In this paper, NCM schedules are bound to a synthetic climate calendar akin to the theme of Rastogi (2016)'s synthetic weather in the sense that while climate data from 2016 and 2017, the 2016 calendar has been offset to match the 2017 day numbers.

Explicit/Implicit: Custom utilisation schedules are generated for all teaching spaces, which are record in the university's class registration system. Utilisation during occupied periods is defined separately for each registered period based on the registration system's definition of each space's capacity and the number of occupants registered for the class. Lighting is defined as Boolean-state based on the present state from the registration system. Where a teaching space has registered periods with zero occupant density the zone is considered in use with zero density. Finally, explicit scheduling considers that a teaching space with zero entries in the registration system has unknown utilisation and are assumed to be utilised as defined by the NCM. The Implicit scenario assumes that the registration system is complete and therefore any teaching space which has no entries in the system is never utilised during schedule year.

Explicit- / Implicit-BMS: Extending the Explicit and Implicit schedules, the rules applied to create the scenarios are used to define HMS system configuration. The data from the registration system used to generate each teaching space's utilisation and lighting schedules are used to modify the heating availability schedule of each space to prevent EnergyPlus from warming the spaces when no occupants are present. A preheat period is added to each presence period at one hour as per the default assumption.

2.3. Lighting design and BMS cost methods

Lighting and HMS installation cost methods were created through reference to a lecture from Philadelphia University and price estimates from the SPON's 2018 Mechanical and Electrical Services Price Book 2018.

2.3.1. Lighting (R-LIG)

Lighting retrofit costs are identified using photometrical computation (Lumens method) as documented in the Philadelphia University Electrical Installation lecture 11. The method uses photometric data to estimate the number of luminaires required to light a given environment through reference to luminaire efficacy, and utilisation and maintenance factors . Given as:

$$N = \left[\frac{EA}{lm.UF.MF} \right] \qquad k = \frac{LW}{(L+W)Hm} \qquad C = N(Fhl + Lc)$$

N: Number of luminaires, **E** = Target lux level for the zone. Where the target lux level is taken to be the design or "light_lux" value from the NCM activities database as per the binding discussed in 4.2.1, **lm** = Total luminous flux from each luminaire, **UF** = Utilisation factor identified from the luminaire's photometric data from the room index (**k**), **MF** = Maintenance factor **- k**: **L** = Room length, **W** = Room width, **Hm** = Ceiling height – work plane height **- C** = Total cost in £, **F** = Location labour cost adjustment factor, **N** = Number of luminaires, **h** = Installation luminaire/hour, **l** = Labour cost £/hour, **Lc** = £/luminaire.

2.3.2. Building management system (R-BMS)

Being a computerized system attached to local control measures, the HMS cost method is a function of the number of registered zones. The method was reduced to two primary costs, Head Equipment priced at £15,000 and Intelligent Unitary Controllers at £500/IUC. The cost method is given as:

$$C = Hc + NI$$

C = Total cost of installation in £, **Hc** = Global cost for head-end equipment (software, computer, commissioning) in £, **I** = Unit cost for each intelligent unitary controller £, **N** = Number of IUCs.

3. Results

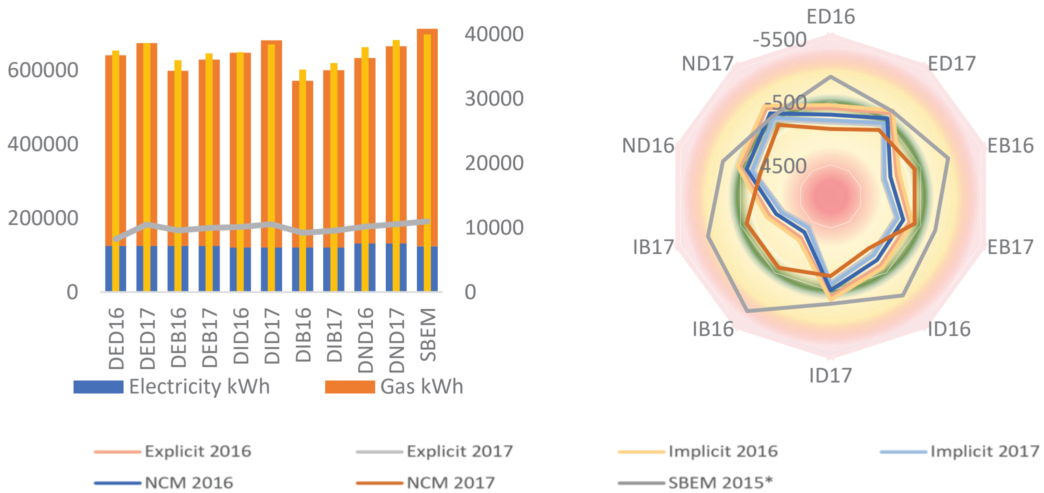

Figure 1 & 2: Estimated annual running cost (right y), consumption and emissions (left y) by Schedule-Climate / engine, and Schedule-Climate scenario running cost disparity. Labels represent strategy and year <schedule>-<BMS>-<year> where (D)efault, (E)xplicit, (I)mplicit, (N)CM, and (B)MS

Where NCM scheduling is considered as design the Explicit scenario results in a 52% reduction in presence hours for the teaching spaces and the Implicit scenario resulting in a reduction of 86%. Figures 1 and 2 show the base model annual net energy demand for each Schedule and Climate (Schedule-Climate) scenario and how they compare to one another. Notably, Explicit- / Implicit hold the highest and lowest annual consumption dependent on whether teaching space heating is managed.

3.1. Schedule presence

Figures 3 and 4 show the difference between NCM and registration system presence demonstrate the disparity cumulative presence and overlap between the NCM and registration system schedules for teaching space GH818. This space has the second-highest presence hours and the greatest overlap between NCM and registration system schedules. There is no cooling in this building however, it is worth noting utilisation during the cooling period is significantly lower than in NCM.

Table 1: Teaching space presence hours by Schedule

	807	813	816	817	818	863	898	801A*	801B*	801C*	801D*	801E*	801F*
NCM	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134
Explicit	---	745	639	611	633	483	675	2,134	2,134	2,134	2,134	2,134	2,134
Implicit	---	745	639	611	633	483	675	---	---	---	---	---	---
%Imp	0.00%	34.91%	29.92%	28.61%	29.66%	22.63%	31.61%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

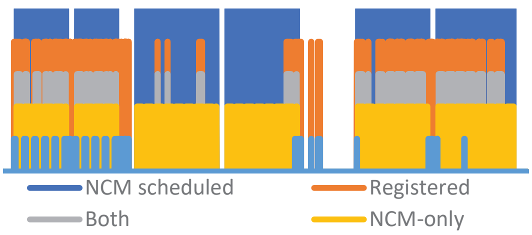

Figure 3: Schedule scenario overlap GH818.

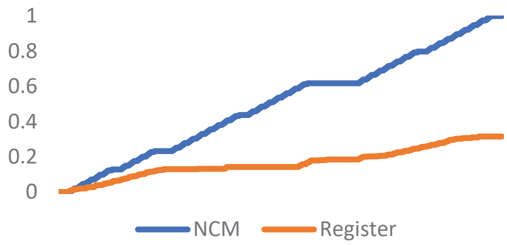

Figure 4: Cumulative presence GH818

3.2. Schedules, lighting and net building energy demand

Table 1 shows annual lighting energy consumption for teaching spaces for each Schedule scenario. NCM scheduled teaching spaces to contribute 20% of the total lighting demand equivalent to 10% of the buildings annual grid-supplied electricity demand. However, with registration system scenarios their contribution is reduced to 10% and 3.6% for Explicit and Implicit scenarios respectively. In absolute terms, these changes reduced grid-supplied electricity demand by 6.8MWh and 10.8MWh. Conversely, absence of internal gains from assumed presence increased natural gas demand for heating by 14.5MWh and 25.1MWh with 2016 climate data and 15.2MWh to 27.3MWh with 2017 climate data for Explicit and Implicit scenarios compared to their NCM counterpart. The increased heating demand is explained primarily by the absence of an HMS. Since an HMS is not present the teaching spaces are heated needlessly, and their heating demand is not mitigated through latent or lighting heat gains.

The relationship between lighting and simulated natural gas demand is not easily expressed due to the temporal, seasonal, utilisation (presence, density, humidity changes), external gains and the latent value internal gains from lighting and occupants. Even when adjacency awareness is ignored, a Wh of electricity consumed by lighting is rarely if ever equivalent to 1Wh of net energy demand due to heat produced by luminaires. Comparing the two registration system 2016 Schedule-Climate scenarios without an HMS against NCM-2016, annual heating demand for teaching spaces increases by 17.5MWh and 28.9MWh for Explicit and Implicit, respectively. The increased demand can be used to estimate the monetary value of each unit of electricity that would have been consumed by lighting in the teaching Heat gains from lighting contributed 23.8% and 23.3% of each teaching space Wh natural gas demand for Explicit and Implicit scenarios though this is reduced to 21.3% when only the academic year is considered. Factoring latent and lighting gains with the existing lighting system into the increase in net energy demand reduces the value of each kWh electricity saved from lighting consumption to 50% and 46% in net energy demand kWh for Explicit and Implicit, respectively. In contrast, Implicit-2016's kWh/kWh lighting to net energy ratio retains 3.1% above 1:1 when heating is managed. In summary, lighting consumption and net energy demand do not have a 1:1 relationship. Under design conditions this means each Wh lighting is worth 1Wh of electricity and a fraction of 1Wh of the heating demand, in the case of this building 1.84Wh. Therefore, under design utilisation each Wh of lighting reduces emissions 0.181gCO_2/Wh and £0.00003/Wh reducing its effective unit cost to £0.1253/kWh. Whereas, Implicit-2016's lighting consumption demand reduction of 10.6MWh electricity increases heating demand by 2.53MWh, nullifying 0.3tCO2 of the electricity-related emissions reduction and increasing the £/kWh cost of the new gas consumption from £0.0358/kWh to £0.044/kWh.

3.3. Lighting retrofit

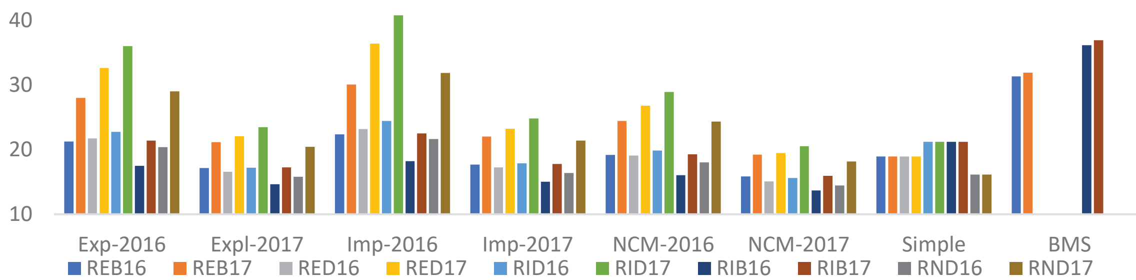

Figure 5: Schedule-Climate scenario relative discounted payback periods at 3.5%

Figure 5 shows the lighting retrofit for the virtual case study in terms of discounted payback period based on the difference between the base model simulated annual running of the x-axis and the savings from the bar labels' associated Schedule-Climate scenarios. BMS represents payback periods where both Schedule-Climate base model and cashflow values are based are consistent. Finally, simply represents payback where net energy demand is ignored As with discussion in 4.2, the discounted payback period is volatile depending on the chosen Schedule-Climate scenario for the base model, and the scenario assumed to produce the closest approximation of the annual run cost savings. Most SBEM results never return on the capital investment at a 3.5% discount rate. Across all scenarios where an HMS is not included in the base model estimated running cost, the payback period difference where x-axis and bar labels do not align ranges from 65% to 162%. SBEM, excluding one result at 55 years has a maximum range of 190%.The difference is between 46% and 88% at the bank base rate which is relevant to later compliance discussion. However, where HMS is presented the range is only 18%. A discount rate of 7% is often suggested for private projects. When this rate is considered, 38 Schedule-Climate scenarios fail to achieve a positive return on investment. The main lighting retrofits (R-LIG) for bars labels as "D" in the BMS label flag are calculated based on the lighting capital cost £83,112 whereas each with "B" for the flag includes £21,500 for the HMS. with a total cost of £104,612. Despite the extra 26% cost the payback period for all heating managed comparisons not compared to the heating managed base model estimate a payback period of lower than any other Schedule-Climate of without an HMS. A key feature of the BMS group is that using the Building Services Compliance Guide efficiency credits method of representing a BMS would not achieve a positive return on investment even though the cost used is ignorant of 66 zones which would normally need to be included in the price. Furthermore, the efficiency credits method would overestimate gas contribution to annual running cost by £3,000 to £3,300 for Implicit 2016- and 2017-HMS respectively.

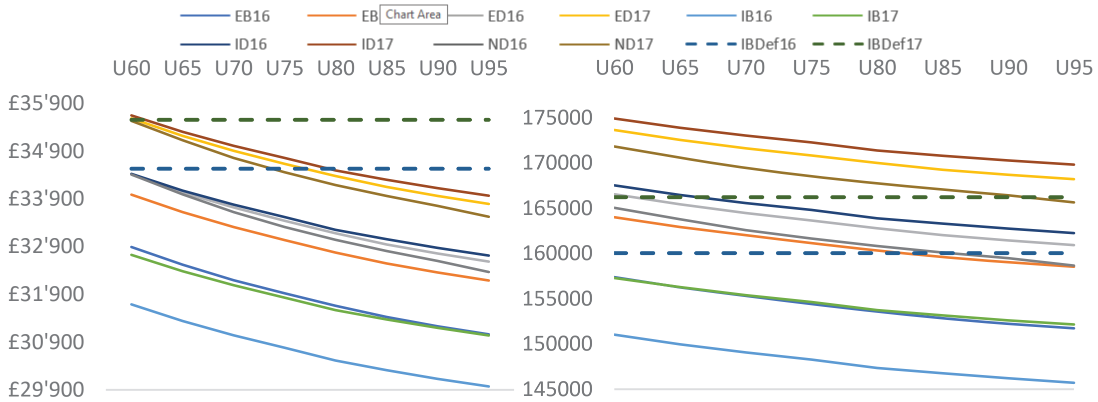

Figure 6: Annual running cost post-retrofit all lighting constant efficacy upgrades at the number of on the x-axis label in lm/cW. Series names represent Schedule-BMS-Year

Figure 7: Annual kgCO_2 post-retrofit for each retrofit with baseline 2016 / 2017 HMS.

Running costs improve in every retrofit scenario however, it can be seen in Figure 6 that the HMS state of each scenario supports previous discussion on net energy demand in low utilisation areas. When there is no HMS the savings from retrofitting are diminished proportionally to the corresponding NCM schedule of each Schedule-Climate. Furthermore, estimated running costs for design utilisation appear lower than with calibrated utilisation but no HMS. Compared to NCM savings as efficacy increases, lower utilisation results diverge from NCM savings further diminishing in return. In contrast, where an HMS is present running costs are significantly lower and become increasingly proportional to NCM scenarios as efficacy increases. However, carbon emissions better illustrate the underlying concern explored in this paper. Ignoring the inherent benefit of an HMS as noted elsewhere, retrofitting the lighting without HMS results under NCM utilisation would yield greater returns than with calibrated utilisation despite the 96.5% reduction in teaching space lighting demand for Implicit- scenarios. Horizontal dotted lines on figures 6 and 7 represent baseline running cost and carbon emissions for each Implicit Schedule-Climate with the HMS. Estimating from SPON's default LED luminaire and labour cost, to achieve those lines through lighting retrofit requires three times the cost of the HMS was it priced based on the method described in 2.3.2. However, a rudimentary installation as discussed by Gupta and Gregg (2016) could ostensibly be installed for less than £1,000 using smart radiator valve controllers.

4. Discussions

More often than not it is either not possible to meter a discrete space or there is no metering available which means there is rarely a meaningful opportunity to use operational data unless servicing is homogenous, and the discrete space represents a significant portion of the total gross internal area.

4.1. Heating management

It is clear from all dynamic simulations where Schedule-Climate scenarios are considered that low utilisation without an HMS has severe adverse effects on the virtual case study's net energy demand, namely its HVAC demand. Grid-supplied electricity demand was reduced by 8.3% and heating demand increased by 5.0%~ for both 2016 and 2017 Implicit Schedule-Climate scenarios without an HMS. However, the impact on the four meaningful metrics, net energy demand, carbon emissions, running cost and cost per kilogram carbon, was volatile depending on the base model Schedule-Climate scenario. Net energy demand increased and running cost decreased for all Schedule-Climate scenarios though not proportionally, carbon emissions and cost per unit carbon did not behave intuitively Were a simple estimation based on reduced lighting used to compare NCM to Implicit, a reduction in 1.97 $kgCO_2/m^2$ would be expected. However, the heating demand increase reduced this to 0.07kgCO2/m² for 2016 and caused 2017's to increase by 0.09 $kgCO_2/m^2$. The results are further compounded when $kgCO_2/£$ is considered, the suggested metric for equiproportionate abatement where a lower value shows greater potential for compliance-oriented application. NCM 2016 surprisingly suggests greater opportunity than NCM-2017, and Implicit-2017 less opportunity than Implicit-2016.

Introducing an HMS to Schedule-Climate scenarios resulted in significant improvements across all metrics, including up to 6$kgCO_2/m^2$ estimated annual emissions for Implicit compared to NCM. Additionally, the expected NCM > Explicit > Implicit relationship was realised. This was not exclusive to emissions The abatement metric now favoured Implicit, and NCM and Explicit were on par. This translated over to lighting as well where although the initial 1.84Wh net energy value of each Wh electricity consumed by lighting e was reduced to 0.5Wh and 0.46Wh without an HMS for Explicit and Implicit respectively, introducing an HMS improved the net energy unit value to 1.03Wh. The case study has no comfort cooling, and the absence during the summer as highlighted in Figure 3 would significantly reduce cooling load, however, GH818 at least is almost never occupied during the cooling period and therefore its cooling demand would be all but wasteful. Though, it is worth noting that all teaching spaces which are not GH801* have NCM scheduled adjacencies whose cooling demand would inherently be slightly reduced. The case study was made aware of the presence of adjacent floors to improve heat transfer calculations; however, the principle of scheduling lower utilisation will only further be skewed as other floors are calibrated.

Without an HMS the case study suffers from reduction in internal gains to the point where for some metrics the 70%~ reduction of presence hours for 23% of the building does not appear significant compared to design occupancy. Not only does low utilisation have a significant effect on simulation results, without management Schedule-Climate scenarios behave unpredictably and lighting waste heat's net energy unit value is roughly twice what it should be. Failure to manage dependent consumers results in volatility across performance metrics that suggest there is an envelope performance and/or HVAC efficiency problem. However, the results show that retrofitting these would remedy the symptoms rather than source of the problem, needles exertion of the HVAC system.

4.1.1. Heating management and compliance

BMS simulation for compliance is not well-defined due to the absence of persistent scheduling data.. The compromise for implementing HVAC control measures is to increase the CoP of heating systems by the relevant allowance identified from the Building Services Compliance Guide. In the case of the case study LTHW boiler, this could be an increase of 4%. The improvement from this is insignificant for Schedule-Climate scenarios without an HMS. Using the SBEM results, which is the most favourable scenario for the efficiency credits method, the improvement only improves heating demand by 7.68kWh/m² or £789/annum. The efficiency credits method is priced on the entire discrete space which would cost £46,000. Even using the MEES DPP rate of 0.75% the efficiency credits method would take 77 years to payback.

The modelling method used in this paper can be applied to the extent registration data is available and is not constrained by a full-building installation. The method, however, faces challenges for compliance modelling for L2B or MEES where it is not yet clear how scheduling would affect the standard energy rating (SER). The reference building is based on the geometry and scheduling of the actual model but HMS as defined in this papers not part of the reference definition. The implementation takes advantage of the heating availability scheduling, which inherently transfers to the reference building. This would mean that if the justification for accepting the approach were accepted by the governing body, accredited level 5 software would need updates to their Notional and Reference building model creation processes.

4.2. Lighting retrofit

The simple calculation bracket presented in section 3.3 serves two purposes 1) it shows how Schedule scenario affects the payback period with a 26% increase despite teaching spaces only representing 23% of gross internal area. 2) The results demonstrate why simple tools claimed to be suitable for nondomestic buildings such as those provided by Emerson, Spirit or Regency Lighting become increasingly inappropriate as utilisation decreases. The results from these tools are not necessarily wholly spurious if the building is notably better insulated and has high utilisation since as noted in 3.2,79% to 76% of gains lost through absence in Schedule scenarios were associated with latent gains from occupants.

Each of the standard six Schedule-Climate scenarios compared to results from all eleven, including SBEM are highly disparate with set comparisons deferring between 48% and 190%. This is obviously not reliable, excluding comparisons between NCM-2016 and NCM-2017 which is 20% to 41% at 3.5%. NCM scenarios highlight sensitivity to climate though at the bank base rate the payback period is only 2 year longer for 2016/2017 to 2017. However, when an HMS is introduced to Schedule-Climate scenarios the maximum difference is only 18% when compared to the retrofit's base model HMS counterpart at 3.5% and only 10% at the bank base rate. This may be attributed to the significantly reduced natural gas demand and retained greater than 1:1 lighting electricity's net energy value when teaching space are managed by the HMS. The HMS was expected to reduce utilisation related heating demand volatility however, the reduced volatility resulting from climate had not been considered before exploring the results. The difference in base model heating demand between Implicit and Implicit-HMS ranged from 81,200kWh and 109,800kWh for 2016 and 2017.These results show why dependent consumer management is not just relevant to mitigating counterintuitive behaviours resulting from retrofitting independent consumers.

Constant efficacy lighting retrofit simulations demonstrate that although improvements are realised across all metrics, the results indicate installation would result in better energy performance if the building was operating at design utilisation despite the significantly higher presence hours. That is, not only would the savings and subsequent cost-benefit analysis results be skewed by NCM over real utilisation schedules, implementing any of the eight full building lighting retrofits without an HMS would result in poorer performance than design utilisation, including running cost. It is universally more expensive to operate the building without an HMS than it is to operate at design utilisation post-retrofit. In terms of Part L2A, this may result in a pass that is underserved and MEES liability would become increasingly concerning.. Where heating is unmanaged, it may receive an undue exemption from upgrade requirements, and the decision-making process may lead to selection strategies which are ineffective to the real world. Current discussions in the private rented sector have turned towards the extent which compliance-led retrofits need to align before liability is a legal concern. ESOS is bound to operation net energy demand rather than emissions and therefore without an HMS the retrofitting lighting would have a negative effect on next stage of report which would not be apparent until 2023. Finally, with the electrification of the grid targets, ignoring heat management would have knock-on effects in terms of lifecycle emissions and reporting. All-in, retrofitting lighting in low utilisation areas without first implementing an HMS is inadvisable for the case study despite supporting results from other research on high utilisation buildings.

4.3. The implication for ESOS-, Part L2B- and Section 63-led retrofitting

Depending on whether NCM or Implicit Schedule-Climate scenarios are used will be the difference between teaching spaces contributing 20% to the overall lighting and 3.5%.Ignoring net energy demand, this equates to an assumption of business, as usual, having a net present value of £10,133 or £8,931 more than expected over 7 years at 3.5% and 7% respectively. This would also be the difference between lighting appearing as 41% to 61% of a Scottish EPC band rather than 7% to 12%, or 11% and 65% of an English EPC band – based on the current SER. ESOS prior to considering retrofitting, however, would perhaps be more concerning since, without some correlation between the reported operational and simulated fuel demands, calibration is untenable.

In terms of MEES for England, Wales and Northern Ireland, the difference in lighting energy consumption is nearly equivalent to paying for the lighting retrofit costs associated with the teaching zones alone less than 3 years outwith the 7-year retrofit measure exemption cut off. Using constant efficacy retrofit simulations, it was shown that unmanaged heating in low utilisation spaces not only resulted in higher running cost estimates than of design utilisation despite 86% lower presence hours in registered spaces. Additionally, retrofitting causes the building to perform worse than estimated for design utilisation. This is not necessarily an explicit concern for decisions made purely for MEES or Section 63 compliance since compliance is often considered less about reducing carbon emissions and more about ticking a box. However, it will not help the reputation of consultants. This should be of particular concern to consultants since conversations surrounding consultant league tables, and partial auditing of 100% of models have been discussed as necessary for MEES since 2013. ESOS and retrofit-as-service which are both bound to operational net energy demand currently are most at risk from failure to manage dependent consumers, and successful electrification of the grid is intricately linked to fuel management. In terms of policy and as service decision-making, lighting on its own is unadvisable by any metric.

None of the Schedule-Climate scenario comparisons are within the 7-year MEES exemption, and therefore the lighting retrofit would not need to be applied or considered as part of a strategy package. However, it does reduce carbon emissions by 13% to 17% for NCM and Implicit-BMS scenarios comparisons respectively when results are compared to their respective base model Schedule-Climate scenario. Although a boiler upgrade was omitted from this paper, it was estimated that were a boiler replacement retrofit included with the R-LIG + R-BMS package and priced using SPON's; the retrofit package payback period would decrease from 32 to 26 years for the lower bound estimate despite the £14,000 estimated boiler installation cost.

5. Conclusion

Design and low utilisation simulated energy performance across monetary, emissions and net energy metrics have a spurious relationship. While with some general understanding of the utilisation one may be able to use intuition to estimate how the relationship between independent on dependent consumers may affect net energy demand and possibly annual running costs to an extent, the relationship when considering Schedule-Climate and engine across all metrics is far from predictable. Though teaching spaces occupied less than 25% of the building, scheduling using registration data had profound effects on the simulation engines' analysis of the building. It is informally known that utilisation in other primary spaces is similarly low, though not registered meaningfully. Where all areas suitably registered, the negative impact would be significantly worse.

Low utilisation resulted in the building behaving erratically. Therefore, it appears necessary that accurate scheduling is a necessary first step not only in calibrating the energy model but also for comparing simulated and operational net energy demand. With an HMS in place, both Schedule-Climate scenario and retrofits measured across all metrics behaved intuitively. It, therefore, seems necessary to consider an HMS before any retrofit that may affect dependent consumers. Without management, retrofit options that appear to be most suitable for the building remedy the symptoms of low utilisation rather not the problems. Under normal circumstances, an HMS cannot be modelled in either EnergyPlus or SBEM and the standard efficiency credits method is not meant for low utilisation buildings. However, the method used in this paper accommodates realistic IUC behaviour modelling enabling meaningful HMS tuning with the utilisation-calibrated model. Finally, the HMS was three times cheaper than the SPON's estimate for the constant efficacy R-LIG to achieve at least the same running cost improvement as unmanaged heating 60lm/cW against 2017 climate and all unmanaged or design schedules emissions reduction until 85lm/cW against 2016. That is, until a global lighting retrofit has an efficacy of 30% greater than current BSCG requirements, spending at least three times the amount of the HMS cost would not result in better energy performance than solely installing an HMS.

Scheduling reduced lighting consumption in the associated spaces to the point where estimating the payback period exclusively on lighting energy consumption still resulted in payback periods longer than luminaire lifecycle even at the bank base rate. When considering net energy demand without an HMS the results were three and a half times greater than MEES exemption criteria at the bank base rate and well outwith the luminaire lifecycle for the at the public project discount rate. However, with heating management installed purely in the registered spaces with Implicit- scenarios were the worst case just over twice the exemption period. All teaching spaces bar one under Implicit- scenarios do not run long enough for LEDs to have merit. Therefore, T5s for teaching spaces may be a more suitable solution.

Rastogi (2016) demonstrates the necessity for a paradigm shift using static climate models during the design phase and retrofit decision-making. This paper expands on his observations through exploration of the impact of disparity between design and operational occupancy. Its main contribution to theory is proving operational heating demand inefficiency can be separated from system inefficiency and how the observations relate to policy. An alternative method of modelling BMS in EnergyPlus was created and shown to align building behaviours closer to what the behaviours represented at design occupancy which can also meaningfully represent real-world BMS installation in EnergyPlus. The industry currently relies heavily on faith in the consistency between virtual and real worlds, this paper both contributes to the literature that challenges these beliefs while providing a means of mitigating the concerns raised..

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