AN OPTIMIZATION METHODOLOGY AND SENSITIVITY ANALYSIS OF EXISTING BUILDING RETROFITS

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ABSTRACT

Retrofitting existing buildings is rapidly becoming increasingly important to building owners, primarily due to the ever-increasing cost of energy. However, it is also in part due to the aging of building stock, resulting in a decrease of the efficiency of the heating equipment and a degradation of fabrics within the buildings. The building retrofit process begins with the requirement by building owners for a quantified return on the investment measures proposed. In relation to retrofitting, no one solution fits all situations and therefore the need for a simplified retrofit decision-making software tool exists. This research focuses on an optimization methodology and subsequent sensitivity analysis to determine the most influential input parameters for a case-study building. In essence, this research forms part of a larger study which is ongoing and ranges from the development of a simplified thermal energy modelling technique to a decision-making retrofit software tool.

INTRODUCTION

The construction of new, domestic and non-domestic buildings in American and European regions has decreased in the past number of years due to the economic climate being experienced. This is particularly true for Ireland, where the case-study building is located. The Irish economy was heavily dependent on the construction industry, which has experienced a consistent decrease in activity in recent years.

Consequently, the average age of the building stock will increase into the future. This will result in ageing heating systems becoming less efficient, along with windows and facade elements becoming less airtight and in need of repair. With the increase in building age, the improvement in technologies available and the ever-increasing cost of energy, the requirement for energy efficiency retrofits will increase.

The reduction in carbon emissions achievable through energy efficiency measures greatly exceeds the contribution from renewable energy improvements (SEAI 2009). This fact, in conjunction with the concept that efficiency is cheaper than fuel (Patterson et al., 2009), suggests that retrofitting will become increasingly prominent in the future.

Model-based building design is becoming more widespread, (Eisenhower et al., 2011) as building owners seek to understand the operational cost of a building prior to construction. Likewise, when a building owner decides to retrofit a building to increase its energy efficiency, the financial investment required, along with the reward and payback period, needs to be equally analysed.

A building energy efficiency retrofit is a compromise between occupant thermal comforts, investment costs and operation costs (Wright et al., 2002). It is also dependent upon the constraints set out at the initiation stage of a project. A case-study building is assessed in this paper as a method of emphasising the importance of the application of the theory to a real building.

The improvement of an ageing building involves two main processes:

1. Current condition assessment
2. Determination of future options and selection/prioritisation

The current condition assessment of the thermal energy usage in existing buildings is detailed in previous work, Murray et al., 2012. This work details a simplified static modelling technique to determine energy usage for retrofit works analysis. The research work validates a simplified modelling technique using monitored data and dynamic modelling simulation data. The case-study building which provides the data for the original research is also used in this paper.

The second process in the improvement of aging building stock has received little attention to-date, (Juan et al., 2010) and in a preliminary form is the focus of this research.

The implementation of an optimization technique for full determination of prioritised retrofit options will be developed on the foundations being established in this research. These foundations are the development of an optimization methodology and the determination of the significance of the input parameters on the model.

OPTIMIZATION METHODOLOGY

Introduction

Optimization is a technique used to obtain the best results from a system or process. It is one of the main focal points of operations research and management science and is a prevalent topic in engineering. The importance of optimization lies in the determination of the best method to adjust a system. The system which is referred to is a functionally related group of elements, in this case is the existing building which is to be retrofitted.

There are varying degrees of complexity concerning optimization. The primary criterion used to determine the optimum operation of a system varies depending on the discipline to which it is applied. In an industrial process the criterion most frequently used is in the form of minimal cost or maximum production. However, in the area of energy efficiency, the criterion is to obtain a solution which considerably reduces energy consumption, at a reasonable capital investment and within a reasonable payback period. There is a common ground in these examples in that they both require that a single quantity be minimised by variation of controlled parameters.

In essence, the importance of optimization lies not in trying to find out all about a system but in finding out, with the least possible effort, the best way to adjust the system (Adby et al., 1974). If this process is carried out well, systems of all sorts can have a more economic and efficient design. This will ultimately lead to systems operating more accurately or at a less cost, and the system designer will have a greater understanding of the effects of parameter interactions and variations of the design. The experience gained will inevitably be transferable to other such problems in the future.

Energy Retrofit Optimization Methodology

There are a number of steps in the determination of an optimized thermal retrofit solution for an existing building. These steps include:

1. *Thermal energy usage audit*
   a) Determination of building element U-values using standard calculation methods
   b) Determination of building element areas and volumes
   c) Analysis of existing heating system
   d) Assessment of the existing building for presence of infiltration and other methods of heat loss and inefficiencies
   e) Thermal energy usage determination using the simplified modelling technique
2. *Sensitivity Analysis to determine the most influential parameters*
   a) Adjustment upwards and downwards of each individual input parameter is required to assess the effect on the overall energy usage
3. *Definition of the Scope of the retrofit*
   a) The scope outlines the metrics upon which the retrofit decision is based
   b) Constraints are also identified in the scope
4. *Optimization of the retrofit solution based on the defined scope*
   a) The most influential parameters identified in the sensitivity analysis are optimized
   b) The optimization adheres to constraints identified in the scope

These steps are neither definitive nor sequential, but a general guide to the manner by which energy retrofit problems could be approached. These steps are also broken down into sub-steps to offer a more holistic methodology, as was applied in this research.

The sensitivity analysis to be carried out will highlight the most influential parameters. In this case the four most influential parameters will be used. Nevertheless, in any particular optimization process any number of parameters may be used.

In the case of this paper, the parameter values to be considered will be those which describe the current condition of the building being studied. These include:

1. U-value of different building components
2. Infiltration rate
3. Heating system efficiency
4. Temperature set-point
5. Building Geometry

There are also quite a number of non-quantifiable criteria, which can be used in the assessment or justification of a retrofit solution, including:

1. Aesthetics
2. Harmfulness to health of the materials used
3. Comfort
4. Functionality
5. Longevity

An overall retrofit solution is a combination of the quantifiable and non-quantifiable criteria which the consumer or stakeholder outlines as acceptable in the scope of the retrofit project.

CASE STUDY BUILDING

Background

The case-study building presented is the Civil & Environmental Engineering Building on the campus of University College Cork. The building is multi-purpose, containing for staff and postgraduate research students along with lecture theatres, computer laboratories and engineering laboratories for undergraduate students. The building in total hosts a floor area of approximately 2000m^2. Its energy usage, thermal and electrical, is monitored continuously since the completion of the retrofit works and is showing signs of improving performance.

Figure 1: Civil & Environmental Engineering Building

Being over 100 years old, means that the building is listed on the University's conservation plan and therefore significant alterations to the building's interior or exterior characteristics would have to be carefully considered.

Current Condition Assessment

The building, in its pre-retrofit condition, was performing poorly. This was attributable to the absence of temperature control resulting in the heating being operated on a broad sweeping on/off sequence, showing no correlation with the outside weather.

In previous work, *(Murray et. al. 2012)* the building was analysed using actual monitored data and modelled data. The modelled data was obtained from the Static Degree Days Simulation Method, outlined in the CIBSE Guide TM41:2006, whilst the dynamic data was obtained from the simulation tool in IES Virtual Environment.

The results shown in Table 1, demonstrate that, for this particular building, the simplified modelling technique is sufficient to predict the savings which can be made in energy use as a result of a retrofit solution, where the measured data is taken as a baseline.

Table 1: Building Energy Consumption Simulation Results (Murray et al. 2012)

	Pre-Retrofit (kWh)	%Deviation from Measured	Post-Retrofit (kWh)	%Deviation from Measured	% Saving
Measured Data	511,965	-	227,410	-	55.58
** Static Simulation	558,412	+ 9.07	260,695	+ 14.64	53.31
*Dynamic Simulation	445,012	- 13.08	258,921	+ 13.86	41.81

** = Degree Days Simulation Method * = IES Virtual Environment Simulation Method

The justification for the simplified modelling technique being sufficient, in this particular case-study, was made in accordance with the following rationale: the pre-retrofit Static Simulation Modelling results are 9.07% greater than the measured data whilst the post-retrofit Static Simulation Modelling results are 14.64% greater. Thus, the deviation in the Static Simulation Modelling results is similar in magnitude, and consistent in direction.

The pre-retrofit Dynamic Simulation Modelling results, in contrast, are 13.08% less than measured data whilst the post-retrofit Dynamic Simulation Modelling results are 13.86% greater than the measured data baseline. The deviation in the results for this modelling technique is similar in magnitude but opposite in direction. This leads to the conclusion that the change in energy consumption due to the retrofit is less accurate with the dynamic modelling technique for this case study building.

Whilst the models are validated, they are not calibrated. However, the comparison between pre-retrofit and post-retrofit modelling indicates that the Static Simulation Modelling is a sufficient modelling technique to identify the magnitude of savings achievable for the respective retrofit measures.

While it is not plausible to extrapolate the conclusions from this case study, the work is ongoing and the intention is to further verify the findings with additional data sets.

Retrofit Works

The retrofit of the Civil and Environmental engineering building took place during the summer of 2009. The retrofit measures undertaken included installation of the following:

1. 200mm Attic insulation
2. Thermostatic Radiator Valves (TRV's)
3. Heat meter for energy usage monitoring
4. Building Management System (BMS) with weather compensation
5. Light replacement with Passive Infrared (PIR) Sensors and Dimming Controls

The BMS installed in the building is the umbrella under which the electronic TRV's, the heat meter and the weather compensation retrofit control measures fall. The heat meter monitors the centrally supplied flow of hot water into the building, along with the temperature difference between the supply and return flows and thus calculates the heat being used on a daily basis.

All radiators in the building have been fitted with mechanically operated TRV's, with the exception of the two computer rooms and one lecture room, which have electronically operated TRV's.

As part of the retrofit works carried out, one lecture room was chosen as a test case room, where more extensive retrofit works were carried out. The reason for this decision, was to implement certain measures which were too expensive implement out throughout the entire building.

Along with the standard retrofit measures outlined previously, further upgrades were also performed, namely:

1. Electrically operated vents to replace existing open vents under two windows
2. Double glazed windows to replace single glazed windows

An air tightness test, including a leak audit was carried out on the lecture room prior to any retrofit works being carried out and once again after the retrofit works had been completed. This highlighted the main causes of the leakages in the lecture room, which included:

1. Penetrations through the floor and ceiling for service pipes
2. Mechanically operated windows not closing properly
3. Passive vents within the room remaining open

The air tightness test also offered an indication of the infiltration into the building as a whole.

DETERMINATION OF RETROFIT OPTIONS

Introduction

The retrofit works had been carried out in the absence of any detailed analysis. The pre-retrofit thermal energy consumption was determined but there was no prediciton of the post-retrofit energy usage resulting from the retrofit works. In addition, there was no investigation to determine if the retrofit works proposed were a suitable solution for the particular situation.

Retrofit analysis in advance of any retrofit should be carried out on every case-study building. Advance analysis allows for the identification of the biggest opportunities for energy savings and allows for the retrofit efforts to be focused here. Without such advance analysis, the opportunity may be lost and the maximum potential of any retrofit cannot be realised.

Sensitivity Analysis

The first step in the determination of alternative retrofit solutions is first to determine the most influential input parameters. This is carried out by changing each individual input parameter by a percentage and assessing the response of the overall energy usage to this change.

Figure 2, shows the effect of a change in each individual parameter on the thermal energy usage in the building. It clearly shows that the two most influential parameters in this building are the temperature set-point and the boiler efficiency. The third and fourth most influential parameters are the roof U-value and the infiltration rate.

Table 2: Pre-Retrofit and Post-Retrofit Input Parameters

Building Fabric	U-value Pre-Retrofit (W/m^2K)	U-value Post-Retrofit (W/m^2K)
External Walls	1.1524	1.1524
Roof	3.3775	0.1589
External Doors	2.1944	2.1944
Ground Floor	1.1258	1.1258
Single Glazed Windows	4.5000	4.5000
Double Glazed Windows	-	1.4552
Characteristic	**Pre-Retrofit Value**	**Post-Retrofit Value**
Infiltration Rate	1.3 ACH	1.3 ACH
Boiler Efficiency	80.8%	80.8%
Building Volume	9686.509 m^3	9686.509m^3
Temperature set point	22.5˚C	21˚C

From this information alone, it would be easy to conclude that a reduction in temperature set point and an increase in boiler efficiency would be the most suitable options for a retrofit solution. However, certain options can sometimes prove very difficult to implement. For instance, a reduction in set-point temperature might only be brought about through the installation of a BMS.

Whilst improving the efficiency of a boiler may seem quite simple in many respects, difficulties may arise when factors outlined in the scope of the works are considered. For instance, many existing buildings may have been built when oil boilers were mainly installed and gas would not have been widely available. As part of the retrofit project there may be a requirement to reduce carbon emissions, in which case a gas boiler would be the more sensible option and then a gas connection would have to be included. Therefore, the scope of the retrofit works needs to be clearly defined as part of the retrofit process.

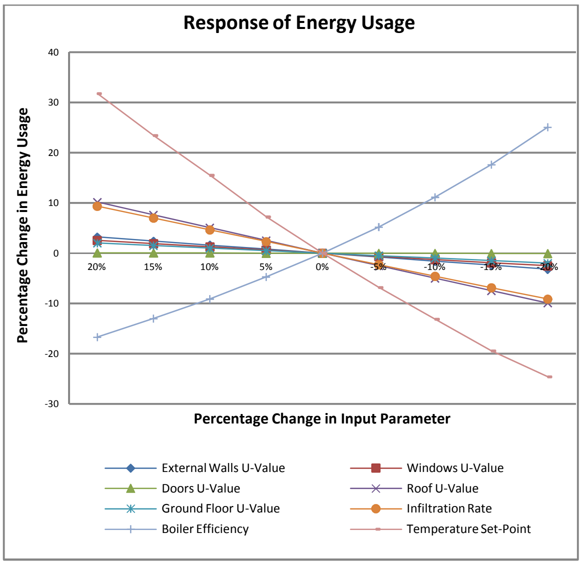

Figure 2: Response of Energy Usage to change in Input Parameters

Definition of Scope of Retrofit Works

An important aspect of the retrofit works process is the definition of a scope of works. The client's preferences need to be addressed, which generally will have concepts included such as:

1. Reduction in energy consumption
2. Reduction in carbon footprint
3. Payback within specific time period
4. Quantification and proof of savings being made

In many ways the scope serves to outline the constraints in the optimization problem. Constraints are very important as without constraints, the objective function would become zero and no heat would be used (Gustafsson et al., 1998).

The general scope of this project, in hindsight of the works being carried out, was:

1. Reduction in energy consumption
2. Increase in occupant comfort level

3. Minimum disruption to staff in building
4. Retrofit carried out under occupancy
5. No interference with external facade allowed
6. Payback in 5 years or less

This scope presented quite a number of constraints. Given that minimum disruption was to be caused to staff and it was to be done under occupation, meant that any measure in relation to the external walls and the addition of dry-lining was eliminated. This, coupled with the fact that there existed no cavity in the wall, meant that the external wall U-value was going to be a constant.

In addition, minimum disruption to staff realistically meant that the changing of the windows and doors was minimised as well as was any interference with the existing floor in the building.

All of the above constraints essentially mean that the input parameters, which can be adjusted in order to determine an optimum solution, are:

1. U-value roof
2. Infiltration Rate
3. Boiler efficiency
4. Temperature set point

Interestingly, these four input parameters have also been determined to be the most influential parameters in the building.

Retrofit Solution Based on the Defined Scope

The retrofit solution is based on the input parameters outlined previously in the scope of the works. These parameters are analysed in isolation to illustrate the effect of each variable on the overall energy usage of the building. There is an associated cost included to give a greater perspective on the implementation of each of the measures.

The roof is the first input parameter to be considered. The pre-retrofit U-value is extremely high, as there was no insulation in the roof of the building. The 2008 Building Regulations, require a U-value of $0.35 W/m^2K$ for a pitched roof with the insulation placed horizontal at ceiling level. The optimum solution, in this case of insulation only, is a thickness 80mm, as it provides the greatest reduction in energy consumption with the least possible investment (Figure 4). However, this insulation thickness gives a U-value of $0.3775 W/m^2K$ for the case study building, which is greater than that allowed if building regulations are to be observed. Therefore an insulation thickness of 90mm would be required, giving a U-value of $0.3397 W/m^2K$, which is below the specified $0.35 W/m^2K$.

Figure 4, shows the total energy costs for a 10 year period for a particular insulation thickness in order to give a general trend and also to illustrate the benefit to the retrofit as against leaving it in its current state. The period of 10 years is chosen, as this would be considered to be the expected lifetime of the retrofit works. There is also an assumption that the cost of energy will increase 6% year on year in this time.

The replacement of a boiler as part of a retrofit project can result in considerable reductions in the energy consumption associated with thermal use. Many boilers decrease in efficiency as they age and thus a 2%, year-on-year, reduction in efficiency has been incorporated into the analysis.

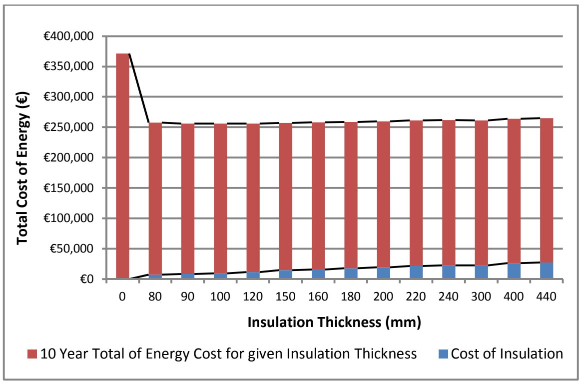

Figure 4: Insulation Changes over 10 Years

The boiler replacement results are illustrated in Figure 5, demonstrating as expected, that with increasing efficiency comes reduced annual energy costs. The recommendation to be taken from these results is that a boiler efficiency needs to be chosen based on the specific requirements of the situation, with capital cost and payback being accounted for also.

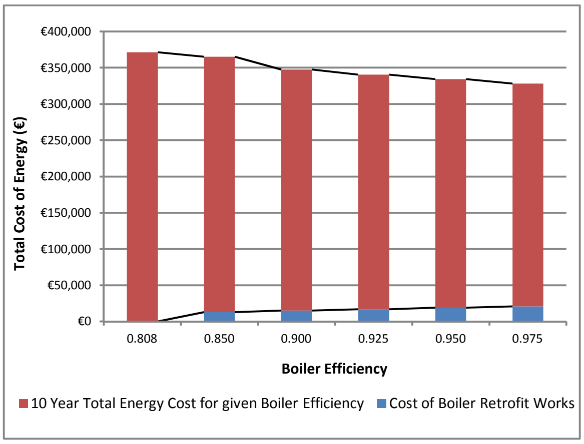

Figure 5: Boiler changes over 10 Years

The infiltration rate is a parameter which has a very significant bearing on a buildings overall energy efficiency performance. While certain amounts of air changes are needed for health reasons, too many air changes result in heat losses and are undesirable. The main contributors to the increase of the infiltration rate in older buildings are the build-up of paint on timber-framed windows, in conjunction with wear in doorframes.

Figures 6 illustrates the results of altering the infiltration rate of the building and are in line with those expected. The works to reduce the infiltration rate would be quite labour intensive, as the majority of the works would involve draught proofing

windows, doors and penetrations. This work would interfere with staff in a minor way and would not be deemed to be outside the scope of the works.
In the analysis of the infiltration rate and the effect of the changes, it is expected that a complete overhaul of the building would attain a 0.7 air changes per hour (ach) infiltration rate. The intermediate values, shown on Figure 6, would be achievable if a certain percentage of the building was overhauled. A percentage overhaul may be draught proofing the windows on one floor of the building, or draught proofing all the external doors of the building.

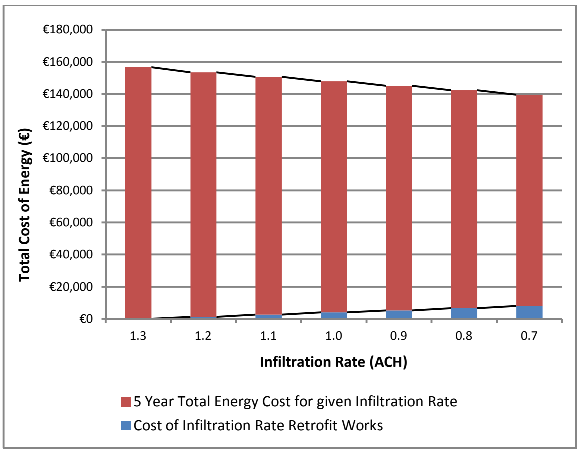

Figure 6: Infiltration Rate changes over 5 Years

The temperature set-point is perhaps the most interesting parameter which was analysed. Whilst a BMS can perform numerous functions, the adjustment and subsequent maintenance of the temperature set-point is probably the most important feature.

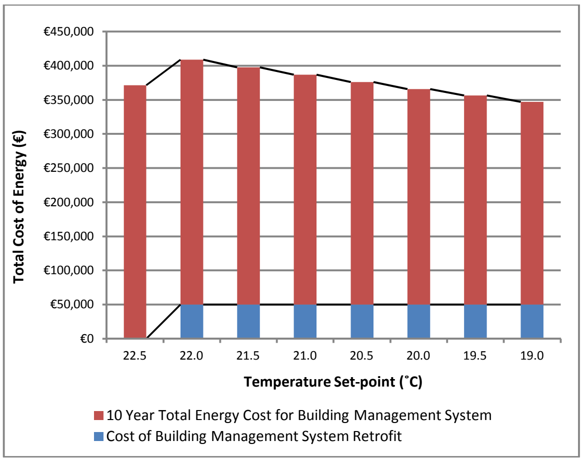

Figure 7: Set-Point Temperature Effects

Figure 7, illustrates the costs associated with the installation of a BMS. The temperature set point is used as an illustrative measure of the savings achievable by the BMS, albeit accepted that the BMS does much more than control the temperature of a building.
Building management systems require the installation of sensors, initial software and software upgrades in order to maintain the required temperature in a building. This equipment is expensive, with a cost of €50,000, put on the initial installation for the case study building.

Comparison of Implemented retrofit solution and the alternative solution.

The implemented retrofit solution, consisted of a number of thermal energy efficiency improvement measures. These consisted of:

1. Fitting of 200mm insulation in the attic
2. Installation of BMS with weather compensation
3. Installation of TRV's
4. Upgrade of windows to double glazing in one lecture room

The BMS and the TRV's could be considered equivalent measures, as electronically operated valves could be controlled by the BMS. This complete retrofit measure not only serves to control the heating in the building but also adds immensely to the comfort of the occupants within the building.
The implemented solution served to reduce the annual energy consumption in the building from 511,965kWh to 227,410kWh, or 55.47%, as determined by previous research. This equates to a thermal energy usage saving of €14,228 (assuming a gas unit price of €0.05) in Year 1 of the investment.
The insulation retrofit has the most significant bearing on the thermal energy use, yielding an annual saving of €9,304 or 33% in Year 1 of the investment and a saving of 34% over the expected 10-year lifetime of the project.
Interestingly, when an insulation thickness of 200mm is considered, the increase in investment cost over 90mm insulation is 56%, while the saving, over the 10-year lifetime, increases to just 36%. This further emphasises the need for pre-retrofit works analysis to be thoroughly carried out.
Additionally, a saving of 16% is possible in Year 1 from the infiltration rate retrofit. This is quite a significant saving potential from a small energy efficiency investment.
Overall, of the four most influential building parameters determined by this research, the implemented retrofit works addressed two, attic insulation and the BMS.

DISCUSSION

This paper proposes a methodology for decision making in relation to the retrofitting of existing buildings. It is not the intention of the paper to discuss the specifics of optimization. However, the methodology described utilises optimization and sensitivity analysis.
The methodology begins the process of determining a fully optimal solution by identifying the most significant parameters to be addressed in the case study building. The technique also shows the potential savings achievable from a relatively small

investment, when considered over the retrofit's lifetime.

The paper progresses to show that attic insulation has the most significant impact on thermal energy usage if one building parameter was to be taken in isolation. When the required thickness of insulation is compared to the installed 200mm thickness, it suggests that the installed thickness was excessive, given the savings resulting from it. This emphasises the point that pre-retrofit works analysis is essential to maximise the return on the energy efficiency investment.

With regards to thermal comfort, the analysis undertaken in this research illustrates that a BMS may have a modest impact on the overall energy usage of a building. However, in existing buildings, it is becoming essential to satisfy the occupant comfort criterion, which is included in almost all retrofit projects which are undertaken.

Another aspect of the thermal comfort criteria attached to a retrofit project is the rebound effect. This effect tends to offset the beneficial effects of the new technology or other measures undertaken. The literature on the rebound effect typically focuses on the effect of the improvements on energy consumption. It is generally expressed as a ratio of the lost benefit compared to the expected environmental benefit when holding consumption constant. The existence of this effect is accepted, however, the size and importance of it in relation to real world situations is, to some extent, unknown.

CONCLUDING REMARKS

The retrofit evaluation of a building is quite an onerous task, due to the fact that a building can often be regarded as a complex system. The influence of sub-systems on each other and on the overall performance efficiency can often be quite detailed.

The analysis carried out as part of this research does not determine a fully optimal solution, but puts in place a methodology, which will be developed through future research using more sophisticated computer software.

This research demonstrates the need for a systematic approach to avoid wastefulness and to maximise the return on an energy-efficiency investment.

NOMENCLATURE

ach, air changes per hour
BMS, Building Management System
TRV, Thermostatic Radiator Valve

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