A RISK FRAMEWORK FOR THE DELIVERY OF LONG-TERM PERFORMANCE THROUGH THE LARGE-SCALE ENERGY FOCUSED RETROFIT OF HOUSING

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The 2019 Climate Action Plan (Ireland) seeks to retrofit approximately 500,000 existing homes to attain a B2 Building Energy Rating by 2030. Although not without merit, this presents a number of risks. The authors, through a review of relevant literature and a survey of leading experts in the field of domestic retrofit, set out to explore if and how the implementation, execution, and performance of retrofit strategies that utilise a uniform approach to the retrofit of the decidedly non-uniform existing dwelling stock could create un-intended consequences. It is demonstrated how issues related to indoor air quality, comfort and overheating may occur due to the narrow focus of housing retrofit on regulated energy. It also established that the application of theoretical modelling can affect dwelling performance. These issues could have significant health and wellbeing impacts on occupants and, furthermore, could be exacerbated by the impacts of climate change. The research incorporates a risk assessment which examined the interdependent factors, including areas that require further research, that present a risk in large-scale deep retrofit. The findings have implications for the policy framework. Without action, there is a risk that the retrofitted dwellings of today become the 'hard to treat' dwellings of the future.

Keywords: retrofit; performance gap; building fabric degradation; ventilation

INTRODUCTION

Consistent with the European Union's ambition to achieve a net-zero target carbon emissions by 2050 (European Union, 2019) Irelands Climate Action Plan 2019 (Department of Communications, Climate Action and Environment, 2019) details a roadmap of measures that seeks to achieve this goal. The residential sector in Ireland accounts for both 25% of the energy and related CO2 emissions (SEAI, 2018). To meet the goals set out above, significant decarbonisation of this sector must occur. In this context Ireland has set an ambitious goal of retrofitting 500,000 existing homes to a Building Energy Rating (BER) of B2 by 2030 (Department of Communications, Climate Action and Environment, 2019). This equates to almost 30% of all residential buildings in Ireland (SEAI, 2020). Whilst such an approach is necessary, it should not be pursued in isolation.

The paper utilised a review of existing literature coupled with a survey of leading participants in the housing retrofit market in Ireland to explore the potential un-

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intended consequences that may arise from a retrofit strategy that is based upon the large-scale reduction of regulated energy. Un-intended consequences can vary from those affecting occupant health and well-being to those that affect the dwelling structure.

The authors note that occupant behaviour can adversely affect the indoor air environment. However, this is true for all dwellings and not just those under review. This paper focusses on current retrofit policy and strategy. Future research will focus further on the impact that occupant behaviour may have.

LITERATURE REVIEW

Performance Gap

The Energy Performance of Buildings Directive (EPBD) (European Parliament, 2010) mandated all EU Member States to adopt a methodology to calculate the energy performance of buildings resulting in the production of an Energy Performance Certificate (EPC) (European Union, 2002). In Ireland, the model used is the Dwelling Energy Assessment Procedure. This model incorporates default values for elements that are utilised when it is too labour intensive or invasive to determine the actual value (Arkesteijn and van Dijk, 2010). Such default values are based on the regulations that were applicable at the time of construction as opposed to empirical data (Gram-Hanssen, 2014). The use of these pessimistic defaults ensures that dwellings do not achieve greater ratings than warranted whilst promoting the positive benefits of carrying out energy upgrade works (Arkesteijn & van Dijk, 2010). The current use and application of such theoretical modelling contributes to the aptly named performance gap, the differential between the expected versus. actual energy consumption.

The performance gap can manifest as the prebound effect (Sunikka-Blank and Galvin, 2012), arising due to the over-estimation of pre-retrofit energy consumption (Gram-Hanssen, 2014) where elements of the building perform much better than the default value suggests or as the rebound effect (Sorrell, 2007) where the energy that is saved as a direct result of low energy retrofit measures is offset by increased use. Realised energy savings can be 10-30% lower than those predicted by theoretical models (Liang *et al.,* 2018).

This presents a risk in large scale retrofit as deeper upgrades than necessary may be specified, leading to additional cost for the homeowner. In addition, not achieving predicted energy, and cost savings may affect ability to repay loans taken for energy upgrade works. In turn, this may limit the ability of the national retrofit strategy in achieving its energy saving goals.

Indoor Air Quality and Ventilation

We now spend over 90% of our time indoors (Klepeis et al, 2001), as a result there is a growing awareness of the importance of Indoor Air Quality (IAQ) in energy efficient buildings along with increasing concern regarding the impact of air-tight dwellings on the health and well-being of occupants (Shrubsole et al. 2014). Inadequate air change rates have a significant impact on IAQ (Yang *et al.,* 2020). Ensuring fresh, clean air together with appropriate temperature and relative humidity are key factors in creating healthy indoor environments (Kraus 2016). Studies have previously linked severity of asthma symptoms to lower air change rates in dwellings (Ucci *et al.,* 2011) with higher indoor concentrations of air pollutants such as volatile organic compounds (VOC's) leading to an increased occurrence of mould growth and condensation

(Kraus, 2016). Research has shown that whilst VOC levels change significantly based on the season, appropriate ventilation strategies can be successful in reducing total levels (Turunen *et al.,* 2019). Demand-controlled ventilation (DCV) systems that do not supply airflow continuously but are controlled by humidity sensors to save energy can pose potential problems for exposure to VOC's (De Jonge *et al.,* 2019). Research by Sharpe *et al.,* (2016) across 85 dwelling typologies that represent 3300 homes found that only 16% of Mechanical Ventilation with Heat Recovery (MVHR) systems were commissioned correctly with respect to air flow and balancing. The reliance on a mechanical ventilation strategy is also predicated on the dwelling occupant's awareness of the system and its service requirements. A case study by Brown and Gorgolewski (2015), showed that dwelling occupants that switched off their MVHR units reported greater satisfaction with the IAQ within their apartment despite quantitative data proving the opposite was the case.

These issues present a risk in large scale retrofit as the adequacy of IAQ is dependent on the implementation of a correct ventilation strategy. Systems need to operate correctly so that they can maintain the appropriate levels of ventilation required. Dwelling occupants need to be aware of maintenance schedules. Airtightness is closely related to this risk as the reduction of unintended air leakage further emphasises the ventilation requirement.

Airtightness and Building Fabric Degradation

The presence of an airtight external envelope can lead to increased internal temperatures (Mavrogianni et al. 2013) and higher concentrations of CO2 (McGill *et al.,* 2015), VOC's and PM2.5 (Derbez et al. 2018) and mould growth (Crump *et al.,* 2009). The Durabilit'air Project (Leprince *et al.,* 2017) reviewed and analysed existing studies on the long-term durability of airtightness measures. In almost every study, the air permeability of part of the dwelling under test had decreased.

Decreases in airtightness may, dependent on the location and the envelope build-up, cause the air permeability to increase leading to uncontrolled ventilation. Leakage of moist air in the opposite direction allows hygroscopic materials within the structural envelope to pick up water molecules at the inner surfaces of their pore system until they reach a water content at equilibrium with the humidity of the ambient air (Kunzel, 1995). This can lead to mould growth and materials degradation depending on construction methods and dwelling typologies (Campbell *et al.,* 2017). In turn, this can have negative implications for occupant health and wellbeing (Shrubsole et al. 2014).

The presence of this issue presents a risk in large scale retrofit where elemental performance takes precedence over hygrothermal performance. This risk is exacerbated in solid wall traditional dwellings but exists in all dwellings where moisture may condense in an uncontrolled fashion across the internal/external elemental divide.

Radon

It is estimated that 9% of deaths associated with lung cancer throughout the EU are due to radon exposure in the home (Crump *et al.,* 2009). However, research regarding radon concentration in dwellings, specifically in retrofitted dwellings, remains limited, particularly in Ireland and the UK. A computational evaluation by Mc Grath et al. (2021) predicts radon concentration increases of up to 107% following an energy retrofit that seeks to remove all uncontrolled ventilation. Europe wide monitoring campaigns that looked at the relationship between indoor radon concentration and low energy upgrades showed that thermal retrofitting can cause increases in indoor radon concentration (Collignan et. al. 2016). Modelling by Akbari *et al.,* (2012) demonstrated that radon concentration falls as relative humidity increases from 30% to 60% whilst an increase in relative humidity above 70% correlates with an increase in air density which prevents radon from moving upwards in the room and escaping through planned ventilation channels. Therefore, it would appear that the presence of a functioning and effective ventilation system in retrofitted dwellings is important. This is furthered by McGrath *et al. (*2021) who found that the addition of dwelling specific ventilation strategies has a positive effect on radon concentration levels.

The presence of this issue presents a risk in large scale retrofit as approximately one-third of Ireland is designated as a high radon area (Radiological Protection Institute of Ireland, 2010). It is not clear at present how the presence of a retrofitted radon barrier and matters such as occupant behaviour may relate to radon levels in retrofitted dwellings. Unintended increases in internal radon levels have the potential to cause serious and long-lasting consequences for dwelling occupants. This is an area requiring further research.

Overheating

The current drive in both new build and retrofit dwellings is focused on heat retention as a climate change mitigation strategy. Although this is not without merit, the dwellings that we design build and retrofit today need to consider the potential impacts of climate change or they risk becoming the hard-to treat dwellings of the future. As such, they need to incorporate adaptive capacity to ensure long-term performance and avoid the 'locked-in' impacts of climate change (de Wilde and Tian, 2011). One of the key climate change related risks to be considered is overheating.

Low-energy dwellings have been associated with an increased overheating risk particularly in warm climates such as Australia, the United States, the UK, and part of Southern and Continental Europe (Jenkins *et al.,* 2014, Hatvani-Kovacs *et al.,* 2018, Sailor *et al.,* 2019, Salthammer *et al.,* 2018). However, overheating has also been identified as a risk in cooler and more temperate climates (Dengel and Swainson, 2012 and Mulville and Stravoravdis 2016). To date, limited research has been undertaken in relation to the overheating risk in low-energy dwellings in Ireland. Washan (2019) found that, in Ireland, single aspect dwellings and dwellings with south and west facing glazing were most at risk and called for further analysis. Mulville and Stravoravdis (2016) found that increasing levels of insulation and air tightness was correlated to overheating risk. Therefore, this issue is particularly relevant in the context of large scale retrofit.

Overheating in dwellings has been associated with negative impacts on occupant health (Dengel and Swainson 2012) whilst occupant adaptations could lead to potential safety concerns. For instance, Baborska-Narożny *et al.,* (2017) found that in a retrofitted apartment block, occupant adaptations included wedging fire doors. As such the research gap regarding overheating risks in cooler climates remains.

METHODS

This paper is part of an ongoing research project that explores the risks associated with the retrofit of housing in Ireland because of the narrow focus on the reduction of regulated energy. It incorporates an exploration of the existing research pertaining to the risk factors identified throughout the literature followed by a survey of leading experts in the field to identify and rank the highest risk factors emanating from the large-scale energy focused retrofit of housing.

The survey was administered online, targeting experienced professionals in the field. Respondents were asked to note overall, and specific housing retrofit experience, any with limited retrofit experience were excluded from the final analysis. An initial pilot of the survey took place with five respondents and some minor amendments were made to the survey following this to aid comprehension. Respondents were asked to note their awareness of the potential risk factors associated with large-scale energy focused dwelling retrofit. An opportunity was provided to add further clarification or additional comments, if required. Respondents were then asked, based on their experience, to note the likelihood of the previously identified potential risk factors occurring in respect to large scale energy focused dwelling retrofit and the magnitude of the impact should they occur. 60 responses were received which allowed the authors to analyse and rank the risk factors identified.

ANALYSIS AND DISCUSSION

Fig 1 demonstrates that experienced retrofit professionals are aware of the potential risk factors associated with large-scale energy focused dwelling retrofit. The greatest awareness is associated with negative impacts on IAQ (Mean 4.07; St. Dev 0.92). This risk factor also has the narrowest standard deviation, demonstrating a high level of agreement across all respondents.

This is followed by the Performance Gap Rebound Effect (Mean 3.85; St. Dev 1.01) showing a similar level of agreement. The position of Overheating Risks (Mean 3.8; St. Dev 0.98) and the level of overall agreement associated with it as a risk factor is surprising. Respondents were aware of and in general agreement in respect to Building Fabric Degradation (Mean 3.50; St. Dev 1.03). This is an important recognition on the part of experienced retrofit professionals.

There is a lower awareness and a greater deviation associated with the Performance Gap Prebound Effect (Mean 3.48; St. Dev 1.21). This may show that whilst there is general industry-wide awareness of pessimistic BER assumptions, respondents may be unsure as to what risk(s) may arise from same.

The largest deviation is associated with Increase in Internal Radon Levels (Mean 3.31; St. Dev 1.55) showing quite a variability of responses, quite possibly due to the limited research available on the subject, however, respondents seem to have an awareness of the link between reduced air movement and its possible effect on radon levels. Presumably, this position is held for VOC's, PM2.5, humidity, etc. as it is also reflected in respondent's position on the risks associated with IAQ.

MVHR Performance over time (Mean 3.19; St. Dev 1.48) also shows a wide range of responses, though some respondents proffered that they were disinclined to specify or use MVHR due to the perceived difficulties associated with commissioning, maintenance, and operability by end-users.

The position of and large deviation associated with Airtightness Reduction over time (Mean 3.17; St. Dev 1.44) suggests that it is also an area that is under-researched in an Irish context. It is also a risk factor that would not arise with any immediacy.

The least level of awareness among retrofit professionals is associated with DCV Performance over time (Mean 2.93; St. Dev 1.25). The relationship of DCV performance to VOC and PM levels is under-researched in an Irish context, as such, widespread acknowledgement of this issue may not exist.

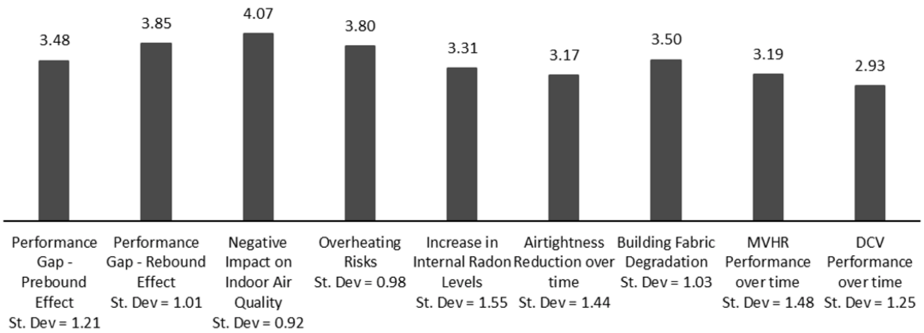

Fig 1: Mean awareness of risk factors among survey respondents

Fig 2 illustrates the likelihood of occurrence of the risk factors under review and the magnitude of the impact should they occur. The data suggests that respondents feel that the impact of each risk factor would be significant, were it to occur. Interestingly, respondents consider that the magnitude of impact associated with the occurrence of Negative Impacts on IAQ (Mean 4.07; St. Dev 0.92) and Increase in Internal Radon Levels (Mean 3.31; St. Dev 1.55) is large, reflective perhaps of the significant effects that the occurrence of both would have on occupant health and wellbeing.

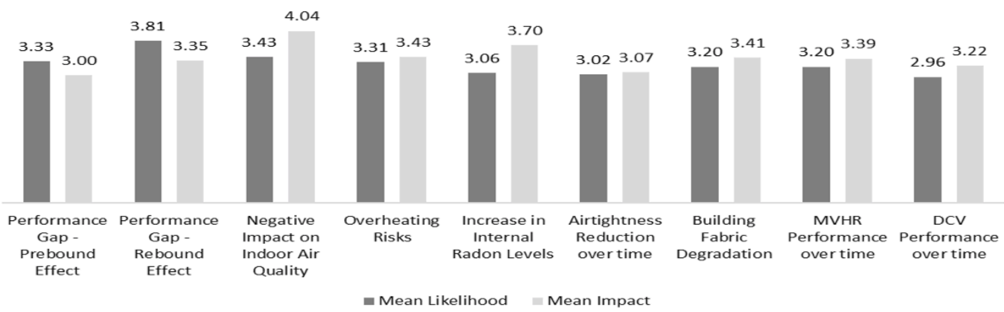

Fig 2: Mean likelihood of occurrence and magnitude of impact

Fig 3 demonstrates the individual rating of each risk factor (mean likelihood of the risk occurring x mean impact), therefore indicating the total amount of risk attached to each factor in respect to large scale energy focused dwelling retrofit.

Negative Impacts on IAQ (Mean 4.07; St. Dev 0.92) is perceived as the greatest risk associated with large-scale energy focused retrofit. This is not surprising given the level of research available (Ucci *et al.,* 2011; Shrubsole et al. 2014; Kraus 2016.).

The risk rating associated with the Performance Gap Rebound Effect (Mean 3.85; St. Dev 1.01) is interesting insofar as it reflects the position of experienced industry professionals if energy focused dwelling retrofits fail to achieve predicted energy targets. This would have serious repercussions in respect to both the overall viability of large-scale energy focused retrofit measures and the required outcome of the scheme in general.

Overheating Risk (Mean 3.8; St. Dev 0.98) and Increased Internal Radon levels (Mean 3.31; St. Dev 1.55) are also rated highly. As noted previously overheating risk and radon levels remain under explored in the Irish context. The presence of overheating risk as being significant is perhaps somewhat surprising as there is limited recorded instances of overheating in Ireland. Potentially this points to underreporting, this could be further exasperated over time due to the impacts of climate change.

Building Fabric Degradation over time (Mean 3.50; St. Dev 1.03) and MVHR Performance over time (Mean 3.19; St. Dev 1.48) are perceived, by survey respondents, to exist in the mid-range in respect to risk. The survey demonstrated that there was general awareness of these risks, with respondents indicating a relatively high impact factor should they arise. Research has shown that these risks have eventuated, following low energy retrofit measures, in other jurisdictions (Leprince *et al.,* 2017; Sharpe *et al.,* 2016; etc.). It may be only a matter of time and further research before we start to see like effects in an Irish context.

The Performance Gap Prebound Effect (Mean 3.48; St. Dev 1.21) is perceived by survey respondents to be a lower risk. However, research has shown that this does exist (Sunikka-Blank and Galvin, 2012) so it may be that general industry awareness is lacking. The survey found that the awareness of this issue is mid-range in respect to the other factors under consideration.

DCV Performance over time (Mean 2.93; St. Dev 1.25) and Airtightness Reduction over time (Mean 3.17; St. Dev 1.44) were also perceived as lower risk by survey respondents. However, the survey also found less overall awareness of these issues. Given the recentness of widescale adoption of DCV within the Irish Construction Industry and the unseen (at least for a considerable period of time) and incremental nature of fabric degradation and air tightness reduction, it is perhaps not unsurprising.

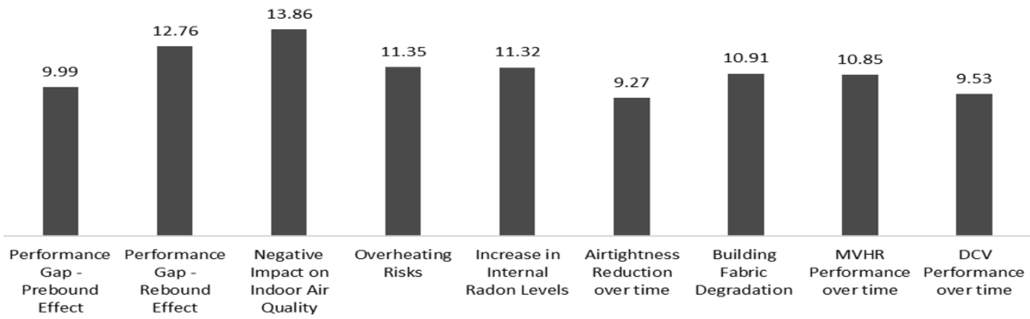

Fig 3: Risk rating - mean likelihood x mean impact

It can be argued that IAQ, Overheating Risk, and Radon Levels can all be associated with ventilation. Research has shown that these risks can be somewhat mitigated by a suitable mechanical ventilation strategy (for instance see McGrath *et al.,* 2021). Whilst welcome as a potential solution, it is important to note that such a strategy is also not without risk. Passive ventilation can be influenced by occupant behaviour (blocking of vents), with purge utilisation based on the occupant's consideration of the indoor environment. DCV can monitor humidity (some monitor CO2) but would need to incorporate VOC and PM sensors, room specific filters for incoming air, and purge capacity. The continuous activation of MVHR systems can ensure that the correct levels of airflow and air management are maintained. However, survey respondents reinforced the literature findings in respect of under-performing systems, lack of awareness among dwelling occupants in respect to operation and maintenance, and poor commissioning of MVHR systems (Brown & Gorgolewski, 2015; Sharpe *et al.,* 2016). All are valid arguments that can be mitigated by the introduction of a regulatory framework in respect of MVHR installation, operation, and maintenance.

CONCLUSIONS

This paper set out to explore if and how the implementation, execution, and performance of retrofit strategies that utilise a uniform approach to the retrofit of the decidedly non-uniform existing dwelling stock could create un-intended consequences for the dwelling and/ or occupants.

The research has confirmed the existence of risks associated with large-scale energy focused dwelling retrofit. These risks can be exacerbated by (but not limited to) poor design, dwelling typology, ventilation strategy, occupant behaviour, theoretical modelling, and building fabric degradation over time leading to airtightness reduction. These risks can negatively impact the indoor air environment in respect to air quality, increased internal radon levels and overheating and can affect the structural integrity of specific dwelling typologies. Further research is required to ascertain the un-intended consequences that can arise or have arisen as a result of the current retrofit strategy in Ireland.

Considering the interdependent risk factors that present a risk in large-scale deep retrofit, it is advisable that a policy framework is created in respect to the specific requirement for mechanical ventilation in dwellings that have undergone low energy upgrade works. The framework must regulate requirements in respect of the regulation of PM, VOC (all types), CO2, humidity levels, and purge requirement. It must also regulate procedures for installation, operation, and maintenance of ventilation systems.

Performance gaps (prebound and rebound) must be viewed as a risk that can affect the viability, therefore the success, of Irelands ambitious goal of retrofitting 500,000 existing homes to a Building Energy Rating (BER) of B2 by 2030.

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