



ASSOCIATION OF RESEARCHERS IN CONSTRUCTION MANAGEMENT

ARCOM Doctoral Workshop on Sustainable Urban Retrofit and Technologies



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WELCOME AND INTRODUCTION

The London South Bank University (LSBU) and Northumbria University (NU) cordially welcome the participants to the doctoral workshop organised by the Association of Researchers in Construction Management (ARCOM). LSBU and NU are, indeed, very pleased to be hosting this event. ARCOM brings together all those interested in construction management research. ARCOM's aim is to facilitate the advancement of knowledge in all aspects of management in construction by supporting education, dissemination and research. The doctoral workshop is a very important activity, which ARCOM organizes. The workshop has three aims, namely: providing the opportunity for students engaged in PhD research to present papers and thus benefit from feedback on methodological and other issues raised by their work; giving all delegates an insight into current research being carried out in construction management; and providing a chance to meet other researchers and practitioners working in similar fields. By achieving these aims, the workshops also help ARCOM to strengthen its contribution to the research community

The focus of this ARCOM sponsored workshop is to explore the theory, management, implementation and utility of sustainable technologies in the built environment. Over the last three decades, there has been a great deal of interest in the study of sustainability, one of the greatest challenges the world is currently facing. In construction, the challenges are large, given the size of the construction industry (which account for 8% of GDP), the enormous amount of the resources it consumes, the major impact of its products and activities on the construction industry (around 40% of our energy use goes on building, construction and maintenance) and the society at large, and the impact on the environment. In tackling some of these issues, technologies have formed the cornerstone of most developments in built environment. Given the growing importance of technologies in achieving sustainable construction and a better built environment, it is not surprising that the significance of the role of technologies is being increasingly recognised in sustainability agenda.

The workshop has therefore, brought together doctoral researchers and practitioners working on projects associated with sustainable urban retrofit, sustainable construction and building to debate on contemporary developments in this area. It provided a platform for doctoral students to share their theoretical and empirical insights on sustainable technologies and urban retrofit research. The workshop examined the areas of **sustainable urban retrofit** and the **role of technologies in delivering sustainable development**. Therefore, potential research areas were identified to form specific themes for discussion, including:

- Retrofit technologies and their research at a range of scales: building, neighbourhood and city
- Urban retrofit research including, but not limited to, metrics and measurement of urban sustainability, urban transition modelling, and large scale regeneration and renewal
- Managerial and theoretical issues including, but is not limited to, research of wider concepts of sustainable development, the opportunities and challenges associated with technological solutions and green benchmarking tools
- The role of IT and BIM in supporting sustainable technologies

As a result of the specific themes, eight papers were accepted. These deal with a range of issues, including how sustainability, retrofit and re-use can be applied in commercial real estate, exploring method of evaluating the life cycle environmental impacts of double skin facades in refurbishments, using of hybrid approach of data quality indicators and statistical

method for improving uncertainty analysis in life cycle analysis of a small off-grid wind turbine, development of a carbon measuring tool to promote sustainable construction, exploring the physical scale and social quality of housing in sheltered independent living, and how the understanding of the drivers, barriers and motivations for energy efficiency can help promote housing retrofit.

I hope you find the papers assembled in these proceedings and the discussions during the workshop, informative and stimulating.

Workshop Convenors:

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WORKSHOP PAPERS

ADAPTING COMMERCIAL REAL ESTATE: URBAN SUSTAINABILITY, RETROFIT AND RE-USE.

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Commercial real estate, in particular secondary office property, is suffering from a combination of functional, physical and economic obsolescence, undermining sustainable economic development and territorial resilience. Commercial real estate is largely absent from the sustainable urban retrofit nomenclature, with emphasis more often on residential property and general concepts of built environment infrastructure. The aim of this paper is to demonstrate a method that isolates those office properties most appropriate for sustainable urban retrofit. A data base that combines National Non Domestic Rate Returns and Valuation Office Summary Valuation data sets has been created that describes commercial office vacancy in the UK. 'Vacancy weight' is a method of analysing this information, placing cost and value upon commercial office market inefficiency. Its output 'acute vacancy' is a means of enhancing sustainable urban retrofit. Its findings reveal that a minority of buildings overhang the office market disproportionately, but at the same time have the inherent characteristics to enable adaptive re-use in either current or alternative use, a win win situation for all concerned. These methods can be used to upscale adaptive re-use and sustainable urban retrofit, moving beyond piece meal action and a 'good idea,' toward systematic use and practical reality. Targeting scarce resources where they can have most impact, the valuation of vacant office property, its quantification, typology, assessment of disproportionate impact and potential re-use, all presented in this paper, are original contributions to office market study in the UK. Conclusions indicate that 'adaptive re-use' and 'sustainable urban retrofit' are most useful when approached in combination rather than isolation, while the decision to adapt and/or retrofit is ultimately defined by economic viability rather than physical feasibility.

Keywords: adaptive re-use, acute vacancy, retrofit, vacancy weight, viability.

INTRODUCTION

The purpose of this paper is to demonstrate a method that isolates those office properties that are most appropriate for adaptive re-use, combining physical feasibility and economic viability. The principle method, 'vacancy weight' places cost and value upon commercial market inefficiency, providing an economic baseline for economic viability appraisal, while 'acute vacancy' provides a rationale for strategic intervention.

This paper proceeds through 4 stages. Stage 1 describes commercial office inefficiency in the UK and the potential for adaptive re-use and sustainable urban retrofit to improve this situation. Stage 2 presents pilot study findings based in the cities of Leeds and Newcastle, introducing 'vacancy weight,' which is a method of isolating inefficient office properties. Stage 3 presents 'acute vacancy,' describing those properties that overhang the office market disproportionately but also have the inherent characteristics to enable adaptive re-use. Stage 4 summarises the arguments in this paper, using 'compound loss' to link the cost of urban inefficiency to the economic decision to adapt and/or retrofit or demolish. Finally it sketches some recommendations for improving the routine practice of adaptive re-use, arguing that 'adaptive re-use' and 'sustainable urban retrofit' are most useful when approached in combination rather than isolation.

THEORETICAL ARGUMENT: ADAPTING SUSTAINABLE URBAN RETROFIT

A key part of achieving resilient cities is the transition toward a future that is low carbon, energy efficient, green and overall, sustainable. This has been magnified by state rescaling and the use of urban decarbonisation as a strategy of urban entrepreneurialism; the zero carbon agenda and concepts of 'smart' and 'future' cities are increasingly prevalent.

A key theme in this transition is sustainable urban retrofit; the 'Retrofit 2050' project (Eames et al 2012:6) defines sustainable urban retrofit in the following way;

"The directed alteration of the fabric, form or systems which comprise the built environment in order to improve energy, water and waste efficiencies."

Closely related is the concept of adaptive re-use, Douglas (2006:14) defined adaptive re-use as

"Any work to a building over and above maintenance to change its capacity, function or performance."

While sustainable urban retrofit generally regards adding new technology to old, adaptive re-use is a broader concept, which most prominently regards adding new use to an outdated buildings form and function. It is about making the most of existing embodied energy in commercial real estate which maximises the building life cycle. It is also about designing new buildings over the long term which flexibly responds to need rather than historical use, designing flexible form rather than rigid function.

Although 'adaptive re-use' and 'sustainable urban retrofit' are both useful means of improving inefficiency in commercial real estate, 'adaptive re-use' has been chosen as the conceptual focus of this paper. It is considered more extensive in terms of its ability to improve inefficient allocations of urban land and property resources. However sustainable urban retrofit plays an important part in the achievement of adaptive re-use and vice versa. One of the central arguments of this paper is that one method of intervention should not be considered without the other. There isn't any point retrofitting an ageing property that has no potential adaptation value, to do so would be a waste in resource. However, in those properties that do have a future in alternative use, sustainable urban retrofit can potentially play an important role in achieving economic viability. Therefore, the methods presented in this paper can be used to inform both 'adaptive re-use' and sustainable urban retrofit,' ideally concurrently.

Hitherto, research regarding adaptive re-use and sustainable urban retrofit has emphasised residential property, transport and broad concepts of the 'built environment.' Commercial real estate and its unique characteristics are generally absent from urban sustainability discourse, in particular commercial office space. This is important; commercial real estate is vital in the urban land definition and reproduction of city centre areas in both the global north and south. Disregarding commercial real estate undermines the 'future city.'

Henneberry and Roberts (2008) argue that commercial real estate is considered necessary for economic development - the quantity and quality of available buildings is crucial in the efficiency of all firms. However, some office accommodation has emerged as a problem, in particular secondary office accommodation. Such buildings display a combination of economic, functional and physical obsolescence. These buildings generate negative externalities; they overhang the local property market and suppress values and investment; they cause visual blight in their immediate surroundings; they represent high embodied energy from their production and are a waste of resources, in terms of capital investment, holding costs and land use.

CBRE (2012) examined the secondary office markets in Aberdeen, Birmingham, Bristol, Edinburgh, Glasgow, Leeds, Liverpool, Manchester and Southampton and found that total second hand availability across the nine regional cities increased from 6.8 million sq ft in 2007 to 13.3 million sq ft by the end of 2011, an increase of 97% (equivalent to 100 football pitches). They indicate that Glasgow witnessed the biggest increase in availability, 213%; Southampton was lowest with less than 50%. Importantly take up of secondary stock has generally remained stable but the supply has increased.

The central argument of this paper is that, independent of market cyclicity, significant quantities of this property will never be efficiently utilised in its current condition again; such property is 'structurally' vacant. However this doesn't mean they should be left unused or immediately demolished. Such properties should first of all be considered for adaptive re-use, either within current or alternative modes of use while properties of the future should be designed with these principles in mind.

Jacobs (1961:247) anticipated adaptive re-use, arguing that,

"Time makes the high building costs of one generation the bargains of the future generation...time makes certain structures obsolete for some enterprises and they become available for others."

At the turn of the millennium Kincaid (2000, 2002) argued that the majority of commercial office space in 2050 has already been built, new development each year only makes a very small contribution to overall supply. In other words we need to make the most of our existing resources, understanding which inefficient properties can be re-used in another use and which should be removed from property supply altogether. Examples of adaptive re-use can be seen in Western Europe, North America and Australasia. Specific examples include the Melbourne 2020 programme, the Dutch Building Covenant and the Lower Manhattan Revitalisation Plan. Although rhetorically popular, adaptive re-use has never been systematically adopted in the UK, rather, efforts have been piecemeal, opportunistic and fragmented (Bullen and Love 2010, Bullen 2007, Shipley et al 2006, Remoy and van der Voordt 2007, Kurul 2007). Similar findings apply to sustainable urban retrofit. The physical attributes that enable adaptive re-use are relatively well theorised, focusing on building fabric and technology. However issues of form, function, price and viability have received less interrogation, hampering the determination of economic viability. The real challenge is isolating those properties that are most assertive in terms of inefficiency and those most appropriate for re-use and then justifying viability in re-use.

The decision to adapt and or retrofit and its potential efficient delivery is ultimately a question of economic viability rather than physical feasibility. Answering this challenge begins to move adaptive re-use from a good idea into a practical reality.

Overall it is questionable whether anyone has a UK-wide appreciation of:

- how much vacant office property exists;
- where it is located;
- what types of office building are most likely to be vacant;
- what types of office property have the greatest potential for adaptive re-use.

An evidence base and decision making tool that moves beyond piece meal activity to methodical activity has a key role to play in urban resilience, urban restructuring and the reduction of vulnerability in the built environment. Subsequent sections of this paper present a methodological framework that resolves these issues based on relative cost and value. 'Vacancy weight' places commercial office vacancy in its relational context, demonstrating the cost of commercial office vacancy. Its output, 'acute vacancy' isolates those properties most assertive in terms of inefficiency and those most appropriate for adaptive re-use.

METHODOLOGICAL FINDINGS: JUSTIFYING ADAPTIVE RE-USE

Traditionally it has been difficult to create a reliable evidence base that articulates office vacancy across the UK, or a model that indicates its typological characteristics. A data collection exercise conducted by the authors in the UK, has revealed that problems persist with access, conformity, comparability and transferability of office market data in part due to existing data sources having been created at different times for diverse purposes. The Government based its own business case for the recent relaxation of permitted development rights for office to residential change of use on statistics published in 2005. Thus a policy decision has been made using nearly 10 year old data from before the recession.

Initial case study findings offer some insight into office vacancy in Leeds and Newcastle and provide a potential means of linking adaptive re-use with those properties that most overhang office markets. The cities of Newcastle and Leeds were chosen because of their mature office market characteristics and 'core city' status. The overall empirical case study covers the UK office market, which includes 30 locations and more than 15,000 underperforming office properties. This is the first time a multi criteria commercial office market data set has been created in the UK which offers the capacity for multi geographic analysis and decision making, from the individual building scale up to the urban conurbation. Currently, there isn't a resource for determining national vacancy averages; as such the preliminary findings in this paper can't be compared to a national average, however subsequent research outputs based on the UK case study will fill this void.

Adapting research in the previous decade carried out by Katyoka and Wyatt (2008) and the Department of Communities and Local Government (2006), this paper exploits National Non Domestic Rate returns and Valuation Office Summary Valuation data to create aggregated building profiles that describe the characteristics of office vacancy, in particular its nature, scale and geography in the UK. National Non Domestic Rate Return information was either made freely available by local authorities or collected after freedom of information request. Summary valuation data was obtained from the National Valuation Office national data set. This paper presents pilot findings based on 449 vacant office properties in Leeds and 258 in Newcastle. In Leeds the vacancy rate for 2012/13 was 14%, in Newcastle it was 17%. This equates to 267,000 m² of vacant office floor space in Leeds and 155,000 m² in Newcastle, illustrating the magnitude of wasted space in both areas. Utilising rateable value as a proxy measure of rental value, the vacant space in Leeds and Newcastle represents £48m and £21m in lost revenue per year. The vast majority of this floor space is secondary, (82 % in Newcastle and 79% in Leeds).

There isn't enough prime accommodation and there is too much secondary accommodation. Arguably there is enough office property, only not of the right type. 'Vacancy weight' was then used to segment secondary vacancy into 'low', 'medium' and 'high' impact. 'Vacancy weight' uses rateable value as a proxy measurement for building age, size, location and prestige and its relative position within the office market. This position moves beyond typologies that focus on only physical characteristic, length of vacancy and standard building condition to capture the commercial office market dynamic in terms of cost and value.

$$VW = \frac{CRV \times ALV}{100}$$

Where:

VW = Vacancy Weight

CRV= Cumulative Rateable Value

ALV= Average Length Vacancy

Each segment is based on an equal number of properties. In both cities, high impact vacancy accounts for roughly 70% of all secondary office property vacancy, demonstrating that a minority of vacant buildings disproportionately impact the secondary office market.

APPLIED FINDINGS: A WIN - WIN SITUATION

Crucially, within 'high impact' vacancy, a further subset of properties exists, that of 'acute vacancy' that captures those properties, which because of their specific characteristic overhang the secondary office market to the greatest degree. Project findings, which build upon a technical adaptive re-use typology published by Barlow and Gann (1996) at the end of the previous century helps illustrate the characteristics of 'acute vacancy.' 'Acute vacancy has:

- robust land value and expectant property value;
- good access to amenities and transport;
- generous car parking;
- sound overall building structure which supports adaptation and alterations to external cladding;
- generous overall size which supports critical mass;
- appropriate building depth allowing access to natural light;
- appropriate floor to ceiling height which allows retrofitted mechanical and electrical alterations; minimal structural obstruction which allows flexible space planning and sub division;
- there is consensus for change.

In Leeds and Newcastle, acute vacancy accounts for only 37 and 24 buildings respectively, but these building equate to approximately 40% and 50% of all vacant secondary office property in the two cities, corresponding to 78,529 m² of floor space in Leeds and 60,922 m² in Newcastle, the compound value³ of which, based on rateable values, is £12.6m in Leeds and £8.8m in Newcastle.

In Leeds and Newcastle such buildings are typically located in city centres, constructed between 1960-1980 and suffer from obsolescence and redundancy to some degree. Relevant to the current permitted development rights debate regarding office to residential conversion, such buildings are also potentially the most viable in terms of adaptive re-use because of their inherent characteristics. If governmental agencies, local authorities, developers and investors were to focus attention on those buildings identified as 'acutely vacant', secondary office vacancy may be reduced by up to 40% in Leeds and potentially halved in Newcastle.

The potential of these findings are not only important in terms of potentially improving the efficiency of the market. 'Vacancy weight' and its output 'acute vacancy' can also be used as an analytical tool which can be used to rationalise the potential re-engineering of an ageing commercial office stock in the UK, linking the commercial office market with sustainable

urban retrofit. Concentrating on those properties that have a viable future makes the best use of finite resource and maximises the potential impact of adaptive re-use and sustainable urban retrofit measures.

At the individual building scale, initial project findings indicate that there are a number of critical considerations that will influence the suitability and viability of specific buildings for adaptive re-use:

- Is there sufficient floor to ceiling height to allow mechanical and electrical service improvements? This has been negated to some extent by wireless technologies
- What is the building's thermal efficiency? Buildings of this era typically have a large area of single glazing and inadequate curtain walling.
- What is the building's energy performance? In 2018 it will be illegal to let a commercial building in the U.K. with an energy performance certificate (EPC) below grade E
- Does the building configuration and depth provide adequate natural light and opportunity for passive ventilation?
- Will the general access arrangements and lift system need to be remodelled?
- What is the environmental condition of the building with respect to asbestos and other contaminants?
- Are the building's fire safety arrangements supportive?
- What is the local planning authority's attitude toward re-use? 'Acute vacancy' generally resides in 'prime' areas; will change of use or mixed-use be countenanced in such areas?
- Is there likely to be need for planning permission as a consequence of external alterations?
- Is there demonstrable demand for potential re-use?
- What evidence based resources and appraisal/solution models are available to practically assess technical feasibility and financial viability?

CONCLUSIONS

Sustainable urban retrofit is only possible in commercial real estate if emphasis is placed upon retrofit technology as well as building form and use. In other words the principles of adaptive re-use must be combined with sustainable urban retrofit. Energy use and embodied carbon should be considered in tandem, especially when considering proposals for demolition; 'acute vacancy' provides a means of maximising and up scaling resources in this regard.

One of the key barriers to systematic urban retrofit, adaptive re-use and the extension of economic life has hitherto been the inability to place value and cost upon inefficiency in commercial real estate (Remoy 2010). Instead focus has been directed toward the physical characteristics of vacancy and potential re-use at the individual building level.

In response, 'vacancy weight,' in particular its use of 'cost' and 'value', integrates commercial real estate, urban land economics, and sustainable urban retrofit and re-use. The valuation of commercial office vacancy helps to create a methodological baseline for calculating the present value of land resources and its potential re-use; a key element in determining economic viability. In particular it helps answer the following question, is it prudent to extend the economic life of a building through adaptive re-use and/or sustainable urban retrofit or is it more prudent to clear the same site and rebuild.

'Compound loss' has been designed to help answer this question. It is an indicator that describes the financial impact of vacant office property and the ageing building stock in the UK. It is a composite indicator utilising rateable value as an approximate measurement of rental value and empty property rate value as an approximate measure of holding cost.

$$CL = CRV + EPR$$

Where:

CL = Compound Loss

CRV = Cumulative Rateable Value

EPR = Empty Property Rates

If the decision is taken to extend the economic life of a given building the objective must be to increase the future net annual returns (NARS) by more than the cost of refurbishment (Jowsey 2011), inability to do so indicates lack of viability. The option of adaptation into alternative use is one means of increasing future rent and presumably counteracting the disadvantage associated with 'compound loss.' The technology of sustainable urban retrofit compliments this process, further reducing likely operating cost and enhancing the business case for building life cycle extension.

This paper specifically regards adaptive re-use and commercial office space; however the methodology presented in this paper and its underlying principles can be utilised in any location and in conjunction with all types of property when the appropriate conditions exist. It provides a strategic means of up scaling adaptive re-use, helping to efficiently realise sustainable urban retrofit at the city and territorial level as well as providing a baseline financial position to consider viability.

This research project is ongoing, subsequent research outputs will include but are not restricted to:

- A typology of vacant office accommodation in the UK;
- A solution typology and model for improving vacant commercial office property;
- A valuation instrument for adaptive re-use and sustainable urban retrofit.

To conclude, the following recommendations sketch some principles that can be used to inform systematic adaptive re-use in commercial office space. These recommendations are based upon initial findings in the research project to date.

Recommendations

- Sustainable urban retrofit must place emphasis on technology and building use. It is not practical to retrofit a property that suffers from either functional, physical or economic obsolescence without a demonstrable potential future use;
- When extending the life of a building through adaptive re-use the future revenue or net annual return (NAR) should be demonstrably higher than the cost of the respective intervention measure;
- Energy use and embodied carbon must be considered in tandem especially when considering potential demolition and redevelopment, together both can enhance future net annual return;
- The symbiotic relationship that exists between commercial real estate, economic development and the consequent production and reproduction of the built environment must be recognized and incorporated into contemporary sustainable urban retrofit and the 'future city' agenda;
- The international regulatory systems should be flexible, dynamic and fluid to reflect the needs of flexible, dynamic and fluid occupier demand. Change in use should be the assumed norm;
- Redundancy, use diversity and flexibility should be a fundamental part of all new development proposals in the Global North and Global South.

Endnotes

1.Prime: Generally the best specification, 'blue-chip' tenants and highest rents.
Secondary: Usually older with dated specifications; often associated with various types of obsolescence and have difficulty maintaining existing and attracting new tenants.
Tertiary: Not considered part of the 'real' office market; often in marginal location and typically exhibit functional, economic and physical obsolescence.

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EXPLORING PERFORMANCE GAP ISSUES IN RETROFIT PROCESSES OF HARD-TO-TREAT PROPERTIES IN ENGLAND: THE RECOGNISED ARCHITECTS' PERSPECTIVE

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European Union and UK energy policy recognise the significant impact of deep housing retrofitting in major carbon reduction. Practising low-carbon housing retrofitting is now necessary for meeting national carbon and energy savings targets. However, low-carbon housing retrofitting is a complex process that frequently fails to match design predictions with actual energy performance. Performance gap issues in low-carbon housing retrofit projects are a major challenge in the field. Closing the gap in such projects could potentially make a novel contribution to major reduction in energy consumption by delivering design predictions. The aim of this research is to identify key performance gap issues in the processes of low-carbon housing projects from the perspective of the UK's recognised architects in the field and highlight some recommendations that could successfully close those gaps. In-depth semi-structured interviews were conducted with the experts, based on a series of Retrofit for the Future projects focusing on hard-to-treat properties. The research found out that major constraints in the performance gap are associated with low level of buildability in deep retrofitting and yet this phenomenon has not been explored comprehensively. There is an urgent need in the industry to recognise the value of this concept and practising high buildability in deep retrofit projects. This study identified a series of key buildability issues standing in the way of meeting design predictions. Lack of retrofit coordination in deep retrofit processes was recognised as one of the major and common issues in buildability despite the fact that every low-carbon project requires a tailored strategy. This research concludes with several recommendations directed at both designers and construction practitioners in the industry to address the performance issues that hinder a successful design delivery of low-carbon housing retrofit projects in England and to practice high buildability in such projects.

Keywords: Low-carbon housing retrofitting, Architects, Retrofit processes, Performance gap, England.

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INTRODUCTION

This research focuses on the UK's housing sector, which accounts for approximately 30% of UK energy consumption, double that of the commercial sector and public buildings (BERR, 2007). The UK government has set an ambitious target to cut carbon dioxide emission levels by at least 80% by 2050 (Climate Change Act, 2008). Nonetheless, Jenkins (2010) and Kelly (2009) argue that the figure is ambitious. In order to meet the target set by the government, all industries, including housing, commercial, public and transport sectors are required to reduce carbon emissions and energy consumption (Fankhauser et al., 2009; Osmani and O'Reilly, 2009; Neme et al., 2011). Similarly Boardman (2012) shares the view of Jenkins (2010) and Kelly (2009) expressing uncertainty in the feasibility of the government target, and stresses the importance of the building sector in carbon emission reduction. The housing sector in particular accounts for nearly a third of total UK energy consumption (DECC, 2012), with 58% of this consumption due to space heating demand (DEFRA, 2001; ODPM, 2001; UG, 2003), and contributes substantially to national carbon dioxide emissions.

Housing has generated the most interest, with the majority of UK buildings falling within this sector (Power, 2010; Roberts, 2008), accounting for 26 million houses (Palmer and Cooper, 2011). The European Union and the UK government have introduced several policies and related initiatives such as: the Energy Performance of Buildings Directive, the EU Renewable Energy Strategy, the Climate Change Act 2008, and the UK Low Carbon Transition Plan (DECC 2009a; DECC 2009b). However, the implementation of strategies towards effective energy efficiency within the UK is currently not sufficient to achieve targeted carbon dioxide reductions (DECC, 2009b; SDC, 2005). The slow progress of carbon reduction in the housing sector and piecemeal policies validate the views of Jenkins (2010), Kelly (2009) and Boardman (2012) on the government's ambitious target. This confirms that the feasibility of achieving the target set by the government is questionable and there is an urgent need for practical action in the industry, as well as government policies, to achieve this ambitious target. In order to tackle the problem of an energy-inefficient housing sector, the government has focused on increasing the number of new buildings as well as improving energy efficiency standards through setting targets of zero-carbon homes for all new buildings by 2016 (DCLG, 2014).

However, recent studies have shown that 75% of the houses that will exist in 2050 have already been built (Ravetz, 2008). This is a major issue. Existing housing has the potential to offer a significant contribution to reducing energy consumption considerably through deep retrofitting. In order to achieve deep carbon emission cuts in the housing sector, it is likely that comprehensive whole-house retrofit will be required, incorporating measures to reduce the rate of heat loss, control ventilation and generate heat and power (TSB, 2014).

Currently, very few homes in the UK are being retrofitted to such a standard (Killip, 2008). In addition to this, low-carbon new-build housing development is slow, contributing only 1% to the existing stock per year (DCLG, 2012; Jenkins, 2010). Existing housing has the potential to offer a significant contribution to reducing energy consumption considerably through deep retrofitting. In order to achieve deep carbon emission cuts in the housing sector, it is likely that comprehensive whole-house retrofit will be required (incorporating measures to reduce the rate of heat loss, control ventilation and generate heat and power). Currently, very few homes in the UK are being retrofitted to such a standard (Killip, 2008). Most importantly, retrofitting existing housing stock is a challenging task (Davies and Osmani, 2011). The Energy performance gap is repeatedly evident between the designed and as-built retrofit performance, and is considered a major issue in this field (Zero Carbon Hub, 2014; Hong et al, 2006).

As a result, such projects frequently fail to deliver design predictions and subsequently do not perform as intended, especially in 'hard-to-treat' properties (Dowson et al., 2012).

THE UK EXISTING HOUSING STOCK

Boardman et al. (2005), and organisations such as (including UKGBC (2012), DECC (2011), Cities Action for Sustainable Housing (2010) and the Parliamentary Office of Science and Technology (2005), acknowledge that the UK's housing stock has been recognised as one of the least energy efficient in Europe. Furthermore, they also highlight that fuel poverty and winter deaths remain serious problems, despite the UK's comparatively low domestic gas and electricity prices (Guertler and Royston, 2013). It is noteworthy that space heating accounts for the most of household energy in the UK (UK-GBC, 2008). Similarly, CLG (2012) confirms that a large proportion of the existing housing is old and energy-inefficient. This is because most it was constructed before 1919, when there were no energy related building standards (Killip, 2005). As such, these houses tend to suffer from major heat loss and thermal bridging (Dowson et al., 2012). CLGC (2008) shares the same view and has also identified the high number of dwellings built before 1919 as problematic, indicating a slow increase in the SAP rating of such properties. The Standard Assessment Procedure (SAP) is a methodology developed by the Building Research Establishment (BRE), and was adopted by the Government to assess and calculate energy performance in the housing sector (Arup, 2008; BRE, 2005b). The SAP calculation is based on a point system scoring up to 100, with a higher score indicating a lower running cost. The assessment determines fuel costs and carbon dioxide emissions by taking into account the building components (Roberts, 2008).

Ravetz (2008) argues that the energy efficiency of existing properties has been improving over the last decade, indicating a slow increase in SAP ratings from 42 points in 1996 to 49 points in 2006. However, DECC (2014) indicate that in 2013 the overall carbon dioxide emissions from this key sector reached nearly 77 MT and revealed a 3% carbon emissions increase in the housing stock, which accounts for most existing buildings between 2012-3.

It is important to note that around 8 million of these are classed as 'hard-to-treat' properties (CSE, 2011; Roberts, 2008) that were predominantly constructed between the 19th and early 20th century (Evert, 2007). The characteristics of such properties include solid-walls, single glazing, no loft space and the use of electricity as their main fuel because they have no gas supply (CLG, 2006). In contrast to Ravetz's optimistic view about the energy efficiency improvements in the existing housing stock, Jenkins (2010) addresses the very low turnover in housing development and stresses the likelihood that most of the existing housing stock will still be in use 2050 (DCLG, 2012; TRCCG, 2008). This confirms the urgent need to tackle the UK's existing inefficient housing stock, particularly the 'hard-to-treat' properties, and to reduce the demand for carbon-intensive energy in order to respond to climate change. Many authors (including Johnston, et al. (2005), Ravetz (2008) and Power (2008) have viewed this challenge as an opportunity to adapt these properties: supporting the sustainable retrofit approach. Furthermore, the diverse and extensive benefits of housing retrofitting have been explored and confirmed.

LOW-CARBON HOUSING RETROFIT

Low-carbon retrofit definition

Baeli (2013) describes the term retrofit as building works undertaken on existing old buildings in need of adaptation that enable such buildings to respond to the climate change. Brown and Swan (2013) indicate that the definition of retrofit is the same as other terms refurbishment, renovation, restoration and repair. In the context of this research the term "low-carbon retrofit" refers to the upgrades and the integration of low-carbon energy-efficiency measures in housing to enable adaptation and to extend its life.

Low-carbon retrofit challenges

Numerous challenges related to low-carbon retrofitting are highlighted in the literature. Integration of retrofit measures is identified as one of the major retrofit considerations, as the effectiveness of such measures is perceived as unreliable (Davies and Osmani, 2011). Swan et al. (2013) conduct a detailed investigation assessing the effectiveness of retrofit measures, which validates such perceptions. Dowson et al. (2012) share the same view, suggesting that retrofit measures ‘may only be half as effective as anticipated’. This indicates that the retrofit measures are to a certain extent unreliable, which effectively has a direct impact on the efficiency of retrofit design integration. In addition, ‘lack of skilled construction personnel with prior low-carbon retrofit’ and ‘lack of installation knowledge’ have been lightly touched upon by Osmani and Davies (2013). However, it is interesting that ‘diversity of housing stock’ in particular has been highlighted the most in literature as the prime retrofit challenge (Osmani and Davies, 2013; Davies and Osmani, 2011; Stafford et al., 2011; Jenkins, 2010; Osmani and O’Reilly, 2009; Plimmer et al., 2008). On the other hand, based on a study conducted by Hong et al. (2006), thermal bridging is evident, and consequently retrofit projects do not perform as expected. Similarly, Ravetz (2008) argues that despite the extensive integration of retrofit measures; there is still a need for major energy performance improvement in housing retrofit. This is a major challenge in housing retrofitting that indicates a clear gap between design predictions and delivered project, and raises critical questions: What are the key energy performance gap issues in low-carbon retrofitting hard-to-treat properties? Where do these issues present themselves the most across the process of low-carbon retrofitting? Furthermore, the current literature related to retrofit performance gap issues is fragmented and only a very few recognised authors have investigated a particular fragment of such issues in detail (Swan et al., 2013; Dowson, 2012). A need was identified to explore the retrofit processes and identify the major issues related to the performance gap.

METHODOLOGY

This research adopted a qualitative approach including a series of in-depth semi-structured interviews. The aim of the face-to-face interviews was to investigate major issues related to performance gap in detail using Delphi approach with the aim of adding to the growing literature to the low-carbon retrofit challenges (Sherriff, G, 2013). The use of open-ended questions based on literature and data from a pilot interview provided maximum benefit to be obtained from the recognised architects. This method was responsive to the interviewees’ view and facilitated a detailed insight into the retrofit processes allowing the architects to share their experiences by unfolding the journey of retrofit projects and to express their perspective on the major performance gap issues across these processes.

A series of semi-structured interviews was conducted with ten architects with extensive retrofit expertise, identified by their roles in the Retrofit for the Future Project (TSB, 2014), who are located in different regions of England. Architects are one of the key professionals in the industry and play a pivotal role in construction projects. Their specialist skills and expertise include providing strategic advice and design solutions to assist clients with the process of commissioning projects, and setting design predictions that are focused on energy performance as well as design quality (Ali et al., 2008). It is crucial to investigate the performance gap issues from an architect’s perspective.

Using a sampling technique, a few architects were identified via attending the key seminars related to low-carbon retrofit where they were presenting. Meeting the architects in person provided an opportunity to identify other architects who are also expert in the field. Implementation of the snow-balling technique (Robson, 2002) offered a faster approach to identifying further interviewees considering the research limitations, which included time,

resources and geographical constraints. Each of the interviewees was involved in small-scale low-carbon housing retrofit projects from Retrofit for the Future Programme. Therefore, applying the snow-balling technique (Robson, 2002) each interview was focused on a specific Retrofit for the Future project in which the recognised architects were involved in. Retrofit for the Future is coordinated by the UK's innovation agency and is driven to reduce energy use in existing housing stock by setting a target of an 80% carbon reduction of each project through low-carbon retrofitting and setting exemplars. The core aim of this programme has been to gain a deeper understanding of the issues around retrofit, and to learn and to share that learning within the peer group.

In order to meet the research aim, a need was identified for a systematic analysis and prioritisation of the unstructured major performance gap issues in order to provide the practitioners in the industry with a structured view of how and where major issues related to performance gap arise in low-carbon housing retrofit projects. The analysis included coding of pertinent quotes and major issues that are considered by the recognised architect to be the key contributors to the performance gap and categorisation of these issues that share similar characteristics into three themes of 'Buildability', 'Hard-to-Treat property' and 'Supply and chain'. Subsequently the analysis involved linking and organising the identified major issues in hierarchies related to the process of low-carbon housing retrofitting in order to evaluate where these issues tend to occur repetitively in order to prioritise the major issues systematically.

FINDINGS

The results of the conducted interviews gave insight into how and where the major retrofit performance gap issues appear across the processes of retrofitting 'hard-to-treat' properties. The architects were asked to explain and elaborate on the journey of the retrofit process they were involved in, and to stress the major issues that they considered are the most significant contributors to the performance gap across the retrofit process. It was anticipated that there would be some limitations in relation to the recognised architects' bias, and unwillingness to share the unsuccessful aspects of their work. However, contrary to expectations, it was found that the architects were open and honest about all aspects of the project they were involved in. The overall results strongly suggest that there is a distinct division in the retrofit community between the construction personnel and the small community of recognised architects, which is disappointing as it has an enormous impact on the retrofit performance gap. This is a challenging issue that needs to be addressed urgently. The respondents' perspectives on the major retrofit performance gap issues are discussed below.

PROCESS OF 'HARD-TO-TREAT' LOW-CARBON RETROFIT

The analysis shows that retrofitting 'hard-to-treat' properties is a challenging task as the process of such projects is highly complex due to the distinct characteristics of such properties and the diverse condition of each dwelling, which frequently posed restrictions (BRE, 2008). In addition, the participants indicated that the majority of such dwellings typically have very low average SAP ratings. Furthermore, the interviewees confirmed that each housing retrofitting requires a tailored design strategy and solutions, regardless of the housing type. Similarly, Baker et al. (2013) confirms that low-carbon housing retrofit is not about archetypes; rather it is about building elements. All participants agreed on the degree of uncertainty that comes with every retrofit project. One of the interviewees referred to the complex nature of the housing retrofit processes and confirmed that 'every property has secrets; things don't necessarily go to plan so we have to learn a lot from every project'. Equally, another interviewee confirmed that 'each building you never really know until

you've stripped it all out', as the existing structure of each dwelling is concealed. This directly conflicts with the perspective of Osmani and Davies (2013), Davies and Osmani (2011), Stafford et al. (2011), Jenkins (2010), Osmani and O'Reilly (2009) and Plimmer et al. (2008), who identified diversity of the existing housing stock as the major barrier to low-carbon housing retrofit as it is not feasible to implement a uniform retrofit design strategy to fit a particular housing type. It is noteworthy that all of the low-carbon housing projects in which the participants were involved significantly exceeded the requirements of building regulations and the minimum building standards. However, all interviewees shared the same view, and confirmed that they faced diverse major issues that greatly impacted on the energy performance of the retrofitted properties. As a result, the projects did not deliver the design predictions (Hong et al., 2006).

RETROFIT DESIGN AND AS-BUILT PERFORMANCE GAP ISSUES

The study shows 16 major issues considered by the recognised architects as the key contributors to the performance gap. Using a coding system, the identified issues have been categorised into three crosscutting themes of 'buildability', 'hard-to-treat properties' and 'supply and chain'. The term 'buildability' is described as 'the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building' (CIRIA 1983). In the context of this research the term 'buildability' refers to the concept that helps to evaluate project design objectives, methodology and construction processes so as to reveal the level of feasibility, complexity and quality of construction on building sites (Patrick et al., 2005). These three themes appear throughout the retrofit process; however the major issues related to the theme of 'buildability' drew the most attention as 12 of the performance gap issues are related to this theme. In addition, the theme of buildability deficiencies is apparent across all the stages of the retrofit process, and significantly more in the design and construction interfaces. Consequently, the analysis involved prioritising the buildability issues, based on the major issues that the participants particularly stressed.

The participants firmly stressed that buildability issues should be one of the main considerations at the early stages of the process when evaluating the feasibility of low-carbon retrofit projects. The survey revealed numerous issues related to the theme of buildability that the interviewees considered to have a major impact on the performance gap. These include a limited understanding of the 'low-carbon retrofit' concept and of the impact of early design decisions on energy performance and other energy-related targets, inadequate sequencing and programming of the work, a lack of skilled site personnel and inadequate consideration of skills and competency at the labour procurement stage, and site management that is not proactive, and that is reluctant to implement unfamiliar products and fails to anticipate uncertainties.

Further primary issues related to the theme of buildability include inadequate delivery and storage logistics, product substitution on site without consideration of energy performance, poor installation of insulation products, poor installation of services, lack of energy performance knowledge and skill on the part of the site team and inadequate measuring of the site in relation to retrofit products' installation or storage space.

Although buildability issues appear to contribute most to the performance gap, the prime issues related to the theme of hard-to-treat properties are equally responsible for the performance gap in the low-carbon retrofit processes. The majority of the participants considered inflexible internal spaces for retrofit measures and unanticipated restrictions caused by the existing structure, such as uneven floor joists, to be the key issues posed by hard-to-treat properties. This was quite closely tied to the supply chain issues opposing the

successful low-carbon retrofit of hard-to-treat properties. Based on the conducted survey there is a widespread perception that currently the effectiveness of retrofit measures is questionable as the participants considered such measures to be unreliable, as confirmed by Swan et al. (2013). The limited availability of retrofit measures and uncertainties about their effectiveness were identified as prime issues related to the theme of the supply and chain.

PRIORITISING BUILDABILITY ISSUES

A total of 12 major issues related to the theme of buildability have been identified as having a strong impact on the performance gap. The findings clearly validate the complexity of low-carbon hard-to-treat retrofit processes. In addition, they reveal that the majority of the buildability issues are related to the knowledge and skills of construction/site personnel. Furthermore, the evaluation of these issues indicates that the construction personnel still operate in a traditional manner, which validates the perspective of the participants on this subject. Most of the interviewees have described the attitude of the construction personnel as 'reactive rather than proactive'. Equally, other participants perceive that the construction personnel are 'not committed' to the delivery of the project objectives.

The lack of a comprehensive understanding of the low-carbon retrofit concept, lack of commitment, lack of skilled and retrofit-experienced construction personnel, lack of site team energy performance knowledge and skill, and lack of effective retrofit measures have been identified by the recognised architects as the prime reason for the performance gap.

CONCLUSIONS

In investigating the major performance gap issues in low-carbon housing retrofit from the recognised architects' perspective, this study showed that most of the prime issues that require to be addressed as priority for action are directly linked to the site personnel. The survey revealed the distinct perspective of the design and the site team, confirming that despite limited experience of low-carbon retrofit, the site team perceive opportunities in this field. This inevitably influences the construction programming and compromises the delivery of the design predictions in low-carbon housing retrofit. In contrast, the small retrofit community of the recognised architects with experience of retrofit, practise retrofit projects with a focus on low-carbon and energy performance. The analysis showed that the leading architects actively provide retrofit advice, specifying accurate design integration. However, experience of low-carbon housing retrofit indicates that the retrofit design strategies frequently fail to deliver at corners and junctions of the building structure interfaces. Consequently, such projects face performance gap issues, most of which are associated with buildability.

In the evaluation of major performance gap issues, it became apparent that issues related to 'buildability' deficiencies are linked primarily to the site team and have the most significant impact on the performance gap. It is noteworthy that the architects have a key role in retrofit and their skills must be used to address and tackle the performance gap issues. In particular there is a need to develop a deeper understanding of the concept of low-carbon retrofit within the construction teams involved in retrofit projects. In addition, transition of the current traditional culture within the construction teams would have a direct impact on sequencing and programming the job, anticipating the uncertainties and considering the most efficient retrofit management required on site to deliver the set design predictions. It is equally important for both the design and construction team to view the complex process of low-carbon retrofit from each other's perspective from the conceptual design stages to the completion and delivery phases. There is an opportunity for the recognised architects to sell their expertise and bank of knowledge to the related practitioners in the field of low-carbon

retrofit, as there is no time to rectify any mistakes if we are to meet the government's ambitious carbon emissions reduction target.

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UNDERSTANDING THE DRIVERS, BARRIERS AND MOTIVATIONS FOR ENERGY EFFICIENCY HOUSING RETROFIT

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The UK government like many of its European counterpart faces a huge political and technical challenge of how to scale up retrofit demand amongst the general public and deliver rapid large scale retrofitting of its entire existing housing stock to meet current carbon targets. To date governmental efforts appear fragmented, incremental and ineffective. A particular challenge and integral to scaling up demand has been within the private homeownership sector where retrofit uptake has faced low consumer appeal. This is often connected with the disparate nature and large numbers of individual household decision-makers (emitters) that constitute the sector and the complexity of their changing lifestyles, consumption patterns and personal needs. Evidence suggests that whilst many people undertake a range of modifications to their homes through home improvements yet very few materialise into energy efficiency retrofitting that is desired by government policy to meet carbon reduction goals. Hence, what remains poorly understood foremost is why people make changes to their home, how they prioritise energy efficiency amongst other factors within their decision-making processes. Unpacking some of the claimed barriers and drivers towards retrofit delivery and implementation – could provide policy and decision makers with a clearer understanding of how to reconfigure current policies and practices to scale-up retrofit demand. This paper provides an introduction to the research problem which is the focus of the authors PhD study, and through a preliminary literature review forwards: a definition of retrofit; a contextual and theoretical background, as well as outlining the proposed methodology – all of which are intended to provide a rationale and justification for why this is a topic of further research interest.

Keywords: decision analysis, energy efficiency, home improvement, methodology, retrofit, technological innovation.

INTRODUCTION

The UK government seeks through policies, such as the Green Deal to build the demand for energy efficiency measures and effectively manage millions of individual homeownership emitters to act. Thus, policy effectiveness is driven by the behaviour and attitudes of individuals who live in these properties (Chahal, Swan & Brown, 2012). The key challenge for retrofit policy is to deliver meaningful carbon reductions through the solutions it employs and which must take account for “the variety in age, size, quality, composition, function and social value of the existing building stock, as well as the different needs, expectations and budgets of homes owners and occupiers” (Dowson et al, 2012:3).

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In particular it has to demonstrate its benefits to a large number of individual households - by suggesting that amongst its many benefits, retrofitting can help save consumers money on their fuel bills, increase their comfort whilst at the same benefitting the environment (EST, 2011). However, despite the array of public media information campaigns, policies, financial and non-financial incentives and the apparent growth in public knowledge of the issues and of the benefits, many households appear reluctant to retrofit (Wetherill, et al. 2012; Dowson et al, 2012). Furthermore, what is unclear is the role and influence of the differing types of barriers and drivers and how they may or may not hinder or enable retrofit uptake at the household level. Hence understanding why this is the case is of critical interest and introduced in this literature review overview paper.

CONTEXTUAL BACKGROUND

Why is energy efficiency retrofitting being adopted?

The UK retrofit agenda is currently driven by the Climate Change Act 2008 setting out legally binding requirements to reduce greenhouse gas emissions to at least 80% by 2050 (to below 1990 levels); and which recommends a greater role for energy efficiency in meeting targets (CCC, 2008). A key challenge is raised by the fact that housing, contributes to over a quarter of the UK's carbon emissions with more than 26m homes in UK, each contributing to an average 5.1 tonnes of CO₂ emissions per year, equating to a total of 129.4 million tonnes of CO₂ per annum, and 28.3% of the total CO₂ emissions (Palmer & Cooper, 2011). However, within this sector, space and water heating - 82% - are the largest emitters with the remainder split between cooking and appliances, hence represents a major opportunity to cut energy use and CO₂ emissions (CLG 2009).

Furthermore, this is exacerbated by the fact that a large majority (over 70%) of homes that will exist in 2050 is already built, and of which private owner occupiers (70%) constitute the largest component of the residential sector containing dwellings in the least efficient Energy Efficiency Rating (EER) Bands F and G. (Power, 2008; Ravetz, 2008). Importantly, it is the detached and semi-detached housing components which are perceived to have the greatest potential for energy reduction. However it is the poor overall energy performance of older buildings, with hard-to-treat 'solid walls, single glazing and uninsulated roofs/floors resulting in wasted heat' that constitutes the largest proportion of existing building stock that is of particular governmental concern (Dowson et al, 2012).

The UK government is concerned that the national rate of replacement and adoption of retrofitting measures is occurring too slowly to able to meet policy goals (Boardman, 2005; 2007; Ravetz, 2008). For example, the current average annual replacement rate of the national housing stock is commonly cited as being less than 1% per year (GOS, 2008; Ravetz, 2008). Across North-western European countries the rates of retrofitting of existing buildings are slightly higher at approximately 1.2% (Weiss et al, 2012). Although, in contrast, current rates of renovation and/or refurbishment rates are between 2.9% and 5% of existing housing stock; and 2-8% for commercial stock (Stafford et al, 2011 in Eames et al, 2013).

Furthermore, DECC (2012) reports that 'almost three quarters of homes have double glazing installed throughout the whole property. Cavity wall insulation is present in 68 per cent of homes with cavity walls. Loft insulation is the next most common measure, with 65 per cent of homes with lofts having at least 125mm in place. The least common energy efficiency measure shown is currently solid wall insulation, with only two per cent of solid wall homes

having the measure in place'³. These figures suggest 'that whilst significant progress has been made in the installation levels of some energy efficiency measures there is plenty of remaining' yet unused 'potential in the domestic sector' (DECC, 2012:28). More specifically in relation to the installation of the more advanced domestic microgeneration technologies that are likely to have greater impact on domestic energy reduction remain significantly low in the consumer market and will mean that national targets are unlikely to be met (DECC, 2012).

In contrast to the low adoption of EE retrofitting, the undertaking of general home improvements is argued to be much higher. For example, the retrofit business sector is estimated to be 'worth around £3.5bn - £6.5bn per year (Green Building Council, 2008:2), whilst approximately £24bn to £27 billion every year is spent on a range of internal and external home improvements, maintenance and repairs⁴ such as plumbing, decorating, roofing, guttering, extensions, etc. (TNS-BMRB, 2011; Green Building Council, 2008:2). These undertakings are deemed highest amongst owner-occupiers who tend to have higher incomes and greater vested interests in their properties and thus more likely to want to make improvements' (EST, 2011). However, most of the implemented measures appear to be undertaken without any express purpose for achieving energy efficiency or saving and therefore, perceived a missed opportunity by policymakers (StieB & Dunkleberg, 2012; Weiss et al, 2012) – an aspect the Green Deal policy seeks to target. This innocuous trend suggests an alternative perspective beyond energy efficiency goals may be appropriate in order to understand why the adoption of retrofit is low. For instance, i.e. that people are seeking others values and needs and desires from the products they choose and why they make changes to their home (EST, 2011).

More specifically homeowner-occupiers of existing housing sector face particular challenges due the perceived shortcomings of existing government policies and funding mechanisms. For instance, current regulations require that all new build housing to be either zero-carbon by 2016; and or meet the Code for Sustainable Home standards, etc., however, there are no equivalent mandatory standards for existing housing retrofits (Wetherill, et al. (2012). To address the inadequacies of existing mechanisms, the government in 2012, introduced the Green Deal - a market-led initiative - designed to build demand and deliver EE measures across all the domestic and non-domestic spheres (Chahal, Swan & Brown, 2012). It contains specific components designed to assist homeowners to overcome at least two of the most critical barriers i.e. that of information and costs (Dowson et al, 2012; EST, 2011). In particular through the provision of energy assessments to deliver accurate information of the correct interventions required to increase the buildings energy performance and other potential benefits; and with the option of financial support through a Green Deal Loan to incentivise and finance (purchasing of) homeowner adoption of the recommended EE measures (Dowson et al, 2012; EST, 2011).

There are emerging concerns over whether or not this policy will effectively overcome the barriers to adoption at the household level (Pelenur & Cruickshank, 2012:3; Dowson et al, 2012). Arguably, the main one appears to be that it does not compulsorily require homeowners to take-up the scheme (Dowson et al; 2012; Chahal, Swan & Brown, 2012); and what is poorly understood is whether or not such a policy can rely on the homeowner

³ DECC 2012: data derived from secondary analysis of a range of statistical sources, p.28.

³ Equivalent comparative figures for how much is spent on EE retrofitting measures could not be found at this point.

voluntary home improvement (hereafter HI) impetus to increase EE retrofitting uptake. A further key challenge is the variation in different individual homeowner's attitudes, preferences and priorities towards energy efficiency of their homes (particularly the physical building structure changes) and within context why some choose to retrofit whilst others (a large proportion) do not. Therefore it seems pertinent to understand the motivations and context in which all types of changes (including energy efficiency and general home improvements) to the home take place. Hence, these are key issues of interest to the wider PhD investigation.

THEORETICAL AND CONCEPTUAL BACKGROUND

What is energy efficiency retrofitting?

Retrofit' at its simplest and at the building level refers to the incorporation of changes to its structure (fabric) or its systems 'after its original construction and occupation' and 'typically it is done with the expectation of improving amenities for the building's occupants and/or improving the performance of the building which can allow for significant reductions in energy and water usage'⁵ (Chahal, Swan & Brown, 2012:2; Rhoads, 2010:6). Within this context, the process of change could typically either include the adoption of a single or combination of measures, broadly divided into: 'fabric, systems, appliances, feedback systems and control measures' (Chahal, Swan & Brown, 2012:2) some of which may have direct or indirect effects on energy use, savings and efficiency (Poortinga et al, 2003). In particular, energy efficiency (hereafter referred to as EE) generally refers to installing or using technologies (and associated changes) in a way that means using less energy to produce energy saving outcomes⁶ (Vaughan, 2009; HOP, 2012)⁷.

Thus, energy efficiency measures installed as part of a housing retrofit can be further distinguished, by placing the differing attributes of each measure within a continuum defined by the degree to which they deliver EE performance (and to some extent by their costs) and which are perceived to be 'qualitatively different' from each other (Boardman, 2007; Clark, 2010; Shorrocks, Henderson & Utley 2005; Lowe et al. 2012:6). For example, basic (shallow or cheaper options) measures are typically delivered by drought proofing; cavity wall and loft insulation, etc.; whereas, more advanced (costly or deep) retrofit is typically achieved by solid wall insulation; replacement of existing heating and ventilating systems, microgeneration and Passive House principles, etc. (Boardman, 2007; Clark, 2010; Killip, 2009; Lowe et al. 2012:6; Shorrocks, Henderson & Utley 2005). Importantly, it is the 'fabric first' insulation measures to the buildings envelope (i.e. walls, floors, roof and windows) which are perceived to be critical for the energy efficiency of houses and often promoted by the building industry (EST, 2010). This is in spite of the fact there appears to be no clear government consensus to date specifying best practice for the order and extent to which differing retrofit measures should be implemented.

Nonetheless, government policy agrees that a combination of 'technical' and 'behavioural' retrofitting measures are needed to meet climate change targets; it is the technical efficiency (not requiring behavioural change) measures requiring one-off 'purchase' decisions (i.e. installation of insulation, microgeneration, etc.) which are more often promoted in policy. This is in spite of their larger initial upfront investment costs (Poortinga et al, 2003) yet

⁵ <https://www.melbourne.vic.gov.au/1200buildings/what/Pages/WhatIsRetrofit.aspx> (accessed on 22.4.2014)

⁶ The actual energy reduction from a baseline and that would otherwise be used without the presence of the intervention (HOP, 2012)

⁷ <http://www.theguardian.com/environment/2009/jul/16/energy-efficiency> (accessed on: 25/2/2014)

viewed as the most stable and cost-effective solution to reducing direct emissions in the residential sector. In contrast, behavioural change measures are viewed relatively less favourably, due to the fact they require repeated action or efforts (i.e. switching off lights when not in use) and change in an individual's lifestyle and habits - and harder to measure their energy savings (DEFRA, 2008; NEF, 2011; Boardman et al, 2005; Boardman, 2007; Roberts, 2008)

What are the key approaches for understanding energy conservation?

In order to develop policies that successfully encourage EE retrofit uptake, it is critical to understand the factors shaping individual preferences in this retrofit decision context which the following section will outline. Retrofit adoption is likely to be determined by a variety of factors, including the payback period of measures, availability of technological developments over time, support through Government schemes, etc. (DECC, 2012). However the discourse of understanding people's motivations and drivers for energy use or behaviour is not new one and can be traced back to the energy crisis in the 1970s (Hens, 2007). Hence this analysis sits against a backdrop of relatively abundant well-established inter and intra disciplinary approaches for understanding energy conservation across, e.g.: economic, psychological, sociological and technical literature, etc.

Key decision-making factors driving retrofit

The attainment of EE retrofitting is viewed as a complex and challenging process including the dwelling and its occupants and requiring interaction between energy, technology and individuals (Lowe et al. 2012). Firstly, the buying decision or the decision to behave in a certain way towards energy use is determined by a wide range of internal and external (intrinsic and extrinsic) factors (Faiers, Cook & Neame, 2007; Chahal, Brown & Swan), i.e. values, norms, habits, preferences, knowledge and a range of practical or contextual considerations (Chahal, Brown & Swan). More broadly, general decisions on HI (with or without an explicit EE aim), are arguably shaped by an alliance of economic and non-economic factors (Zundel & Steiss 2011; Steiss & Dunkelberg, 2013). Thus, any changes to the home are not only seen as a financial investment but also a consumer good (micro-purchase) acquisition (for the attainment of comfort, convenience, belonging, etc.), suggesting that whilst rational economic choices are an important aspect they are one of many factors influencing decisions (Zundel & Steiss 2010; Steiss & Dunkelberg, 2013). Greater understanding of the interplay of these factors could help to alleviate the perceived barriers in the adoption of EE and strengthen policies.

Economic perspectives/Financial factors

Furthermore, the pre-eminence of 'economic factors' has generally been highlighted within economic and behavioural literature (i.e. through behavioural economic and individual cognition theories) on emerging EE policy debates, in which EE decisions are often perceived as investment decisions (Zundel & Steiss 2010; Steiss & Dunkelberg, 2013; Poortinga, et al., 2003). Evidence suggests that the adoption rate of energy efficiency measures often fall short of their full potential (Pelenur & Cruickshank, 2012; Ravetze, 2008). This has often been termed the 'value-action gap' and refers to the gap between environmental concerns people state they hold yet their actual behaviour may contradict that concern (Kolmuss & Agyeman, 2002). Hence, current government policies are aimed at increasing the EE of private homes seeks to solve this discrepancy by turning people's environmental values or concerns into tangible pro-environmental behaviour.

Economic perspectives suggest that this gap 'should be seen more as a delay in consumer adoption', and is 'due to market failures, such as a lack of transparent information about the benefits of EE, and non-market failures, such as the transaction costs of adopting new

technology or the use of inaccurate discount rates by consumers making energy efficient retrofit decisions' (Pelenur & Cruickshank, 2012: 3). In particular, as a result of inaccurate financial discounting people are likely to delay investments in EE technologies in the present context, despite the medium - and long-term financial benefits of such investments. As a result of information distortions, home owners may underestimate the gains and overestimate the risks and losses linked to EE measures. Therefore, psychological and socio-psychological factors are important when explaining purchasing behaviour in terms of homeowner's perception of upfront costs, risk and payback period in investment decisions. The key limitations of a focus on economic or financial factors is that it starts on the premise that the adoption of EE measures is driven solely as an economic investment decision, whereas there is increasing evidence suggesting that non-economic factors and motives are equally influential in decision making processes (Zundel & Steiss 2010; Hodek, et al. 2013; Steiss & Dunkelberg, 2013).

Non-economic factors:

Social science perspectives acknowledge that whilst economic factors are an important driver they are one of many other social, personal and contextual aspects. For example, socio-economic demographic factors such as age, education and income are often found to be influential in individual decisions about energy conservation measures (Nair et al, 2010; Steiss & Dunkelberg, 2013). One key contextual factor - access to information – is considered generally important in all refurbishment contexts and because both can be complex activities requiring specialised information and skills. Homeowners are not usually trained in construction and technology and therefore may have to seek out knowledge either expert knowledge or from other sources. The appropriation of expert knowledge is considered particularly important in the context of EE technologies, e.g.: some claim the adoption of EE technologies “are the result of purposeful planning and strategic long-term decisions concerning energy consumption - decisions that are made only a few time in a person's life” (Steiss & Dunkelberg, 2013: 251).

Furthermore, others have asserted that socio-cultural factors shaping consumption practices in everyday life (e.g.: comfort, convenience, aesthetics, fashion, desire for new products, etc.) and which can play an important role for the acceptance or rejection of EE technologies. Arguably these influence housing practices and related attitudes towards the home, its maintenance, upkeep and improvements must be taken into account (Gram-Hanssen, et al. 2007; Zundel & Steiss, 2010). In this context, home improvement is assumed to be an established mainstream social practice and a form of consumption which can be frequently undertaken to meet the home occupant's social, symbolic aspirations, needs and requirements (Maller & Horne, 2011; Shove, 2003; 2010). However, the existing research literature very rarely examines HI in the context of the retrofit discourse.

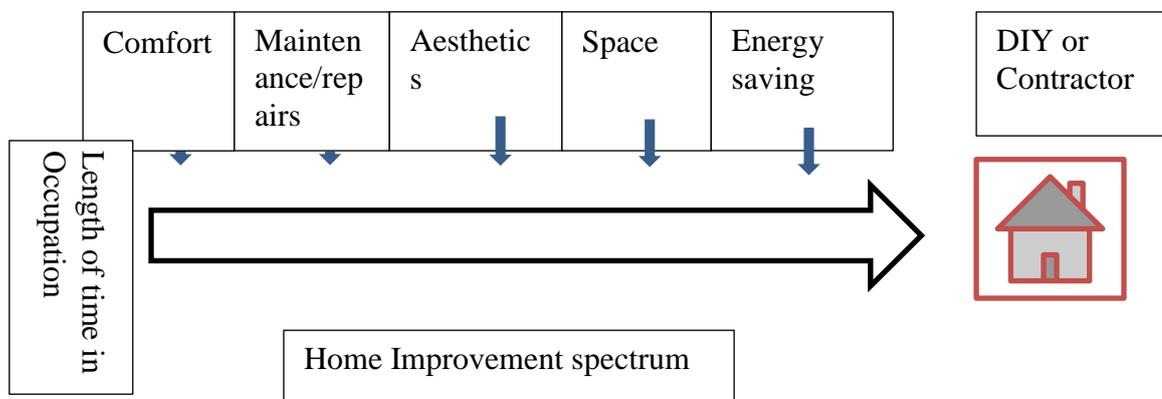
Home improvement context

In contrast to the abundant research interest and analysis of EE retrofitting, the topic of HI has been significantly overlooked across both technical and social sciences. Housing studies through the social policy and land-use planning stance have tended to focus on its design, supply and affordability whilst largely overlooking its maintenance, operation and lived experience components. Furthermore ‘technical disciplines associated with building science and construction has adopted a focus on building performance, recently extended to include EE retrofitting. This typically focuses on the ‘costs and benefits, decision making and the uses of buildings and which simplify the behaviour of occupants’ (Maller & Horne, 2011:61). In relation to EE retrofitting, these focus on the 'regulations and incorporate performance-based approaches to EE using models which draw on extensive assumptions and default settings regarding the operation and occupation preferences of building occupants' (Maller & Horne,

2011:61). Hence, within the dominant discourse of 'housing' and 'sustainable communities' policy, it is the conventions and practices of households such as home improvements which appear to be neglected.

The limited existing literature (within technical and social sciences) examining HI is fragmented and its relationships with EE is particularly under-developed as a research topic. Within 'sociological approaches' typically, HI are perceived as a 'social practice' which results in the reconfiguration of domestic spaces (Hand et al., 2007; Shove et al., 2007; Hand, Shove & Southerton, 2007). HI is defined as a change to a dwelling-house comprising 'internal and external improvements maintenance and repairs including extensions, double glazing, refurbishing existing kitchens or bathrooms, general decorating and both emergency and non-emergency repairs' (TNS-BMRB, 2011). The differing types of home improvements can be characterised by their goals, e.g. to improve comfort levels for its occupant, internal or external maintenance/repairs; to provide additional space; and to save energy (e.g. implementation of thermal insulation), etc. (see Table 1). It suggests that this 'once episodic' activity is increasingly carried out regularly across many societies and is 'embedded within household cultural practices and is an integral part of homemaking' (Maller & Horne, 2011:60). Furthermore, many ageing houses are 'frequently remodelled and remade to suit homeowners' aspirations and the reported scale of activity also presents itself as a significant opportunity for climate change mitigation as part of the retrofit agenda (Maller & Horne, 2011:59; EST, 2011). However, existing research seldom combines and examines EE through the lens and context of HI - an aspect which will be built upon through further empirical investigation as part of the wider PhD objective.

Table 1: Different home improvement types can have either one or more goals



Innovation Adoption Theory

There are numerous established models and theories that have overtime explored and sought to explain a range of issues in relation to how individuals act with respect to environmental conservation. A comprehensive review of a range of the key theories and models on consumer behaviour and behavioural change has been undertaken by Jackson (2005) who suggests that apart from cognitive assessment and rational choice there are emotional influences, i.e. societal and cultural issues that influence the consumer buying and behavioural choices. In addition, Faiers, Cook & Neame (2007) have also produced a succinct categorisation of main theories that relate to the key internal and external factors influencing consumer choice in relation to energy use. The categories are:

1. Consumer choice;
2. Needs, values and attitudes;

3. Learning;
4. Social learning;
5. Buying process;
6. Categorisation of consumers; and
7. Product attributes and categorisation.

Of particular interest is the fifth and seventh point, which is analysis of the buying process and how homeowners the consumers adopts (purchases and installs) particular technology/products for their home. Rogers' 'Diffusion of Innovation' or 'Innovation Adoption' theory (2003), provides a useful theoretical model of what consumers expect of products against their attributes, and the way these specific expectations can have a strong influence on people's willingness to buy (adopt/implement) the product. Diffusion of Innovation theory places its emphasis on innovation as an agent of behaviour change, thereby moving the entire focus away from individual decision-makers or social structures. The theory is considered appropriate as it offers a critical framework from which to commence explorations of the research problem on 2 levels: firstly, it can take account of the low adoption rates from an individual homeowner adopter level and secondly, and link its cumulative impact within wider societal contexts. Thus, it is the perceived attributes of an innovation which are likely to determine its rate of adoption to a greater extent than the characteristics of the adopters.

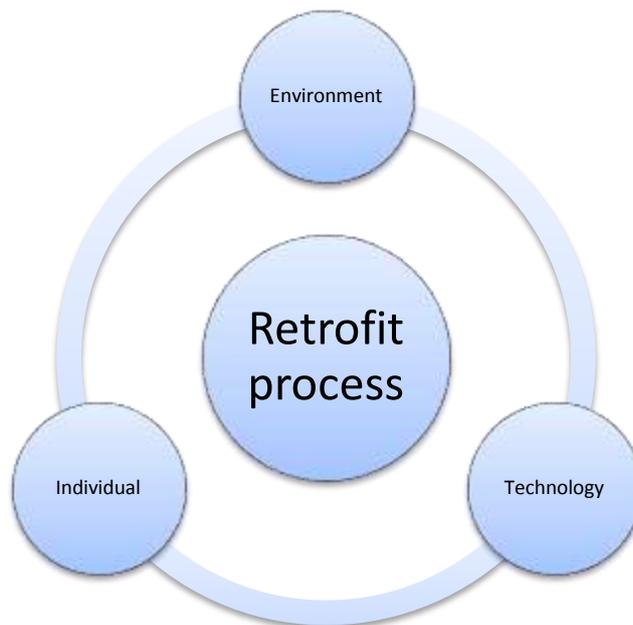
According to Roger's theory, innovation is defined as 'an idea, practice, or object perceived as new' (Rogers 2003: 12). Hence, an innovation can only be such if it has the prospect of then being adopted and make an improvement in society (Edwards et al. 2004; Rogers, 2003). The theory identifies 5 key intrinsic characteristics of innovations or products that are defined against five predominant attributes; relative advantage, compatibility, observability, trialability, and complexity (Rogers, 1995) and which greatly influence whether or not it has the potential to be adopted. In this context, potential adopters or consumers are likely to assess the feasibility of attributes through these phases but not necessarily in linear progression.

Furthermore, Roger's theory asserts that adoption of an innovation is the outcome of a decision-making process occurring in stages: knowledge, persuasion, decision, implementation and confirmation (2003). In particular, the approach also suggests that rational choice approaches are potentially compatible with the innovation decision process (Rogers, 1995) in as far as the 'individuals recognises a need for a product, generates an awareness of the product based on its attributes and then decide to either consume or reject the product'. However, its key limiting factor is that rational choice does not incorporate the fact that individuals also rely on their emotional and social values when choosing whether or not to either ally or distance themselves to goods or services they like or dislike (Hansen, 2005 in Faiers, Cook & Neame, 2007:4386).

However, the model does not adequately explain the role and influence of other contextual factors, i.e. the differences in the types of adopters, their characteristics (to do with their attitudes, aspirations and perceptions) and external issues, i.e. such as government policies and interactions with energy advisers, builders, installers, etc. All of which are likely to manifest themselves differently in different cultural settings. The theory accepts that due to barriers along the way not all innovations would successfully diffuse among their potential adopters; and time will be required for innovations to reach a critical mass (market saturation) in society (Hawkins et al., 2007; Nair, 2010; Rogers, 2003).

Notwithstanding its simplistic normative assumptions, the Rogers model provides a conceptual framework from which to build analysis of the contextual factors affecting retrofit adoption decision making processes and from which to highlight the drivers and barriers relating to the relevant stages of the diffusion process, i.e. the differential effects of constraints on adoption will be explored in the study which could then inform policies. The concepts validity will be further evaluated and built upon following comparative analysis of the usefulness of other theoretical and conceptual models (e.g. social practice theory, technology acceptance model, domestication theory, etc.) as part of the ongoing literature review for the wider PhD research.

Figure 1: Key factors in the retrofit adoption process.



The preceding analysis has shown the buying decision, or adoption decision towards EE is influenced by a wide range of internal and external factors due to the fact that individuals operate in a social context and the influence of cultural, social and emotional influences are unquestionable. Integral to these assumptions is the 'causal relationships between the three central factors of the adoption decision, i.e. the product, the individual and the environment in which they are placed' (see Table 2) (Faiers, Cook & Neame, 2007:4389).

PROPOSED RESEARCH INVESTIGATION STRATEGY

Importantly, the issues discussed in the contextual and theoretical analysis raise the following key questions that require further exploration:

- what is the context in which people make changes to their home and what factors then result in energy efficiency measures being implemented (i.e. in terms personal circumstances, i.e. motivations, needs, desires, wants, triggers, etc.);
- How do people conceive and select products (and their attributes) for their home and why do they choose specific products (over others);
- What is the role and influence of internal and external factors in individual decision-making (particularly in response to external socio-economic factors);
- What is the role and influence of external actors/agency (e.g. builders, policies, information, etc.) and how do homeowners interact with these actors;

What are the key drivers and motivations for making changes to the home; and
What are the barriers to adoption, their effects and where do they emerge in the
decision-making process.

Thus, the main aim of this research is to identify and understand the drivers, barriers and motivations underpinning homeowner occupier's (living in single dwelling houses) adoption of EE measures; and in particular to compare why and how homeowners undertake home improvements in contrast to those explicitly undertaking EE retrofitting of their homes. Focusing on why and how people undertake HIs can provide greater understanding of the context within which EE retrofitting rates could then be increased. Through a contrasting approach it specifically seeks to understand and isolate factors distinct to EE actions as well as the influence of external environmental conditions, such as funding availability and constraints, political and socio-economic drivers, local social and spatial factors, etc.

Given the multivariate nature of the research problem and the components that need to be examined, i.e.: in terms of the analysis of perceptions, actions, interventions and policies - a mixed methods approach is appropriate. The research will adopt a pragmatic knowledge claim by applying a mix of inductive and deductive approaches through the use of both quantitative and qualitative methods. The empirical investigation proposes a twofold investigative approach: first, undertake both surveys and interviews of homeowner decision-making processes (through purposive and snow-ball sampling in England). Second, through stakeholder interviews to capture the practitioner perspective on the effectiveness of current policy instruments, and how/if they should be improved. It proposes to identify the ways in which homeowner attitudes and behaviours might be changed, increasing the potential for delivering EE measures. The key outcome of the research seeks to provide recommendations on the ways existing policy mixes could be reformed, particularly to maximise EE retrofitting coinciding alongside HI undertakings.

CONCLUSIONS

In sum, the existing evidence suggests that retrofit suffers from low uptake amongst homeowners, that legislation and key policies to address the problem do not appear to be the best drivers for retrofit uptake, as much of the uptake rests on the householders 'choice' to materialise. Although, overall retrofit uptake is low some householders have been more proactive in adopting EE measures than others, therefore a key research area is to understand what factors prevent others from making similar decisions. Unpacking some of the problems with retrofit delivery— at the individual household level – could provide policy/decision makers with a clearer understanding of how to reconfigure current policies and practices. The implications of this research are considered timely given government concerns in meeting carbon targets for 2050 and its wider sustainability goals.

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DEVELOPING A CARBON MEASUREMENT TOOL TO PROMOTE SUSTAINABLE CONSTRUCTION

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Unsustainable consumption of finite resources by the construction industry conflicts with the prime goal of sustainable development. As such, promotion of sustainable construction is crucial, particularly to developing countries, where such concepts are rather still new. In order to evaluate actions towards sustainable construction, tools that can quantitatively assess environmental performance become indispensable – we cannot manage what we cannot measure. The aim of this work is to present a tool that can be used to quantify carbon emissions associated with a building construction project in the context of a developing country. Currently at prototyping stage, ongoing efforts towards developing the tool are elaborated. The method used to develop the tool involves use of rapid application development and prototyping. The working name of the prototype version is CaMeT, an acronym of Carbon Measurement Tool. CaMeT computes energy and consequently emissions accruing in the pre-construction and construction stages of a building. It is envisaged that CaMeT will have several benefits among which include improving stakeholders' understanding of the impact of their actions to the environment, supporting global initiatives like the Clean Development Mechanisms, and aiding built environment professionals to make environmentally sound decisions.

Keywords: building projects, carbon measurement tool, embodied carbon, sustainable construction, Uganda.

INTRODUCTION

Sustainability assessment of construction works involves assessing environmental, social and economic aspects related to construction (BS EN 15978:2011). Environmental aspects (e.g. energy use, water use and emissions) are of particular importance since they engender some of the greatest threats to humankind, like climate change and resource depletion. Particularly, the relationship between energy and carbon emissions is important since carbon emissions contribute to climate change. Whereas utilisation of energy, especially that of non-renewable type, has played a key role in transforming civilisation, unintended consequences like release of greenhouse gases (e.g. carbon dioxide) into the atmosphere have been detrimental to the environment (Dincer and Rosen 1999). As such, utilising energy in a way that does not cause harm to future generations is a call for any sustainability initiative. Certainly, it is imperative to focus on sectors and activities that significantly consume energy.

Globally, the building sector is both energy and carbon intensive, and for developing countries, the situation could be worse. The sector globally consumes up to 40% of the final energy and releases 30% of the annual global emissions (UNEP 2009; WBCSD 2012). Moreover, if the energy consumed during the construction phase is considered, buildings account for more than 50% of the global energy consumption (WBCSD 2012). With increased construction in developing economies, coupled with energy inefficiencies in the

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existing building-stock globally, building-related emissions are to increase in the coming decades (UNEP 2009; Cheng et al. 2008), if not controlled. In developing economies like that of Uganda, many “don’t yet have adequate building codes, let alone regulations for energy efficiency in buildings” (Cheng et al. 2008: 33). In Uganda for instance, there exists no specific regulation or guidelines to address environmental performance of buildings, besides efforts to review the prevailing archaic building regulations and standards (The Parliament of Uganda 2012; United Nations 2011), which are hitherto futile. Moreover, prevailing environmental assessments of prospective construction projects do not quantitatively evaluate their environmental performance, contrary to the growing practices (see BS EN 15978:2011) in the global built environment. At a minimum, this implies that the country has no benchmarks to initiate any efforts of fostering sustainable construction, an issue that undermines sustainable development.

As a first-step initiative in evaluating actions towards sustainable construction, and consequently, sustainable development, measurement tools that can help understand the environmental performance of building projects become indispensable since ‘we cannot manage what we cannot measure’. A focus on embodied carbon (EC) emissions (i.e. those arising from material manufacture, transportation and construction activities) is paramount, since it is now widely acknowledged (Iddon and Firth 2013; Hacker et al. 2008) that EC will become a significant proportion of building’s lifetime emissions, if the focus remains on only reducing operating emissions (i.e. those arising from building-use like heating, cooling, and lighting). Moreover, “...for traditional buildings in developing countries, the embodied energy can be large...” (Levine et al. 2007: 405). The aim of this work is to present a tool (and ongoing efforts) that can be used to quantify carbon emissions associated with building construction projects in a context of a developing country, Uganda.

WHY ANOTHER TOOL YET MANY ARE AVAILABLE

There are several tools that can be used to compute carbon emissions, albeit with limitations. For instance, the European Commission Joint Research Center (2014) and the Greenhouse gas protocol (2014) both present lists of several software tools with their corresponding versions, vendors, the boundaries they consider, and interface languages. Whilst some software have inherent customised databases, third party databases can also be utilised by software under appropriate licence provisions. For instance, SimaPro (developed in Netherlands), and Gabi (developed in Germany), which are among the most used software in recent times (Ciroth 2012), have provisions for the renown Ecoinvent database (Frischknecht and Rebitzer 2005). However, for precision and relevance, country specific databases ought to be applied when assessing carbon emissions. This is so because among the factors that could affect variation of emissions is the geographical boundary (Hammond and Jones 2008) and moreover, even in the same country, emissions can differ by region depending on the energy mix. Meanwhile, a calculation tool ought to be tailored to the kind and nature of database. This has at least been among the aims of the Swiss based Ecoinvent database, to be compatible/exchangeable with most software tools (Frischknecht and Rebitzer 2005). Ideally, one would expect a meticulous tool, and database, to distinguish emissions of a country on a region-by-region basis. However, any software tool, be it a database, is in one way or another skewed to a certain geographical boundary. As such, no single calculation tool or database is a panacea to addressing geographical variations of emissions globally. It is thus less surprising that, besides databases, most tools are country specific (see recent lists at Greenhouse gas protocol 2014; Joint Research Center 2014) in order to suitably incorporate national circumstances. Against this background, the Carbon Measurement Tool presented in this work takes into account country circumstances of Uganda. In a setting where concepts of sustainability in construction are still new, a tool with a rather steep learning curve, like most available proprietary ones (e.g. Gabi), is likely to stifle initiatives of encouraging sustainability

assessment. Therefore, other underlying intentions were to develop a user friendly tool that does not require significant specialist knowledge to use it.

METHODOLOGY

The aim of the work presented in this paper was to develop a tool that is in form of software. A software development methodology was necessary, and Rapid Application Development (RAD) was the methodology adopted. This methodology was coined by Martin in the 1990s, through several renowned texts (e.g. Martin 1992) that sought to challenge the mundane traditional software development methodologies (e.g. the waterfalls model). In traditional systems, the software development process takes a series of sequential steps which conclude with the developed software tool at the end of the development cycle (Gottesdiener 1995). One of the major criticisms of traditional approaches is that of the long time it takes to have the final product, due to the many activities/processes involved. Most worryingly, by the time the tool is produced, it may be obsolete and incapable of satisfying the newly emerged user requirements. A RAD project can take up to six months to be completed and the rationale is that, a project taking significantly more than that time is likely to be overtaken by new events (Beynon-Davies et al. 1999). While traditional approaches focus on activities, RAD's focus is on deliverables (Beynon-Davies and Holmes 2002). RAD entails successive iteration, improvement and prototyping, a procedure that enhances the process to be expedited towards the final version (Agarwal et al. 2000) in a rather shorter time. A PhD scholar ought to be cognizant of the time and monetary limitations associated with research and any decision taken, whether it is one of methodology choice, should consider such (Dunleavy 2003). The concepts of Chunking, Time boxing, Rapid prototyping (Gottesdiener 1995; Gordon and Bieman 1995; Jones and Richey 2000), which are philosophically enshrined in RAD, were deemed appropriate for managing such research limitations. Moreover, one of RAD objectives is delivering products at low costs, yet at high quality (Martin 1992). Therefore, as a methodology of delivering the aim of this work, RAD was appropriate.

RAPID APPLICATION DEVELOPMENT

The RAD process

RAD begins by defining the requirements of the application to be developed. In this phase, the scope of the work (i.e. data and processes to include) is clarified and a time box (i.e. a fixed period for developing a chunk of the application) is also chosen (Gottesdiener 1995). In RAD, time boxes are used as project control devices to the extent that when the duration overruns, the contents in the box may be adjusted and rather not the box's duration (Beynon-Davies et al. 1999). In a time box, several iterations involving design, modelling (process and data), architectural building and prototyping (Gottesdiener 1995) are conducted (see Figure 1). The outputs of a time box constitute a chunk. A chunk of an application can take around six to nine months (Gottesdiener 1995), though with the advent of technology (e.g. programming languages), it could take a shorter time. Multiple time boxes can be executed in parallel, sequentially or staggered (Gottesdiener 1995). Of importance also are joint application development (JAD) workshops/interactions with various stakeholders in order to draw in requirements; JAD interactions could also continue at several phases of development (Beynon-Davies et al. 1999). Prototyping, a key point of divergence of RAD from the traditional software development lifecycles, is important during such interactions (Beynon-Davies et al. 1999).

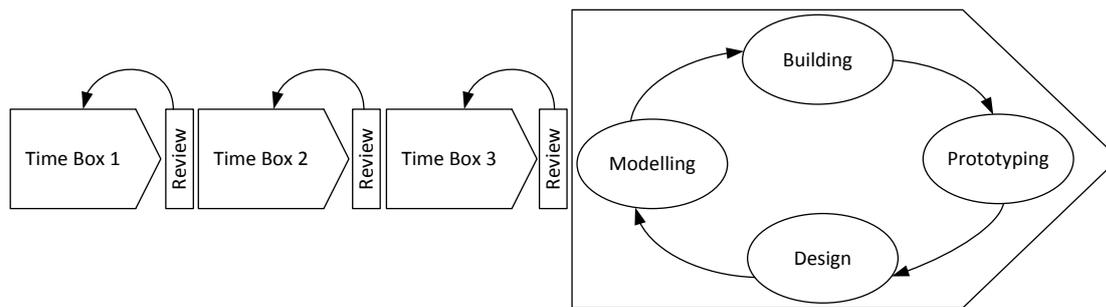


Figure 1: Sequencing of time boxes(left) and typical contents of a single time box (right) (Beynon-Davies et al. 1999; Gottesdiener 1995)

The prototyping concept

Prototyping is an important aspect of any kind of product development. A prototype “is a primitive version of a system” (Lauesen 2005: 58). Prototyping of such primitive versions (i.e. prototypes) is aimed at clarifying the requirements of the tool or reviewing other critical design deliberations, before the final version is implemented (Gordon and Bieman 1995). As such, there are various advantages to be gained from prototyping (see Lauesen 2005; Vredenburg et al. 2002; Gordon and Bieman 1995). Meanwhile, there are two types of prototyping approaches, ‘throw-away’ approach where the prototype is totally discarded and not part of the final product, and ‘evolutionary’ or ‘keep-it’ approach, where the prototype or some of its parts form the final product (Gordon and Bieman 1995). Evolutionary prototyping is preferred in this work as there are interests of keeping the same or considerable part of the prototype as part of the final product.

Although literature suggests varied taxonomies of prototypes, prototyping can be envisaged as a continuum of the product development process, with a final version of the product on one extreme end, and a primitive version on the other. In Lauesen (2005: 58-60) prototypes are classified as: hand drawn prototypes (i.e. paper sketches of user interfaces), computer drawn prototypes (i.e. user interfaces drawn with computer software), screen prototypes (i.e. user interfaces with little functionality), and functional prototypes (i.e. having full functionality for the buttons, menus and manipulation of data). Prototype classification in Vredenburg et al. (2002: 138-141) takes a dichotomous form of low-fidelity prototypes and high-fidelity prototypes. The former are ones with limited or no functionality and interaction, and are often produced quickly using 'paper and pencil', whereas the latter are more interactive, functional, and can be as realistic as the envisaged final product (ibid). From those explanations, it can be concluded that prototyping is a process that traverses several steps, each with incremental improvements, towards the final product. Consequently, the procedure adopted in this work traverses all prototyping taxonomies, towards the final product. The current stage of this work can be placed somewhere on the continuum, just before implementing functionality.

Implementing the RAD process

Requirements of the tool to be developed were elicited from extant literature, together with the author’s subjective experience of construction practices in the context. From the information garnered, the basic components of the tool were identified. Using process and mathematical modelling techniques, the relationships between the components were derived. One of the shortfalls found in literature was that the techniques used provided aggregated results where it is not possible to differentiate the contribution of various energy sources to emissions. In closing this gap, the approach adopted ensured disaggregation, whereby results can show the extent of emissions from various sources of energy used. At the core of the RAD process are computer-aided software engineering (CASE) 'tools' (Beynon-Davies et al.

1999; Gottesdiener 1995). Business Process Modelling and Notation (BPMN) (OMG 2014) and Microsoft Visual basic applications (VBA) with Excel 2010, were the ‘CASE tools’ considered for the RAD process in this work. In addition, the approaches adopted conformed with global standards and protocols of carbon emissions accounting, such as life cycle assessment (LCA) (ISO 14044: 2006; ISO 14040: 2006), sustainability assessment of construction works (BS EN 15978:2011), and greenhouse gas accounting and reporting (ENCORD 2012; WRI/WBCSD 2004).

RESULTS AND DISCUSSIONS

Components considered in developing CaMeT

From extant literature reviewed, it was concluded that emissions for a building construction project (i.e. considering the partial LCA of 'cradle' to 'practical completion' boundary) emanate from construction materials, plant/machinery and workforce (Chang et al. 2012; Jiao et al. 2012; Monahan and Powell 2011; Nässén et al. 2007; Guggemos and Horvath 2006; Scheuer et al. 2003; Cole 1998).

Construction materials

Total emissions from materials include emissions from manufacture and transportation. Manufacturing emissions are computed by obtaining the ‘mathematical product’ of the quantity of a material, quantity of energy to manufacture it, the carbon emission factor, and the percentage of that energy used. The latter element is considered in order to accord the disaggregation aspect since a material can be manufactured from different types of energy. Process emissions are also added to cater for those materials (e.g. cement) whose production process substantially produces other emissions that are not energy-related. Emissions from transporting materials are considered with three options A, B and C. Option A is applicable where the weight of materials is significant and known, and the distance of transportation can be estimated. Option B is applicable where the weight of materials is insignificant (whether known or unknown) and the quantity of energy used is known. Option C is suitable where weight of materials is insignificant. For option A, the total emissions are taken as the product of the quantity of material type, the quantity of energy to transport a unit of material per unit distance, the transport distance for the material, the carbon emission factor per unit energy used and the disaggregation factor of energy used in transportation. In option B, the total emissions are taken as a product of the quantity of energy to transport material, the carbon emission per unit energy used and the disaggregation factor of the energy used in transportation. Lastly, option C considers total transportation emissions as the product of the transport distance for material, the carbon emission factor per unit distance with respect to the corresponding transportation energy and the disaggregation factor of energy used in transportation.

Plant

Total emissions from plant constitute operating and transportation emissions. Operating emissions are computed as the product of the number of plant types, the quantity of energy used for operating plant, the carbon emission factor per unit energy used, and the disaggregation factor of the energy used. The total emissions from transporting plant are taken as a product of the weight of plant, the quantity of energy to transport a given weight of plant per unit distance, the transport distance for plant, and the disaggregation factor of energy used in transportation. The options B and C mentioned for material transportation can equally apply to transportation of plant.

Workforce

Total emissions from workforce include emissions from transportation, considered with two options A and B. Option A is applicable where the duration of using the workforce and the quantity of energy used per unit duration are known. Option B is applicable where the duration of using the workforce, the quantity of workforce, the distance travelled, and the

modes of transport used are all known. For option A, the total emissions from workforce transportation are computed as a product of the total duration of using workforce, the quantity of energy to transport workforce per unit duration, the carbon emission factor of the transport energy used, and the disaggregation factor of the energy used for transportation. For Option B, the total emissions are taken as the product of the duration of using the workforce, the number of people in the workforce, the distance travelled by a person per unit duration, the carbon emission factor per person per unit distance depending on the mode (e.g. bus, train, cycle) of transport used, and the disaggregation factor of the energy used.

Classification of emissions

In adherence to relevant universal standards of accounting and reporting of emissions, classification of emissions is necessary, though often varies among standards. In this work, emissions were broadly classified into direct emissions (i.e. from sources owned or controlled by the project) and indirect emissions (i.e. from sources not owned or controlled but a consequence of the project) (WRI/WBCSD 2004). Emissions were further delineated as scope 1, scope 2 or scope 3 emissions (ibid). Scope 1 emissions are those occurring from sources that are owned/controlled by the project, scope 2 emissions are those from purchased electricity, and scope 3 includes emissions caused by the project though from sources not owned/controlled by it (ibid). For the case of emission-sources (see ENCORD 2012), emissions were classified as source 1 and 2 (onsite fuel use), source 3 (process emissions), source 4 and 5 (onsite electricity use), source 7 (vehicle fuel), source 8 (public transport), source 9 (subcontractors), and source 11 (material manufacture and transportation). Source 6 (imported heat), source 10 (waste), and source 12 (building-use) were beyond the scope of this work.

Structuring CaMeT: integrating qualitative descriptions with functionality

Using BPMN (OMG 2011), a ‘non-executable’ process model was created to conceptualise CaMeT (see Figure 2). Shown in the figure, is only the top level process for purposes easing readability, otherwise, elements contain sub elements. In addition, detailed explanations of the semantics of the BPMN standard were beyond the scope of this paper but anyone would need to acquaint him/herself with such in order to produce sound process models using that standard (see OMG 2011; Silver 2011). Conscious of that, the presentations in this work focused on the simplest elements of BPMN which are perhaps comprehensible with common knowledge from the traditional flowcharting techniques.

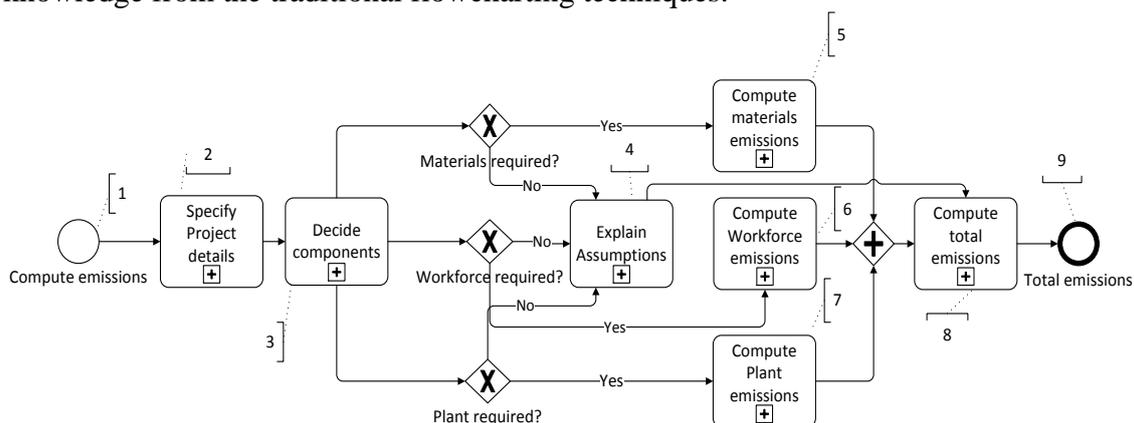


Figure 2: The top level process model for CaMeT

With reference to Figure 2, the process begins when there is need to compute emissions of a building project. In the process model, this is denoted as an event by element 1, where an action is taken to initiate or trigger the process. This action can be likened to ‘clicking’ to open CaMeT. At element 2, some information (e.g. type of building) about the project is entered. This is also where specifics like the geographical location (e.g. region, district) of the project can be specified. At element 3, decisions are made on which component (i.e. among

materials, plant and workforce) to compute emissions for. The three paths (representing the three components) from element 3 are routed through exclusive decisions. If there are intentions to miss out any of the three components (i.e. following the unhappy 'No' path), justifying-assumptions have to be clearly stated at element 4. These assumptions are later forwarded to element 8 to offer explanations for any missing components when total emissions are computed. Where emissions for the desired element are to be computed (i.e. following the happy 'Yes' path), this is done at elements 5, 6 and 7, where also classification of emissions can be done. The total emissions are assessed at element 8 where there is an option to click and view a summary of the emissions computed. Depending on the purpose of carrying out the assessment of emissions, this is communicated at element 9. Actions under element 9 would essentially include printing out the emissions' summary sheet, communicating the results to the intended recipients, among others.

FUTURE WORK

Implementing the user interface and functionality

Since the outputs of the tool ought to be quantifiable (i.e. quantitative), mathematical relations, specifically algebraic expressions, will be implemented in a rather familiar modelling environment of Microsoft Excel 2010. Separate data tables containing energy requirements and emission factors for each component will be created in Excel 2010. These databases will be implemented under elements 5, 6 and 7 of Figure 2. Data for computing emissions (e.g. electricity used by manufacturers) can be obtained from the sources (e.g. manufacturers, suppliers) in the region/district and where this is not possible, literature provides a wealth of secondary data bases that can be consulted, albeit with caution. For imported materials, data from their countries of origin shall be used. A separate calculation sheet (i.e. attached to element 8 in Figure 2) will be created using Excel 2010 formula to query data from the tables depending on the results desired.

In order to enable a user access the formulae and data in a presentable way, a graphical user interface (GUI) will be implemented. Of necessity is the need to create a GUI that is simple, yet intuitive enough to enable the users to access elements and more importantly, perform various queries in view of computing emissions. The GUI will be implemented using VBA in Excel 2010. Literature on GUIs (Spolsky 2001) suggests that good user interfaces have to align the program model with the user model, an aspect that is usually not easily conformed with in software development, yet it is very crucial. In the user model, users have an expectation of how a program would work, whereas the program too has a model (i.e. the program model), that is, the procedures (e.g. the code executions, relationships, button functions etc.) to fulfil the aim of the program. The choice of a rather familiar modelling environment of Excel 2010 and the architecture of the GUI will ensure that the User and Program models are kept in sync. At each of the elements 1 to 9 in Figure 2, the GUI will provide mechanisms in form of 'Forms' (i.e. of materials, plant, workforce and subsequent sub processes) for the user to input and query data. The forms shall have objects such as buttons, dropdown lists, tabs and text boxes to navigate to a component of choice in order to proceed with computing emissions or any other desired action. In addition, usability tests (Lauesen 2005; Vredenburg et al. 2002) intended be carried out with fellow postgraduate students throughout the development phase shall be invaluable.

Prospective uses of CaMeT

Upon application for a building permit by the developers, the authorities in charge could require the developers to include quantitative environmental impacts of their proposed developments, in relation to carbon emissions. The developers or authorities could then use CaMeT to compute the embodied emissions associated with the development. From the

results generated, areas of improvement (i.e. where emissions are high) shall be identified, and necessary actions (e.g. advice) taken.

The initiative of computing carbon emissions associated with prospective developments is likely to have several benefits. It will improve stakeholders' understanding of the impact of their intended developments to the environment. This will potentially facilitate policy makers and environmental authorities in furthering environmental policy. If this practice extends for a considerable time, benchmarks shall be established from which a basis of mitigating emissions can be hinged. In the ongoing global initiatives (e.g. Clean Development Mechanisms) aimed at reducing emissions, the practice will provide first-hand information (e.g. baselines) about the extent of emissions in construction. Perhaps most importantly, the built environment professionals will gain awareness about the environmental consequences related to the decisions they make. It is envisaged that the existing environmental impact assessment and monitoring framework will suffice, albeit with some qualifications, to implement this initiative.

CONCLUSIONS

This paper has documented the process of developing a carbon emissions measurement tool in the context of a one developing country, Uganda. A methodology that involves using Rapid Application Development (RAD) and prototyping has been presented. CaMeT (a prototype name of the tool) was introduced in form of a process conceptualisation model. Future work has been highlighted among which includes using Microsoft Visual Basic and a graphical user interface in order to develop the tool into a fully-fledged functional version. It was argued that such tools are invaluable in tracking the environmental performance of construction in such countries where no specific policies and regulations about sustainable construction exist. On the whole, the initiatives contribute to the overarching goal of fostering sustainable construction and consequently, sustainable development.

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A METHOD TO EVALUATE THE LIFE CYCLE ENVIRONMENTAL IMPACTS OF DOUBLE SKIN FAÇADES IN REFURBISHMENTS

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Refurbishment of existing buildings represents a major challenge for the UK Government to meet the greenhouse gases (GHG) target. Double Skin Façades are one possible solution for low-carbon façade retrofit of existing non-domestic buildings. Available research mainly focused on the operational energy, overlooking the embodied energy which often accounts for up to 50% of the life cycle energy. Due to the lack of available tools with a specific focus to assess life cycle environmental performances of composite materials, a ISO-compliant method has been developed. A review of current standards and seminal literatures about life cycle assessment of buildings and building façades led to a framework based on elementary life cycle processes and different life cycle stages. Mathematical equations to assess whole-life energy, whole-life carbon, and global warming potential have been derived from those available at a building level. The method proposed diminishes the risk of double counting figures throughout the life cycle study as it follows a consequentiality-based approach. The specific focus on composite materials helps achieve more accurate figures at the material level in the assessment of the life cycle environmental impacts.

Keywords: Environmental impact, Life cycle, Refurbishment, Consequential-based approach, Double Skin Façade.

INTRODUCTION

The building sector is responsible for about 40% of the world energy consumption and its related greenhouse gases (GHG) emissions (Ibn-Mohammed et al. 2013). Given the vintage nature of the European stock, the major challenge for the future has been indicated as “to promote the sustainable refurbishment of that consolidated stock” (Ferreira, Pinheiro and Brito 2013). This is particularly true for the UK where more than 75% of non-domestic buildings were built before 1985 and about 60% of them will still exist in 2050 (Carbon-Trust 2009). In terms of energy consumption and CO₂ emissions at national level, buildings account for nearly half of the total (Babangida, Olubodun and Kangwa 2012).

In refurbishments, the improvement of the envelope thermal insulation has been indicated as the most beneficial action for CO₂ emissions reduction (Ardente et al. 2011). In this respect, there is a growing tendency in Europe towards the use of the Double Skin Façade (DSF) for office renovations. In evaluating the suitability of DSFs to refurbish offices in the UK, a review of published studies on DSF performances in temperate climates has shown that this technology is capable of significant reductions to the operational energy consumption, with values in the range of 30% - 60% (Pomponi, Ip and Piroozfar 2013).

However, every construction product also consumes energy in all its other lifecycle stages. These include phases from the extraction of raw materials, processing, manufacturing and transportation, to maintenance, dismantling, and final disposal. The energy related to all the stages other than the use phase is commonly referred to as embodied energy (Cabeza et al.

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2014, Dixit et al. 2010). A review of studies in the UK indicated embodied energy can account for up to 70% (Ibn-Mohammed et al. 2013) and it is too often neglected in sustainability studies either on construction products or buildings as a whole (Stephan, Crawford and De Myttenaere 2012).

To overcome this limitation, thermal efficiency of buildings has to be linked with a whole-life holistic approach of all the materials used (Peuportier, Thiers and Guiavarch 2013). A true environmental benefit, in fact, is only achieved when GHG emissions related to the embodied energy are compensated by the diminution of the GHG emitted in the operational phase. Embodied energy is not currently a subject of regulation, and in the UK these figures are rarely calculated (Moncaster and Symons 2013). One of the main impediments in appraising embodied impacts is the particular shortage of data in the construction sector (Moncaster and Song 2012). This is exacerbated for composite components, which are well represented by the DSF as it includes diverse materials coming from varied production processes spread across the country and, sometimes, the world.

This paper, as a part of a broader research aimed at establishing the life cycle environmental impacts of DSFs for office refurbishments in the UK, sets out to develop a method to assess energy consumption and carbon emissions of composite materials, and to evaluate their global warming potential (GWP) over the whole life cycle. The paper reviews existing literatures, and it builds on them to overcome some of the limitations that arise when the focus switches to building composite components. The aim is to deliver a tool to achieve a more accurate and consistent flow of data and information throughout both different life cycle stages and processes.

CURRENT STANDARDS FOR LIFE CYCLE ASSESSMENT

A Life Cycle Assessment (LCA) is intended as the “compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle” (Iso 2006). Nowadays, in conducting an LCA, ISO standards 14040/44 are the indispensable basis to refer to. The methodological frameworks the standards suggest consist of four phases (Figure 1): goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation. Two main approaches have been widely acknowledged: attributional LCA and consequential LCA (Finnveden et al. 2009).

Attributional LCA aims to describe and quantify the physical flows to and from a life cycle and its subsystems by means of average figures and excludes the use of marginal data, whereas consequential LCA aims to analyse how environmentally significant flows will affect the outcome in response to different possible decisions, and marginal data are used to assess the consequences (Finnveden et al. 2009, Ip and Miller 2012). Attributional LCA is the approach recommended by current standards when assessing the GHG emissions of goods and services (Bsi 2011).

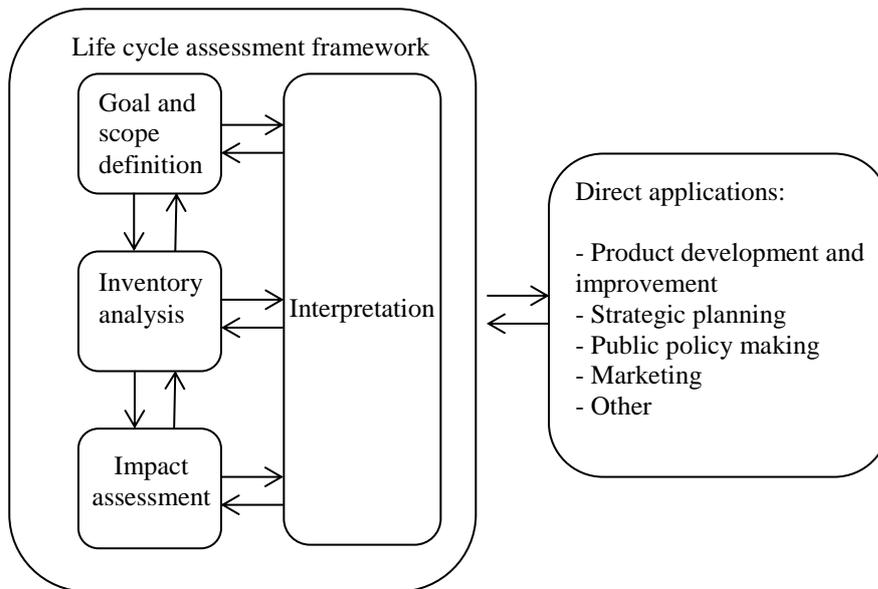


Figure 1 - Life Cycle Assessment Methodological Framework (ISO, 2006a)

Despite the fundamental role ISO standards play in the LCA panorama, there exists a populated scenario of developed methodologies, coming either from national bodies or research groups. A representative example is the Publicly Available Specification PAS2050:2011 for the UK, which is specifically focused on the assessment of GHG emissions within the life cycle of goods and services (Bsi 2011). Some authors asked whether the need for additional documents is real (Weidema et al. 2008). If on the one hand they cover the same areas of the existing ones, on the other hand it is recognised that ISO standards show limitations and vagueness about important aspects (Weidema et al. 2008). One of the most important regards the little guidance provided by ISO standards which led researchers to respond with new approaches and techniques (Lloyd and Ries 2007). In the specific case of PAS, therefore, its implementation is welcomed (Weidema et al. 2008), since it builds on established standards but it also provides clarifications and well-defined techniques.

Life cycle assessment of buildings

Sustainability assessment of buildings throughout their whole life is currently not regulated by policy framework in the EU or the UK (Moncaster and Song 2012). A recent analysis by Cabeza et al. (2014) confirmed a very scattered scenario about LCA of buildings and in the construction industry. The authors highlighted major impediments in comparing the results. Different lifetime figures, lack of parametric approaches addressing multiple scenarios, differences in functional units considered, diverse methodologies and methods for conducting the studies, and the focus mainly on real buildings which makes hard any generalisation are the most important reasons (Cabeza et al. 2014). Such diversity is justified by and originates from the innate complexity of the construction sector where each of the materials used has its own specific life cycle and all interact dynamically in both temporal and spatial variations (Collinge et al. 2013, Erlandsson and Borg 2003). Additionally, the long lifespans of buildings imply lower predictability and higher uncertainty of variables, parameters, and future scenarios (Buyle, Braet and Audenaert 2013).

However, efforts have been made by the European Technical Committee CEN/TC 350 to develop and provide standards that look at the sustainability of construction works, and aim to quantify, calculate and assess the life cycle performances of buildings (Bsi 2010). Moncaster and Symons (2013) used the aforementioned standards as the basis for the recently developed whole life tool which addresses the Embodied Carbon and Energy of Buildings (ECEB) for the UK. The focus on embodied carbon and energy is widely supported to assess the lifecycle environmental impacts of buildings and building components (Monahan and Powell 2011,

Radhi and Sharples 2013). Moncaster and Symons (2013), following the TC 350 methodology, decomposed the building into its assemblies (e.g. external walls), then further into elements (e.g. cavity wall construction), and eventually into components (e.g. bricks). The method for the whole life embodied carbon calculation used in the ECEB tool is expressed by Equation 1 (Moncaster and Symons 2013):

$$EC_{\text{whole-life}} = \sum_{i=1}^n EC_{\text{mat}}(\text{comp})_i + \sum_{i=1}^n EC_{\text{transp}}(\text{comp})_i + EC_{\text{constr}} + \sum_{i=1}^n EC_{\text{refurb}}(\text{comp})_i + EC_{\text{endlife}} - EC_{\text{recover}}$$

Eq. 1: Method for whole life embodied carbon calculation (Moncaster and Symons 2013)

The equation starts with the production of all materials, their transportation, the construction activities, refurbishments cycles throughout the building life, and it ends with the end of life scenario and the potential recover of some of the materials.

It can be observed from the equation that the transportation stage always happens after the manufacturing one. This may turn extremely delicate when dealing with composite components, such as the DSF. In fact, in these cases, components exit a production plant to be transported into another manufacturing site, and this may continue for few stages before the prefabricated assembly travels eventually to the construction site. The authors are aware that composite components deserve a different approach and therefore they proposed to address this issue by estimating a defining coefficient based on similar components made of a single material. However, the authors recognised that that approach is of limited accuracy (Moncaster and Symons 2013).

Another recent framework for the assessment of the life cycle energy of a building has been published by Dixit et al. (2012) based on earlier work from Dixit et al. (2010). Also in this case the energy is divided between embodied and operational. Once again, building materials are treated as single-site manufactured products. This is a simplified assumption which often does not happen in reality. If one tries to fit each part of the composite components into the ‘manufacturing box’ for the calculation of the initial embodied energy, then the risk of double counting transportation figures when considering upstream and downstream flows become relevant.

In conclusions, due to the complexity of the construction industry, it seems composite components have not been addressed carefully enough, being the main focus on the whole building. This issue is not new in the field, and it echoes the lack of reliable and complete data about energy contents of buildings materials and assemblies that would allow, if existent, for greater environmental benefits (Crawford 2009, Peereboom et al. 1998, Reap et al. 2008).

Life cycle studies on building façades

Very few life cycle studies have been published on building façades, despite their role as the elements with the highest heat transfer between the outdoors and indoors. Taborianski and Prado (2012) evaluated the CO₂ emissions in the life cycle of office building façades in Brazil. Their methodology is mainly based on ISO-LCA but it additionally takes into account the emissions related to the use stage by means of software thermal simulation. Their results indicate that embodied energy is extremely significant: it ranges from 40% to 70% among the various types of façades considered in the study. The authors concluded encouraging life cycle studies at the material level and highlighting the importance of having regional and local foci due to peculiarities typical of specific contexts (Taborianski and Prado 2012). Wadel et al. (2013) adopted a simplified LCA in the design of building skins with the specific focus on an innovative type of façade (FB720). The study accounted for the environmental impacts of all but the use phase. The impacts assessed consistently throughout the study are energy consumption (MJ/m²), and CO₂ emissions (kg CO₂/m²), being the functional unit 1 m² of façade with a useful lifetime of 50 years. The best version of the FB720 façade is capable of 50% energy consumption and CO₂ emissions reduction compared to conventional modular façade (Wadel et al. 2013).

De Gracia et al. (2013) conducted a life cycle assessment of a ventilated double skin façade (VDSF) with phase change materials (PCM) in its air chamber. Their LCA study is based on the Eco-Indicator 99 (EI99) endpoints impact assessment methodology. The functional units used are the whole two cubicles constructed in Spain. Results showed that the VDSF reduces by 7.5% the environmental impact over 50 years compared to the reference case (De Gracia et al. 2013).

Damage-oriented, endpoints-based methodologies such as the EI99 used in the study above are useful to assess various impacts along different damage categories but they increase the difficulties in comparing and assessing results. Presenting results in terms of gross energy requirement (GER), carbon dioxide emissions equivalent (CO₂e), or global warming potential (GWP), instead, may be a crude approach but it proves beneficial to ease the understanding and enhance the transparency of the study (Weidema et al. 2008). Additionally, when GWP assessments have been compared with fully fledged LCAs, results have been satisfactorily accurate, showing no lack of scientific rigour (Bala et al. 2010). Therefore, the focus on energy, carbon, and GWP over a 100-year period represents a robust approach, which is well agreed upon in literature and commonly used when it comes to buildings and construction materials (Ardente et al. 2011, Hammond and Jones 2008, Monahan and Powell 2011).

All the studies presented above refer to specific façade typologies, and are based in well-defined and peculiar contexts, thus increasing the difficulty in comparing results and replicating the methodological approach followed. Stating the importance of regional and local foci when conducting life cycle studies, more generic perspectives could allow for a broader use of the methods and could also ease the comparability of results within different contexts. In this respect, Lapinskiene and Martinaitis (2013) developed an optimization model for building envelopes. Their tool is based on building performance energy simulation, the software tool SimaPro, and the multiple criteria complex proportional assessment (COPRAS) for decision making (Lapinskiene and Martinaitis 2013). However, their study is not based on available life cycle standards, nor takes it into account any of the phases for life cycle studies. The most comprehensive and accurate whole life study related to building façades here examined has been recently published by Jin and Overend (2013). The method underneath their study is the whole-life value (WLV) approach which addresses social, economic, and environmental aspects related to the project, manufacturing, operation, dismantling, and disposal of an asset (Jin and Overend 2013). The tool developed is heavily MATLAB-based, requiring a certain level of computing experience for the users to interact with it. The tool has been trialled on a real project of a 13-storey steel-framed office building in London and proved able to save up to 340 tons of CO₂e over a 25-year service life compared to the original design option (Jin and Overend 2013). Notwithstanding the impressive potential of the tool developed, it does show some limitations when looked from a LCA perspective since it lacks a standardised, ISO-based methodology.

The review of published life cycle studies on building façades has shown limitations of the available tools to conduct a consistent environmental impact assessment of composite materials which is compliant with ISO standards. Specifically, the main issues are related to a lack of system boundaries, functional units, and good quality data, and the divergence from current standards. The following section includes the proposed method specifically focussed on life cycle studies of composite materials.

A METHOD FOR LIFE CYCLE STUDIES OF COMPOSITE MATERIALS

The main shift of the method here proposed is to adopt a perspective based on elementary life-cycle processes (LCPs) within each of the life-cycle stage identified by TC350 standards. The rationale behind this choice is to ‘follow the flows’ that happen in reality. Each elementary LCP can be constituted of several activities within the same manufacturing plant.

If a firm needs to outsource a manufacturing activity on its products, this suddenly becomes another elementary LCP and the two are linked by transportation (both back and forth if products then return to the original plant).

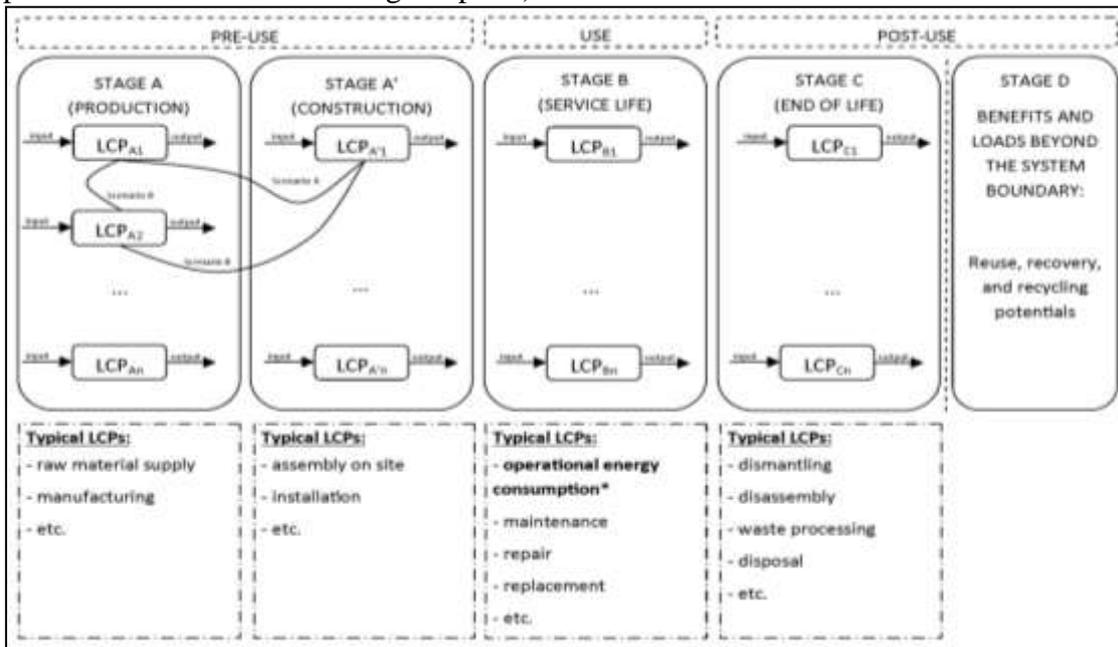


Figure 2 - Framework for composite materials developed from BS EN 15643-2:2011

Such an approach greatly reduces the risk of double counting since it follows the actual consequentiality of events and it switches the upstream/downstream vertical approach to a before/after horizontal one. It can be observed in Figure 2 that multi-scenario options are also accounted for.

Based on the framework proposed, mathematical equations adapted from those available at a building level have been developed for whole-life energy (WLE), whole-life carbon (WLC), and global warming potential (GWP) over a 100-year time horizon (Equations 2, 3, and 4 respectively).

$$WLE = \sum_{i=A}^D \sum_{j=1}^n ELCP_{ij} + \sum_{i=A}^D \sum_{j=1}^n ET_{ij} + \sum_{i=1}^x AOE$$

$$WLC = \sum_{i=A}^D \sum_{j=1}^n CLCP_{ij} + \sum_{i=A}^D \sum_{j=1}^n CT_{ij} + \sum_{i=1}^x AOC$$

$$GWP_{100y}(CO_{2e}) = \sum CO_2 + \chi_1 \sum CH_4 + \chi_2 \sum N_2O$$

Eq. 2, 3, and 4: whole-life energy, whole-life carbon, and global warming potential respectively.

where:

- ELPCij (CLPCij) is the energy (carbon) related to all the activities within the specific elementary life-cycle process 'j' of the stage 'i';
- ETij (CTij) is the energy (carbon) related to transportation from the specific elementary life-cycle process 'j' of the stage 'i' to whichever is the destination – this avoids double counting since all the 'lines' going out from a LCP are accounted for only once;
- AOE (AOC) is the value for the annual operational energy (carbon);
- x is the number of years under consideration as the service life;
- χ_1 is the factor to convert methane emissions into carbon dioxide equivalent – whose current value is 25 (Ipcc 2007);
- χ_2 is the factor to convert nitrous oxide emissions into carbon dioxide equivalent – whose current value is 298 (Ipcc 2007).
-

It is worth clarifying that energy and carbon figures (mainly for Stage D which deals with reusing and recycling potential) may have negative signs and this is to be taken into account in the summations. Due to the UK context of this research, it is advised to refer to Hill et al. (2011), which contains guidelines for GHG conversion factors, and to publications from the Department of Energy and Climate Change (Decc 2013a, b) to distinguish between direct and indirect carbon emissions for fuels, electricity, and transport, and to use figures consistent with the UK energy mix. These data have already been used for life cycle studies of UK buildings, and the GHG there considered are the most common and significant emitted in the construction sector – Carbon Dioxide [CO₂], Methane [CH₄], and Nitrous Oxide [N₂O] (Moncaster and Symons 2013). On the transportation side, related emissions can be more accurate and further refined by taking into account the effect of traffic congestions (see, among others, Mckinnon et al., 2009).

Operational Energy Figures

Operational energy consumption and indoor comfort are closely related and one influences the other. It has been often argued that, generally, LCAs overlook important issues related to the indoor climate and the occupants well-being (Assefa et al. 2007, Cabeza et al. 2014, Hellweg et al. 2005, Jönsson 2000). To overcome such limitation, in the approach here proposed it is advised to subordinate operational energy consumption to indoor thermal comfort. In other words, the priority is on achieving acceptable levels of indoor thermal comfort and then optimising and minimising operational energy consumption. In the UK, CIBSE has recently published the Technical Memorandum TM52 (Cibse 2013) which sets out to assess indoor thermal comfort based on the adaptive method in naturally ventilated European office buildings with a particular focus on overheating problems. These boundaries represent exactly the context of this research. In fact, existing offices in the UK are mostly naturally ventilated, and the main risk of using DSFs lays indeed in overheating phenomena during the warm/hot season (Gratia and De Herde 2004). Additionally, IES VE, the dynamic energy simulation software tool used in this research, has recently included a TM52-compliant thermal comfort assessment within its modules. These preventive measures for operational energy figures can avoid that the optimisation of DSF life-cycle performances is at the expense of users' wellbeing.

CONCLUSIONS

Sustainable refurbishments of the existing building stock are a priority if the established GHG targets are to be met. In this respect, it is worth focusing on building envelopes and façades as their improvement is the most beneficial action for the reduction of CO₂ emissions. So far, the focus has often been on operational energy consumption and its related emissions whereas embodied energy figures have been overlooked. However, there is a strong agreement that embodied energy must be included when assessing sustainable solutions for the construction sector since it accounts for a major share of the whole-life energy. Efforts have been made in recent years to develop a robust methodology for life cycle sustainability assessment of buildings as a whole, which has been translated into ISO standards. However, in refurbishments, composite materials and components often account for the most. New double glazed units and window frames, layered wall insulation, or the double skin façade which is the focus of this research, all fail to fit into the single-plant-manufactured assumption of the frameworks available at building level.

Therefore, based on current standards, a method has been developed which facilitates the assessment of composite materials. The proposed method focuses on elementary life cycle processes within each life cycle stage and it aims to lead to a consistent flow of data throughout the different stages. The main shift has been switching from a vertical, supply

chain-oriented perspective to a horizontal, consequentiality-based one. Additionally, the developed method takes into account a multi-scenario perspective and it includes the option - which is often the case - for products to be manufactured in more than one plant before they reach their final destination. Mathematical equations have been adapted from those available at building level to determine whole life energy, whole life carbon, and global warming potential of the materials under assessment. Although the method has been recently developed and it is likely to be further refined as the research progresses, it can be a useful tool to approach more accurately life-cycle studies of building composite materials.

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A HYBRID DATA QUALITY INDICATOR AND STATISTICAL METHOD FOR IMPROVING UNCERTAINTY ANALYSIS IN LCA OF A SMALL OFF-GRID WIND TURBINE

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In Life Cycle Assessment (LCA) uncertainty analysis has been recommended when choosing sustainable products. Both Data Quality Indicator and statistical methods are used to estimate data uncertainties in LCA. Neither of these alone is however adequate enough to address the challenges in LCA of a complex system due to data scarcity and large quantity of material types. This paper applies a hybrid stochastic method, combining the statistical and Data Quality Indicator methods by using a pre-screening process based on Monte Carlo rank-order correlation sensitivity analysis, to improve the uncertainty estimate in wind turbine LCA with data limitations. In the presented case study which performed the stochastic estimation of CO₂ emissions, similar results from the hybrid method were observed compared to the pure Data Quality Indicator method. Summarily, the presented hybrid method can be used as a possible alternative for evaluating deterministic LCA results like CO₂ emissions, when results that are more reliable are desired with limited availability of data.

Keywords: CO₂ emission, data quality indicator, lca, statistical, monte carlo simulation.

INTRODUCTION

Estimating CO₂ emissions is a significant part of wind energy LCA's. Traditionally CO₂ emission is estimated with a deterministic approach which uses a fixed point value to represent emission factor and generate a single fixed point result. Due to differences in emission factors which may vary by industrial process (Wang and Sun, 2012), there could be significant variations in emission factors among different life cycle inventory (LCI) databases. These variations can affect the results of CO₂ emissions significantly. Incorporating the analysis of data uncertainty of emission factors could be an important improvement to the deterministic approach as it can provide more information for decision making. According to Wang and Sun (2012), CO₂ emission is given by the following formula:

$$\begin{aligned} Emission &= \sum_{i=1}^n Emission_i \\ &= \sum_{i=1}^n Activity\ Level_i \times Emission\ Factor_i \end{aligned} \quad (1)$$

Where,

Emission i: Amount of CO₂ emitted from the consumption of material i (e.g. iron)

Activity level i: Material consumption for material i

Emission factor i: Consumption of material i's emission factor

Data quality indicator (DQI) and statistical methods are often used to estimate data uncertainty in LCA with differing shortcomings and advantages (Sugiyama et al., 2005; Junnila and Horvath, 2003; EPA, 1995; Hanssen and Asbjørnsen, 1996). DQI estimates the uncertainty and reliability of data based on expert knowledge and descriptive metadata such as the data's completeness, geographical correlation, etc. It is mentioned in Coulon et al., (2011) and Junnila and Horvath (2003) that DQI can be used both quantitatively and

qualitatively in LCA studies. On the other hand, the statistical method fits data samples with a goodness of fit test to characterize data range with probabilistic distributions if enough data samples are available. DQI although less accurate than the statistical method costs less compared to the statistical method (Venkatesh et al., 2011; Tan et al., 2002b). Due to the high cost of implementing the statistical method, though it is desirable when high accuracy is required, DQI is extensively applied when high accuracy of an uncertainty estimate is not critical or the size of a data sample is not large enough for meaningful statistical analysis (Sugiyama et al., 2005). Considering the trade-offs between cost of implementation and accuracy, Wang and Shen (2013) presented an alternative stochastic solution using a hybrid DQI-statistical (HDS) approach to improve the quality of pure DQI method while reducing the cost of the pure statistical method in whole-building LCA. The key departure from previous works being the stochastic pre-screening process using quantitative DQI and Monte Carlo simulation (MCS) to determine the influence of the contribution of parameters. After the categorization, the statistical method is adopted for the critical parameters, and DQI based distributions are used for non-critical parameters. An application test case to wind turbine LCA is presented to validate the presented solution. The aim of this paper is to present the hybrid DQI-statistical (HDS) method to improve the uncertainty estimate of CO₂ emissions of a small off-grid wind turbine combining the advantages of the traditional DQI and the statistical method to develop a more practical approach. This method can be used as a valuable tool to evaluate deterministic results of CO₂ emissions when uncertainty information is needed for decision making.

Methodology

The DQI Method

DQI characterizes the quality of data using descriptive indicators often formatted as a data quality pedigree matrix (DQPM) as shown in Table 1. Columns in the matrix represent data quality indicators such as data's completeness, age etc. while rows represent the quality scale from 1 – 5. The overall quality of data can be characterized by an aggregated number that takes into account all the individual indicators (Junnila and Horvath, 2003). All the indicators are treated equal in weight, for example, if (5, 4, 3) are assigned to three indicators respectively, the aggregated DQI score for the parameter is $T = 5 \times 1/3 + 4 \times 1/3 + 3 \times 1/3 = 1.61$.

Quantitative DQI

Quantitative DQI enables the transformation of aggregated DQI scores to probability density functions for the quantification of uncertainty (Weidema and Wesnæs, 1996; Tan et al., 2002b, Maurice et al., 2000; May and Brennan, 2003). The idea being to characterize data of different quality by probability density functions based on the “rule of thumb” (Finnveden and Lindfors, 1998). The DQI transformation matrix is often used to convert aggregated DQI scores into beta functions (May and Brennan, 2003; Canter et al., 2002; Tan et al., 2002b; Kennedy et al., 1997; Kennedy et al., 1996).

$$f(x; \alpha, \beta, a, b) = \left[\frac{1}{b-a} \right] * \left\{ \frac{\Gamma(\alpha+\beta)}{[\Gamma(\alpha)*\Gamma(\beta)]} \right\} * \left[\frac{x-a}{b-a} \right]^{\alpha-1} * \left[\frac{b-x}{b-a} \right]^{\beta-1} \quad (2)$$

$$(a \leq x \leq b)$$

Where α, β are distribution shape parameters and a, b are selected range endpoints. Canter et al. (2002) suggests the use of the beta function due to the fact that “shape parameters and range end points allow virtually any shape probability distributions to be represented”. As expressed by Canter et al., (2002), “the shape parameters establish the shape of the distribution and thus the location of the probability mass, whereas the endpoints limit the range of possible values”.

HDS Approach

Wang and Shen (2013) states that the HDS approach consists of four steps: (a) Quantitative DQI with MCS; (b) Parameter characterization; (c) Detailed probability distributions estimation for parameters; and (d) Final MCS calculation. The parameter characterization identifies the critical parameters based on the parameters' degree of uncertainty and their influences. The final stochastic results will be produced through a MCS calculation.

Table 1: Data quality pedigree matrix (DQPM) based on National Energy Technology Laboratory (NETL) LCI&C Guideline Document

Indicator	Score				
	1	2	3	4	5
Source Reliability (for most applications, source quality guidelines only factor)	data verified based on measurements	data verified based on some assumptions and/or standard science and engineering calculations	data verified with many assumptions, or non-verified but from quality source	qualified estimate	non-qualified estimate
	source quality guidelines met		source quality guidelines not met		
	data cross checks, greater than or equal to 3 quality sources	2 or less data sources available for cross check, or data sources available that do not meet quality standards		no data available for cross check	
Completeness	representative data from a sufficient sample of sites over an adequate period of time	smaller number of site but an adequate period of time	sufficient number of sites but a less adequate period of time	smaller number of sites and shorter periods or incomplete data from an adequate number of sites or periods	representativeness unknown or incomplete data sets
Temporal Correlation	less than three years of difference to year of study/current year	less than 6 years of difference	less than 10 years difference	less than 15 years difference	age of data unknown or more than 15 years difference
Geographical Correlation	data from area under study	average data from larger area or specific data from a close area	data from area with similar production conditions	data from area with slightly similar production conditions	data from unknown area or area with very different production conditions
Technological Correlation	data from technology, process or materials being studied	data from a different technology using the same process and/or materials		data on related process or material using the same technology	data or related process or material using a different technology

a) Quantitative DQI with MCS

This step follows Canter et al. (2002)'s methodology beginning with data quality assessment using DQI. All parameters used for the deterministic calculations are evaluated based on the DQPM. After the calculation of aggregated DQI scores, probability distributions for each of the parameters are estimated based on the transformation matrix (Table 2), and used as inputs for the MCS to perform an influence analysis.

b) Parameter characterization

The degree of parameter uncertainty can be obtained in the process of data quality assessment. Accordingly, parameters will be classified into groups of four with DQI scores belonging to the intervals of (Alcorn and Baird, 1996; Ortiz et al., 2009), (4, 5), (3, 4), (2, 3) and (1, 2) respectively. The group containing parameters with DQI scores within the interval of (1, 2) and (2, 3) show the highest uncertainty, and the group with parameters scored within the (3, 4) and (4, 5) interval depict the highest certainty. Sugiyama et al. (2005) shows that a parameter's influence on the final resulting uncertainty comes from a rank-order correlation analysis in MCS (Equations (3) and (4)).

$$IA_{p,q} = r_{p,q}^2 [\sum_p r_{p,q}^2]^{-1} \times 100\% \quad (3)$$

Where $IA_{p,q}$ is the influence of input parameter p to output q ; $r_{p,q}$ is the rank-order correlation factor between input p and the output q . $r_{p,q}$ can be computed via:

$$r_{p,q} = 1 - [6/(N^3 - N)] \sum_{i=1}^N [rank(p_i) - rank(q_i)]^2 \quad (4)$$

Where $rank(p_i)$ and $rank(q_i)$ are the ranks of p_i and q_i among the N tuple data points.

Table 2: Transformation matrix based on (Canter et al., 2002 and Weidema and Wesnæs, 1996).

Aggregated DQI scores	Beta distribution function	
	Shape parameters (α, β)	Range endpoints (+/- %)
5.0	(5, 5)	10 4.5
	(4, 4)	15 4.0
	(3, 3)	20 3.5
	(2, 2)	25 3.0
	(1, 1)	30 2.5
1)		35 2.0
		40 1.5
		45
	(1, 1)	50

c) Detailed probability distributions estimation for parameters

The statistical method will be applied, after the parameter categorization, to the process of fitting probability distributions of the identified critical parameters. Kolmogorov-Smirnov goodness of fit test (K-S test) is a statistical tool that can be applied for determining whether a data sample is drawn from a population with a specifically hypothesized distribution by measuring the maximum vertical distance between the two cumulative distribution functions (Massey, 1951). If this distance is smaller than the designated critical table value, the null hypothesis that “The data sample follows the hypothesized distribution” can be accepted (Massey, 1951). The K-S test statistic is defined as:

$$D = \max_{1 \leq i \leq N} \left[F(Y_i) - \frac{i-1}{N}, \frac{i}{N} - F(Y_i) \right] \quad (5)$$

Where F is the theoretical cumulative distribution of the distribution being tested; N meaning N ordered data points $Y_1, Y_2 \dots Y_i \dots, Y_N$. For the non-critical parameters of lower uncertainty and influence, the probability distribution will be estimated based on the DQI scores and the transformation matrix.

d) Final MCS calculation

The final step is calculating the stochastic results by MCS algorithm, according to the relationship between inputs and outputs, using the elaborately estimated parameter probability distributions as inputs. The probability distributions of non-critical parameters are obtained from the quantitative DQI.

Validation

To validate benefits of the HDS, it is compared to the pure DQI using two measurements to measure the difference between the results. Mean Magnitude of Relative Error (MRE) (Eq. (6)) (Abdou et al., 2004) and Coefficient of Variation (CV) (Eq. (7)) (Venkatesh et al. 2010). A large CV value indicates wide spread of a distribution.

$$MRE = \frac{(M_{HDS} - M_{DQI})}{M_{HDS}} \times 100\% \quad (6)$$

Where M_{HDS} is the mean of the HDS results and M_{DQI} is the mean of the pure DQI results

$$CV = SD/M$$

(7)

Where SD is the standard deviation and M is the mean.

TEST CASE RESULTS AND DISCUSSION

Estimation of the CO₂ emissions for three unit processes (Produce Air-X-9, Produce Tower and Produce Batteries), out of six, of a wind turbine LCA test case adopted from Fleck and Huot (2009) was performed. The reason only three of the processes were considered is in a large part, due to time constraints regarding the deadline for the submission of this paper. Since the quantities of the wind turbine components were from the same data source, they have very little or no variations. The deterministic estimate result was used as a benchmark for comparison of the stochastic estimation outputs.

Quantitative DQI transformation

Aggregated DQI scores were rounded off to the nearest nominal value in order to use the transformation matrix. Figure 1 shows the aggregated DQI scores. Because most of the parameters used in this test case were adopted from the same data source they showed the same DQI score of 4 and the same transformation beta function parameters ($\alpha = 3, \beta = 3$), with the exception of battery and galvanized steel with DQI scores of 3.5 and 3 respectively.

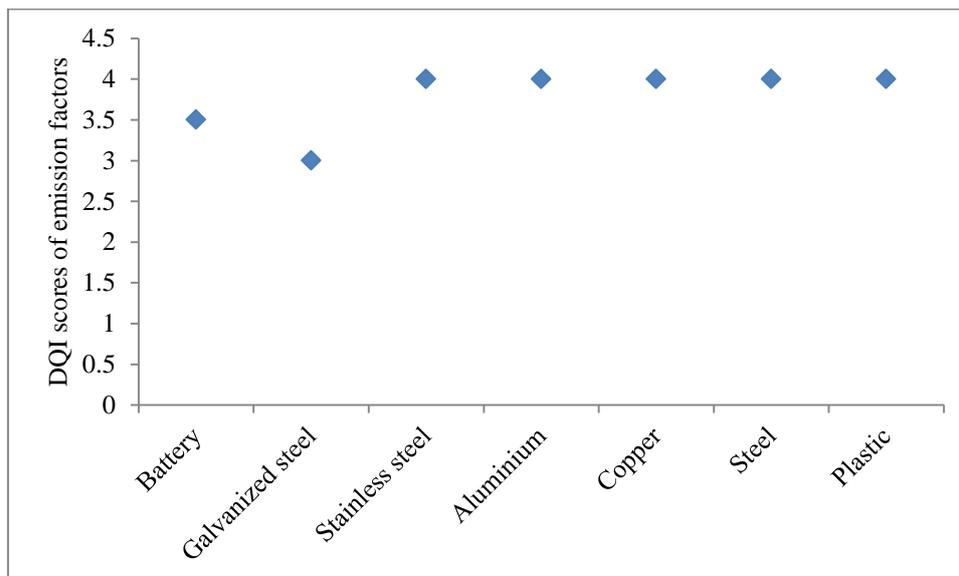


Figure 1: Aggregated DQI scores

Categorizing Parameters

The influence analysis results (2,000 runs MCS) are shown in figure 2. Aluminium emission factor shows the largest influence contributing 25% of the resulting uncertainty. The following parameter is plastic emission factor, contributing 21% of the resulting uncertainty. Majority of the data are of good quality with corresponding DQI scores of 4. The parameter galvanized steel emission factor is the most uncertain with a DQI score of 3. With these results aluminium emission factor and plastic emission factor were positioned for further analysis using the statistical method, while others obtained their values from the quantitative DQI.

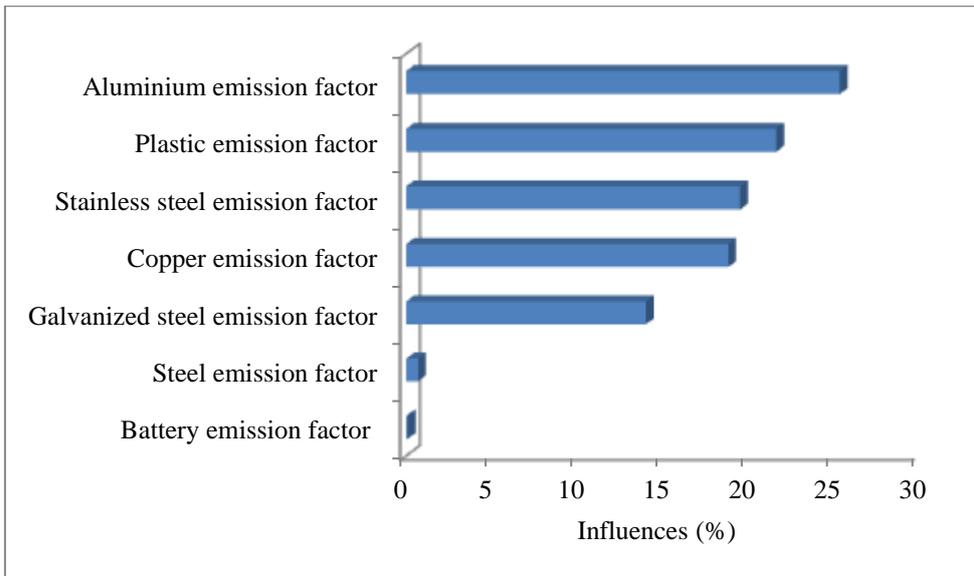


Figure 2: Influence Analysis

Probability Distributions Estimation

Beta (4.5, 5.2) was fitted to 32 data points manually collected from previous studies for aluminium emission factor with a mean value of 11.58 kg CO₂eq/kg. While for plastic emission factor, beta (1.8, 11.3) was fitted to 33 data points manually collected from literature with a mean value of 3.8 kg CO₂eq/kg.

Comparison of the HDS, Pure DQI and Deterministic Results

Figure 3 shows the stochastic result (2,000 runs MCS) using DQI. Beta distribution (4.5, 4) (K-S test) was fitted, with a mean value of 3531 kg CO₂eq and standard deviation of 401 kg CO₂eq. The HDS result follows a beta distribution (6.9, 9.7) (K-S test), with a mean value of 3535 kg CO₂eq and standard deviation of 327 kg CO₂eq. Thus, there is little difference in the dispersion from the DQI result. The CV value of the HDS result is 0.09, about 81% less than the value of 0.11 for the pure DQI result. The (10%, 90%) certainty interval for the output of the DQI is (3,032 kg CO₂eq, 4,083 kg CO₂eq) with a span of 1051 kg CO₂eq, while a slightly narrower (10%, 90%) certainty interval of (3,117 kg CO₂eq, 3,961 kg CO₂eq) with a span of 844 kg CO₂eq is presented for the HDS result. In terms of MRE, 0.11% difference was observed between the HDS and pure DQI result. This indicates that HDS, given the scope of this study, does not capture more possible outcomes than pure DQI, i.e. pure DQI does not underestimate the uncertainty of the result. The differences between the three results (deterministic, pure DQI and HDS) can also be seen from the cumulative distribution function. As seen in Figure 4, it can be concluded that about 50% of the possible results are smaller than the obtained deterministic result based on the HDS and pure DQI result curves. From the procedure of HDS which identifies critical parameters and handles them with the statistical method, which is presumed accurate, it can be seen that the final results generated from HDS are somewhat jeopardized. Since the identified critical parameters that explained the majority of the overall uncertainty was around 46%, it can be hypothesized that there is not much uncertainty in the data related to these processes given the little differences in the influences between the parameters. Consideration of the three remaining transport processes, where the data might have significant scatter, could meaningfully influence the result.

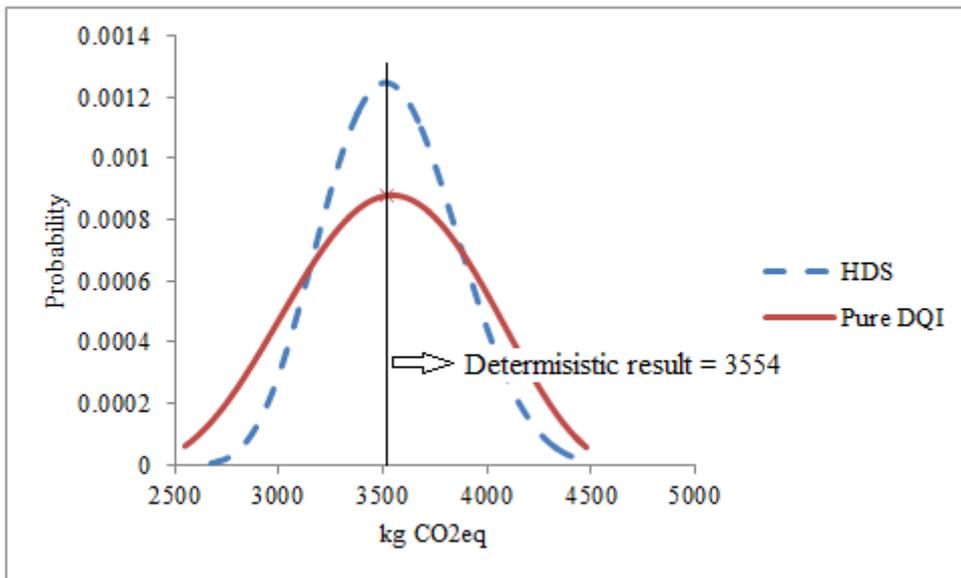


Figure 3: Comparison of resulting probability distributions between HDS and pure DQI

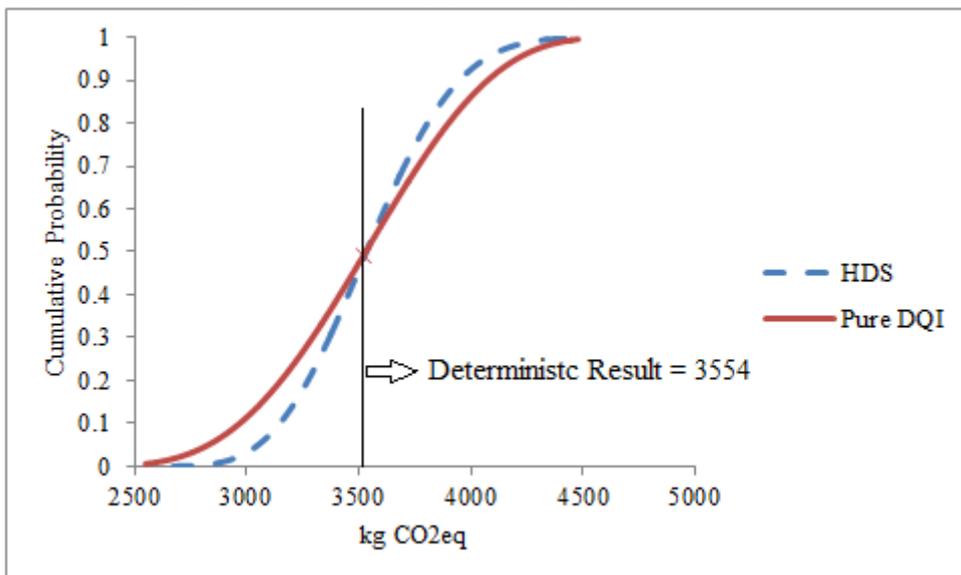


Figure 4: Comparison of cumulative probability results between HDS and pure DQI

CONCLUSIONS

The presented hybrid approach using a pre-screening technique based on Monte Carlo rank-order correlation sensitivity analysis did not demonstrate its effectiveness in evaluating deterministic results of CO₂ emissions emitted. The quantitative DQI method did not underestimate the data uncertainties compared to the HDS, which used the statistical method to estimate the most influential parameters. The results measured by MRE and CV between both methods indicate that HDS did not capture a wider range of uncertainties when compared to pure DQI. Evaluating the reliability of the deterministic value of CO₂ emissions, HDS did not show improved estimate of data uncertainties compared to DQI, meaning HDS approach did not mitigate the uncertainty underestimation deficiency of DQI. From Figure 4 it can be seen there is about 50% chance that the deterministic result is greater than the actual value using both methods. Thus decisions based on either approach are reliable.

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SCALE TO FIT, PHYSICAL SCALE AND SOCIAL QUALITY OF HOUSING IN SHELTERED INDEPENDENT LIVING

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Since the eighties, Dutch residents of care homes have been housed in sheltered independent living in order to age in place and live with higher social quality of housing. Physical scale and social quality of housing of sheltered independent living have not yet been explored. Initiators decide on experience and intuition or guided by government policy and exploitation. The question arises: Are choices in scale for sheltered independent living based on quality factors or guided by institutional influences such as legislation and financing? A desk research of 265 projects and a multiple case study in 24 projects were conducted as a PhD research. Significant relations were found, partly in line with presuppositions on quality drivers, partly difficult to explain. Legislation and financing showed to have plausible relations. There are limiting factors of the physical scale towards the social quality of housing in sheltered independent living. Given the distribution of preferences of elderly, there is no single optimal value for the physical scale.

Keywords: Building performance, Decision analysis, Physical scale, Social Quality of Housing.

INTRODUCTION

Housing for the elderly in the Netherlands is changing constantly. Once-valued homes for the elderly have been replaced by care homes and nursing homes (van der Voordt & Terpstra 1995). These homes have subsequently been replaced by small-scale housing facilities (Boekhorst et al. 2008). And the residents of care homes are housed in sheltered independent living or more preferably, in areas with integrated neighbourhood services (Edwards 2001). The goal: independent living for longer.

The latest research on sheltered independent living dates from 2005 (Singelenberg, 2005). It is considered out of date as a form of housing and exhausted as a subject for research.

Nevertheless, they are still being built, changing in character, intended for a wider variety of target groups, resulting in lighter and heavier versions of the concept (Singelenberg & Triest 2009). Present definitions should be widened. The question is whether a wider group mix leads to more integration and a better social quality of housing?

Small-scale living has already been researched within the field of care for people with dementia (Hamel 2005; van Liempd, Hoekstra, Jans, Huibers, & van Oel 2010). Findings lead to a reevaluation, and at the same time administrative measures are taken. Objections arise as well (Geelen 2005). The physical scale of ALFs and its effect on housing quality have not been explored. Initiators decide on the basis of previous experiences, intuition and good intentions, guided by policy and focused on exploitation.

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Decisions can scarcely be taken on the basis of general literature about the social quality of housing, as this seems to be lacking since 1990. Changing government involvement, less control and more customer orientation are possible causes. With new initiatives in which a number of target groups are deliberately mixed and facilities are strongly developed, decision-makers aim to improve the social quality of housing and improve integration, but almost without any scientific basis.

This paper concentrates on the influence of the physical scale, which leads to the following main question: What is the effect of physical scale on the social quality of housing in sheltered independent living?

METHODS

An extensive literature review with regard to the notion of scale in organizational theory produced a composition in the independent variable physical scale, the structural scale and the mental scale (van Zijp 1997). This relates to concepts of scale derived from architectural theory that distinguish external, relative and internal scales (Boudon 1978, Ching 1979). In addition, the dependent variable social quality of living has been studied (Van der Voordt 2009, Alexander 1979, Zwart 1989, De Vreeze 1987).

In a preliminary study, thirteen locations were examined briefly to define the research question and explore the field. The first findings were: several very large-scale complexes with respect to the surrounding area of coverage, some facilities closed within a year, wide variety in terms of liveliness and calmness, leading to a first conceptual model.

Mixed method

This research provides insight into the effect of physical scale on the social quality of housing. It consists of a desk study of 265 projects and a case study of 24 projects. The aim is to contribute to a more informed and evidence-based assessment among initiators. For this purpose, the results will appear in a hard copy and an online atlas after the thesis has been completed.

The desk research on the basis of the CBZ archive (CBZ 1998-2010). and the Assisted Living Facilities databank of the Expertise Centre Housing and Care (KCWZ 2010) database shows the relationships between physical scale, target group mixture and level of facilities, and the relationship with legislation and funding during the research period. Both databases are controlled, filtered according to the research question, and analysed for associations and significance of correlations.

The multiple case study shows the influence of the variation found in physical scale, group mix, and level of facilities and the experience of social quality of living on the basis of a strategic selection of 24 cases from the desk research.

To this end, semi-structured interviews were conducted with 174 inhabitants, 40 professionals and 35 decision-making employees in sheltered independent living projects according to an intensive narrative research method (Van Biene 2008). In addition, the research team conducted 171 observations for triangulation of the primary narrative results.

The narratives are arranged in sets of cases according to the research variables of physical scale, group mix and amenity level in order to conduct not only a qualitative but also a quantitative analysis according to the Qualitative Comparative Analysis method (Ragin & Rihoux 2008; Wagemann & Schneider 2010).

All fourteen hypotheses were tested using this broad, combined approach. Of those, eight hypotheses were supported, five hypotheses were nuanced, and one was partly rejected. In addition, the exploratory method of data collecting provided eight meaningful conclusions.

Methodological reflection

The strategic selection regarding physical scale succeeded broadly. All three sets of physical scale (small, medium, large) were adequately represented in the sample in order to meet current requirements for a theoretical and practical saturation. However, attempts to find sufficient cases of less obvious combinations of small physical scale in towns and large physical scale in villages were unsuccessful. The addition of these deviant cases would be of great value for conclusions concerning the influence of physical scale and location.

The relatively balanced number of positive and negative statements could indicate the relatively high reliability of the prevailing narrative method, which generates both positive and negative statements.

With the successful testing of all fourteen hypotheses, this combination of QCA with larger sets of narratives proves to be a potential hypothesis-testing methodology that requires further elaboration in future research. This is appropriate in the development of mixed methods and mixed models of research that combines quantitative and qualitative methods. Besides QCA, 'Big Data' techniques could be considered in exploring rather than testing hypotheses with the narrative data from this study or other studies.

For the professional field, the development of the draft hardcopy and online Sheltered Independent Living Atlas is recommended, much of the work for which has already been carried out. Since the observations are related to individual cases, this material can be incorporated. For further development of the atlas, it is desirable to present a prototype to decision-makers and residents as potential occupants.

FINDINGS

The desk research focuses on minor questions and hypotheses concerning the distribution of and relations between physical scale, group mix and level of facilities, and the legislation and funding in the period 1998-2010. The desk research offers quantitative overviews of these independent and mediating research variables related to time, to location and to each other, and thus a picture of the variation in ALFs in the period 1998-2010.

The distribution and variation was then the prime consideration in the strategic selection of the case study. For this selection, the KCWZ database was taken as the basis on account of the higher representative nature of this database for sheltered independent living, the larger time span and the completeness of the data.

The range in physical scale observed is used for classification into scale groups for the strategic selection. The observed correlation with changes in legislation and the larger variation in the city are key to the qualitative analysis of these aspects in the case study.

The strategic selection of the multiple case study regarding the range of physical scale was successful.

The broad narrative analysis has delivered a very large amount of data. This is rich in content, but also complex. For the testing of the hypotheses the cases are arranged in sets, varying according to the three independent and mediating variables. These sets are quantitatively and qualitatively analysed to provide a combination of Qualitative Comparative Analysis (QCA) and a narrative method.

Due to the specific data per case, the triangulation method of the observations is of limited use for comparing the sets. The source triangulation of the interviews with residents, professionals and decision-makers proved to be valuable owing to the comparison of various perspectives.

The most striking result in general is the finding that, in addition to the social function, ensuring security and belonging is a relatively important function of sheltered independent living for residents.

Regarding the influence of physical scale, the variation in the desired scale is surprising, with as many supporters of large scale as of small scale, related to the location in towns or villages.

CONCLUSIONS

The conclusions regarding the influence of physical scale are the following:

- There is an even distribution of physical scale among sheltered independent living in the Netherlands in the period 1998-2010 despite the increased focus on small scale and large scale.
- Smaller sheltered independent living projects are not relatively more common in villages, and larger complexes are not relatively more common in towns.
- The larger number of inhabitants in cities does not lead to small scale as a result of a broad variety in facilities. The smaller number of inhabitants in villages does not lead to large scale as a result of a concentration in facilities.
- Small scale is valued by inhabitants and decision makers because of the expected domesticity and safety and by decision makers because of the customization possibilities. However, large scale is valued to a similar extent by inhabitants and decision makers for its liveliness, anonymity, choice of contacts and activities.
- The desired scale for the social quality of housing does not differ according to the region in the Netherlands.

Recommendations

The recommendations regarding the influence of physical scale are:

- Realize enough vibrancy and viability. Range of lower limit: 25-40 housing units.
- Realize sufficient familiarity and identifiability. Range of upper limit: 300-350 housing units.
- Provide desired balance in social control and anonymity. Range for tipping point: 80-120 housing units.
- Provide for harmonization with location. Range for harmonization with village locations: 25-120 housing units; range for urban locations: 80-350 housing units.

And regarding decision-making:

- Develop the concept Sheltered Independent Living Atlas with the professional field into a hard copy and online decision-making tool.

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SPATIOTEMPORAL ANALYSIS OF E-MOBILITY RECHARGING FACILITIES

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The world is witnessing an accelerating expansion of urban areas and intensive urbanization. The robust relation between transport infrastructure and urban planning is reflected in how integrated and reliable system is within the urban fabrics. Designing an integrated infrastructure to support full electric vehicle (EV) use is a crucial matter which worries planning authorities, policy makers, as well as current and potential users. Reducing range anxiety by facilitating access to public recharging facilities is designed to overcome the main barrier that stops potential users to utilise EVs. The uncertainty of having a reliable and integrated charging infrastructure presents hurdles to, and slows down, the growing trend of smart ecosystems and sustainable urban communities as whole. Automotive, batteries and utilities technologies have formed the cornerstone of the EV industry to compete with currently mainstream means of transport, and to gain more prominence within many regions. Strategically locating public EV charging points will help to pave the way for a better market penetration of EVs. This paper analyses real information about EV users in one of these metropolitan areas spanning one year of EV operation, year 2012. A case study of 38 charging points with over 120 EV users located in the inner urban core (NE1, NE4 and NE8 postcode districts) of a metropolitan area in the North-East England, the city of Newcastle upon Tyne, incorporating space-time analysis of the EV population, is presented. Information about usage and charging patterns is collected from the main local service provider in the North East of England, Charge Your Car (CYC) Ltd. The methodology employed is a clustering analysis. It is conducted as a dimensional analysis technique for data mining and for significant analysis of quantitative datasets. A spatial and temporal analysis of charging patterns is conducted using SPSS and predictive analytics software. The study outcomes provide recommendations, exploring design theory and the implementation of public EV recharging infrastructure. The chapter presents a methodological approach useful for planning authorities, policy makers and commercial agents in evaluating and measuring the degree of usability of the public electric mobility system.

Keywords: charging patterns, clustering analysis, electric vehicles, recharging facilities, spatiotemporal analysis

INTRODUCTION

Electric drivers are needed to replace the internal combustion engines (ICT) for cars and small vans (Robinson et al. 2013). There is a growing momentum behind owning a plug-in electric vehicle (PEVs). CENEX (2008) forecast that there will be between 0.5 and 5.8 million EVs in the UK by 2030. In developed countries and industrial regions, the low carbon emissions vehicles market is expanding. The transport demand is soaring continuously due to the expansion of the urban patterns and contexts. However, it is too early to assert whether electrification will dominate the alternative equivalent vehicle market. Adding incentives, promoting initiatives, wise marketing, and spreading awareness likewise tax exemption, plug-in places and cars, government's subsidies, dedicated parking lots, driving zones, and special lanes strongly boost up the probability of having more customers. However, anticipating the

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buyer behaviour is a key factor that would positively direct stakeholder towards a maturing market. One main shortcoming of EVs is their limited range, which can be below 62 mile/ 100 km a daily road trip (Wirges & Linder 2012). In order to overcome this obstacle, focus attention to be given to driver's confidence level and comfort zone. The success of a mass roll out of Electric Vehicle (EV) is strongly associated and underpinned by the development and the design of integrated recharging infrastructure network (Namdeo, A., Tiwary, A. and Dziurla 2013).

The planning of EV recharging infrastructure network is a learning process. The more factors are considered, the better vision of the system. These factors and attributes are identified and quantified after a prolonged phase of investigation of the system and its variables. These variables and predictors vary in nature. Behavioural variation within the population is one of crucial one and can be shown in several examples. The first reaction of the early adapters to the limited range of the EV was reflected to the small comfort zone which they will never risk it and step out of it. This comfort zone is the opposite of the range anxiety limits. Whenever the comfort zone ends, the anxiety starts which was starting in earlier stages compared to the more confident EV users. The practice of driving an EV is an influential factor that affect the charging pattern of the driver hence its interpretability and usability of the system.

Considering the domestic charging is first choice of all EV drivers who have access to it, the use of the public charging became more popular due to the extension of the comfort zone. Yet, the comfort zone of an EV driver is way smaller than conventional means of transport passengers.

Research Focus

The goal of this study is to undertake exploratory analyses trying to interpret the current sociobehavioral configuration of EV system by data summarization, inference, and intuition about EV users charging path data. It introduces the drivers' charging behaviour and attempts to cluster their usage patterns via recording the transactions made to use the publically available RFs. Spatial configuration analysis is conducted to ultimately help developing design tools for planning authorities and policy makers. It works on clustering the RFs into groups of charging points and describing the prototypical path of a general cluster of an EV recharging infrastructure network in metropolitan area. This article presents a methodological approach for planning authorities and policy makers to evaluate and measure the degree of usability of the electric mobility system. This study tests the hypothesis that states a correlation between the design configuration of e-mobility recharging network and the charging patterns and the emergent behaviour of the EV crowd.

THEORETICAL BACKGROUND

The EV is a promising form of technology pathway for cutting oil use and CO₂ emissions; it is perceived as a central pillar for a new era of alternative smart and green means of transport (ElBanhawy et al. 2013); (ElBanhawy and Dalton 2013). EVs offer considerable potential to make progress in a variety of wider environmental, societal and economic objectives, which accelerates the development of smarter cities (ElBanhawy et al. 2012); (Lindblad 2012). Nevertheless, the transitional phase between using purely conventional means of transportations to state of art technological ones is a long way of development and awareness. The absence of a proactive and constructive approach and feasible schedule for recharging infrastructure is a major impediment to mainstream market especially to EV due the sole dependency on batteries as a source of power hence range limits and longer recharging time (Namdeo, A., Tiwary, A. and Dziurla 2013). The EV recharging facilities has to be integrated enough to support the on-street and off -street charging demand. The location and size of the RFs are fundamental issues, likewise the gas stations. Locating these stations, particularly in

the early 30's, when it was newly introduced to the market, are an intrinsic matter that affects the organization. Potential users would be concerned about the level of durability and reliability of the charging stations as they would be afraid to run out of fuel in the middle of the roads. Likewise the gas based vehicles, or likewise any private vehicles, car passengers have an everlasting concern especially when it is a niche market. The problem with the planners and policy makers is that they deal with locating and sizing the recharging infrastructure network as a static location planning problem (Wirges & Linder 2012). From a closer look into the literature, there were several ways of tackling this planning issue. Geographic information systems, connection to grid, ownership preference and business need, modelling and clustering market segmentation, or genetic algorithm-based solutions solving layout faculty management (Wang 2005).

Spatial Configuration Attributes

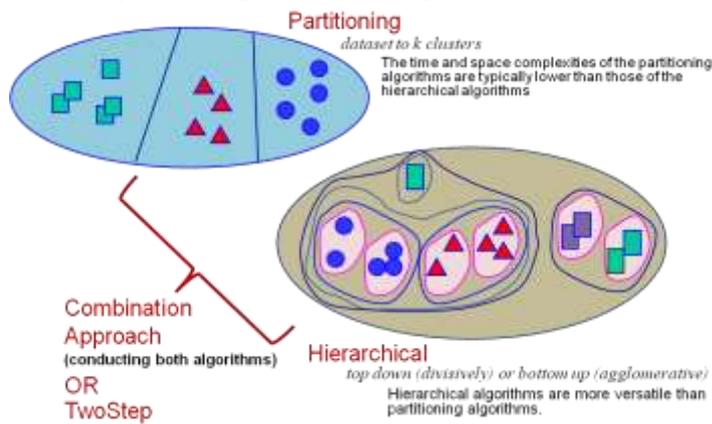
Spatial analysis often employs methods adapted from conventional analysis to address these problems in which spatial location is the most important explanatory variable. The idea of the configuration modelling revolves around the space theory that incorporates the space topological relationships and its relation with the movement. It has been also asserted though can't be generalized that the principle of configuration models, street segments with high accessibility indexes strongly present a high level of connectivity with other links hence high potential uses (Barros et al. 2007). It can be observed from the study presented by Barros, De Silva, & Holanda (2007), that configuration modelling in general and space syntax in particular can play a role in the transport studies especially in the early planning stages. This study employs space syntax spatial analysis software, Depthmap. Depthmap basically transforms the street pattern into a network graph by disaggregating the network at the intersections. The travel cost between a pair of segments, is measured by the shortest path approach. The distance is weighted by three key cost relations: connectivity, angular integration (Topo-geometrical) and mean depth. The spatial analysis starts with generating road network centreline mapping via using AutoCAD and converting it to a segment map using Depthmap.

MEHTODOLOGY

Data clustering is a continuous fine-tuned process of grouping sets of data. It is a convenient method for identifying homogeneous groups of objects, called clusters (E. Mooi and M. Sarstedt 2011). Clustering analysis is used for identifying groups within the data while being able to analyze groups of similar observations instead of individual observations. It also works on simplifying the structure and showing relationship weren't revealed before (Caccam & Refran 2012). It is finding a group of similar objects sharing many characteristics and qualities, which are unrelated to other objects not belonging to that group aiming at reducing the size of the large data sets. These objects (cases, or observations) (E. Mooi and M. Sarstedt 2011) can be customers, products, employees, users, clients...etc. It is to analyze their behaviour, preference, pattern, usage or any other quantified parameter and classify this into groups (Larson et al. 2005). To group the observations into clusters, many techniques begin with similarities between all pairs of observations (Schaeffer 2007).

The classification of the data clustering algorithms can be in different shapes. In the present study, we are presenting the classification as per the platform being used. SPSS, predictive analytics software is the commercial platform is being used. SPSS has three techniques with different algorithms: K-means (Partitioning or Flat-Hierarchical) clustering, Hierarchical clustering and TwoStep. The first one works on dividing the data into non-overlapping subsets, Fig.1. The second one is to divide them into nested clusters organized as a hierarchical tree, Fig.1.

TwoStep is the selected technique for the research problem; it conducts a hybrid approach, which starts with the hierarchical approach (partitioning) followed by flat hierarchical approach, Fig.1. The first is used to determine the number of clusters and profile clusters centres (centroid) that would serve as initial cluster formation in the partitioning one. The second phase would take place to provide more accurate cluster membership (as the K-means clustering needs to identify the number of clusters as a first step). This enables the advantage of the hierarchal methods to complement the partitioning method in being able to refine the results by allowing the switching of the cluster membership.



Figures1: Significant spatial data clustering algorithms

TwoStep

The SPSS TwoStep clustering was developed for the analysis of large data sets (Chiu et al. 2001). This hybrid method creates clusters based on both continuous and categorical variables which is needed for the present study due to the variety of the data. It has the ability of automatically selecting the number of clusters as well as analysing large data files in an efficient manner (Caccam and Refran, 2012). The clustering algorithm is based on a distance measure that yields the best results if all variables are independent, and it deals with continuous and categorical data set (Mooi and Sarstedt, 2011).

There are some key alterations that can be made to the selection of the variables, display, maximum and minimum number of clusters, and evaluations fields. Cluster analysis involves several procedures as summarized by (Milligan 1996): selecting clustering objects and clustering variables (dependent and independent), deciding on the type of data, variable standardization, choosing the measure of association, selecting the clustering method, determining the number of clusters and interpretation, validation and replication. This includes a description of administration procedure of data collection, data cleaning and description of the data set. The dataset is analysed and classified as per the predefined three pillars.

THE CASE STUDY-NEWCASTLE UPON TYNE

The case study is the inner urban core of Newcastle-Gateshead area, NE1, NE4 and NE8 postal districts of the Boroughs of Newcastle and Gateshead. Newcastle upon Tyne is one of the famous cities in the North East of England. This region is considered as one of the greenest regions that call for sustainable development and implement rigid plans towards resilience concepts. The study area, naming it "The ZONE" presents several express and arterial long roads, which vary in width, speed and capacity. The ZONE is a virtuous experimental area to be syntactically studied; a rich area of trip assignments and movements, which enables the researchers to study the flow of EV population, and the behavioural characteristic of system reflects on the usage patterns. Particularly, NE1 which covers the city centre of the metropolitan area, contains two universities, schools, shopping and recreational

areas, commercial buildings, train station, squares, parks, and partially, most of the busy residential wards of Newcastle area (NE1 2009).

Spatial Clustering of RFs

Spatiotemporal analysis of users' charging and driving patterns is presented and discussed. As per the latest update of CYC Ltd, there are 35 charging sites covering NE1, NE4 and NE8. This study is analysing the 23 active sites out of the 25. For each charging point, spatiotemporal analysis is carried out. The analysis incorporates design configuration values, demographic data, traffic count, and level of awareness data. All data is measured if it is continuous data or quantified in the case of categorical data. Some values are converted into dummy values for higher accuracy and validation purposes. The data forms thirteen factors. So the input includes 38 observations analysed among thirteen levels.

The clusters membership is formed based on the predictors. The predictors are basically the levels; however, each one affects the cluster differently. There are some influential ones and some other are not. Depends on the selected levels and the variety of continuous and categorical data, the predictors' affect, order and number change. The iterations take place until the back algorithm comes out with the optimal quality of the clusters. SPSS generates the outcome in a report where the quality is indicated and scaled in a scale bar showing how good and homogenous are the clusters. T reflects its level of cohesion and separation. Table 1, summarises the final list of factors considered for this study starting with the most influential predictor.

Table 1: Model Variables and ways of measurement

	Attributes	Explanation/ Measurement Technique
1	Public Awareness (P)	Is the measurement of to what extent are the potential users aware of the charging network. This is examined through a spatial questionnaire disseminated over 45 potential users. Response is collected and summed up.
2	On / Off Street (O)	This value is dummy. Zero for off street charging points, and value of 1 for on street charging point.
3	Integration (I)	Space Syntax measure, calculated by DepthMap.
4	Traffic Counts (T)	Actual travel demand provided by the Traffic Monitoring Unit in Newcastle (UTMC). The values are for the main corridors feeding the RFs sites
5	History (H)	In months, the total number of months the charging point has been installed and used. (CYC data)
6	Connectivity(C)	Space Syntax measure, calculated by DepthMap
7	No. of users (η)	The total number of EV drivers used the charging point over 2012 (CYC data)
8	Distance from centres (I)	Metric distance measuring the road length between the charging point and the nearest residential district core.
9	Transactions (τ)	The total number of transactions made by the users in 2012 in each charging point. (point not site)
10	Average time spent (A)	In minutes, the average time spent by drivers charging their cars using RF. (CYC data)
11	Most Frequent Time (M)	Discreet data, showing the most frequent time of the day the drivers tend to charge their cars using a specific charging point. (morning = 1, Afternoon =2 and Evening =3)
12	Total Energy Used (A)	In KW, the total energy spent charging cars by each RF in year 2012. (Dependent variable, Profit indicator)
13	Weekdays (ω)	Percentile, the weekday to weekend ratio converted into percentage. This value shows when the RF is being used over the week.

The model is based on analysing 420 users record spanning the year 2012 using the 38 charging points. The majority of these RFs is located in NE1, having 26 charging points in 6 KM sq. where there are 4 charging points in NE4, 14 KM sq., and 8 charging points in NE8, 16 KM sq., Fig. 2. In AutoCAD, every charging point was mapped using an urban grid; RF locator with the latitude and longitude values, Fig. 2.

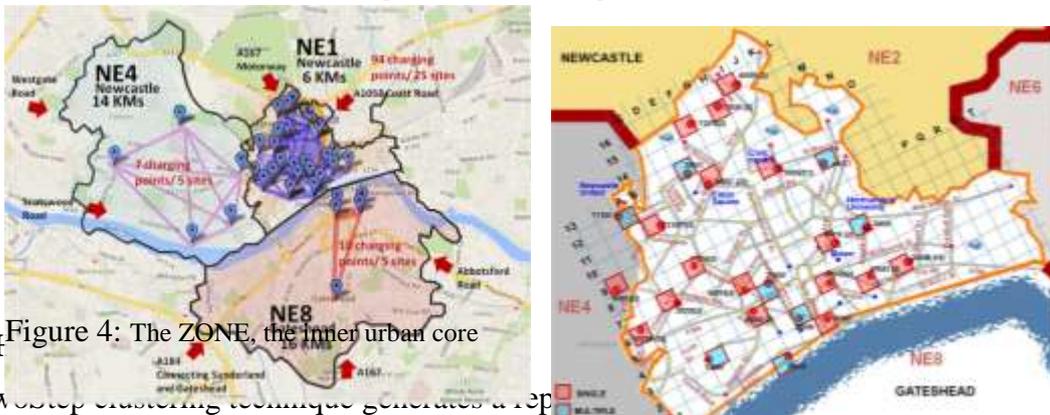


Figure 4: The ZONE, the inner urban core

Two-step clustering technique generates a report on the cluster quality, size, structure, and influential variables, Fig. 4. The clustering process took several iterations till we reach the chosen one. The decision is made based on the cluster quality, reasonable number of clusters, and ratio of clusters' sizes. The quality should not be poor, and the ratio should not exceed three. The model contains 4 clusters with a ratio of 1.5, which is very good. The number of inputs (categorical and continues selected variables) is thirteen. The overall distribution of cluster is quite decent and balanced as it is indicated in the cluster quality bar. There is not a dominant influential variable; public awareness, On Street and OFF Street, Integration, traffic Counts, and History are the main predictors. The quality could have been better with more number of cases and a variety of variables.

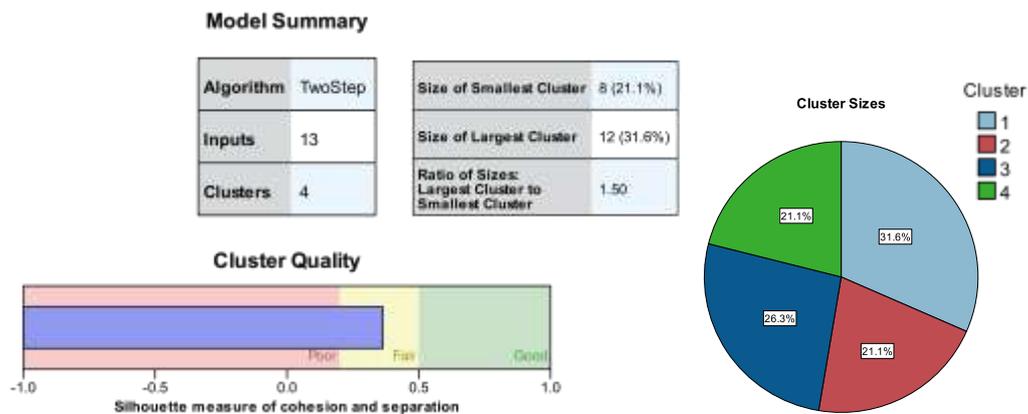


Figure 5: SPSS reports the clusters quality, separation and distribution

Each cluster has been formed based on the thirteen level of analysis; the model presents the cluster architecture. The values of the variables (high, intermediate, low) are presented here as (+, +, -), respectively.

CLUSTERS ARCHITECTURE

The four clusters are organised based on the size of the clusters. The first group is the “The Settled” charging points. This group forms the biggest cluster which contains nine sites with a total of the twelve charging points. It covers (20006, 20059, 30051, 40004, 40005, 40018, 40019, 30058, 30059, 20046, 30055, and 30060). This cluster contains a selection of ON street charging points which are well recognised by the public, (P+). Spatial design attributes of this cluster scores high (I++) and (C++). All RFs of this cluster were in operation for almost two years, 2011 and 2012.

The second group is the “The Misplaced” charging points. This group forms the second biggest cluster containing 6 ON Street sites with a total of 10 charging points: 40012, 40013, 40025, 40026, 30056, 30057, 10029, 40009, 40021, and 40011). This group of RFs has been in operation also for almost two years, (**I++**) and (**C+**). This cluster score the lowest (**-Λ**) with a limited number of users and number of transactions (**-η**) and (**-τ**).

The third group is the “The Well Known” charging points. It contains only two sites; however, the one of the sites has six charging points (20007, 20008, 10002-10007). These two sites are the most popular OFF Street sites (**P++**), highest number of users and transactions (**η+**) and (**τ++**). These RFs are usually occupied in the Afternoon, and for 1-2 hrs. as (**A+**). What really signify this cluster that although it is profitable and OFF street, the spatial design parameters score low values. This is justified as the sites are located one at the civic centre of the city, and the other is at the city centre shopping mall car park.

The fourth group is the “The Unexpected” charging points. This group has eight charging points located in six different sites (20049, 30050, 11077, 10026, 40010, 30007, 30008, 11067). This group is not recognised by public (**-P**), and the charging points are newly added to the network (**-H**); however, it is reasonably used, people tend to charge long chargers (**A++**) especially in Mornings. Also this cluster is used over the weekends (20%) which is relatively a high percentage compared to other clusters.

DISCUSSION

Four different clusters of RFs have been generated as the outcome of the TwoStep spatial built-in clustering algorithm. Each cluster has main features that identify and configure common RFs usability attributes, recharging static design characteristics and spatial configuration values. This analysis was conducted before by the author; however, the focus of the study was different. The present study focuses on the On Street RFs. By analysing each cluster, the clusters with (**Λ++**), are the profitable ones. Among the four clusters, only the first and the second ones are ON Street. Despite the fact that the OFF Street RFs are recognised as a source of charging in the study, these sites have other factors that affect the usability. Destination oriented or road trips type would influence the charging decision. In other word, the user might plug in the car to charge in the parking area of a shopping mall/ wok place not because it is running on empty, but being at the place itself so why not to make use of the wait.

The first cluster, The Settled, Fig. 4, is perfectly designed to accommodate charging services especially for fast charging option. The spatiotemporal analysis showed positive correlation between the usability of the RF and other Independent Variables (IV) in the model. The sites of this cluster are highly recognised by the public and the current user. The profit is generated due to the high number of users which means users tend to use the charging points more often but for shorter time of charge (time of the charging event). This sheds light on a crucial matter; many charging events with less time spent might generate more profit than fewer charging events with longer time spent, which makes more sense. People tend to rely on domestic charging due to the unwillingness to spend time charging in public points especially the ON Street. However, it is convenient and manageable to stop for a shorter period of time to charge during their daily road trips.

In the contrarily, the second cluster, The Misplaced, Fig. 5, has significant features. It has poor parametric design that results having an under-used RF. The 6 sites of this cluster are not recognised by the public. The latter is positively correlated with the integration values of the sites. The sites are relatively distant from urban cores (**I+**) which negatively affect (**η-**) and (**τ-**) and directly proportional with (**T-**). Two main observations can be stated; this cluster is not accessible and has poor marketing. Marketing plays a major role in EV market, which is clearly reflected in this cluster.

We can observe that the spatial design attributes are not the only factor that we should consider while planning for RFs; behavioural attributes should be incorporated with the analysis alongside the demographic and travel demand. Designing RFs is a complex design process that needs integration and sociotechnical and behavioural considerations. These considerations should be based on real users' feedback and experience, which justifies the importance of this research.

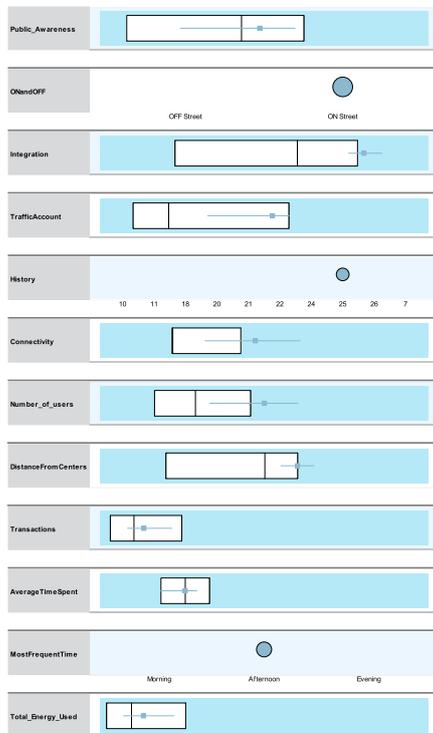


Figure 4: The Settled



Figure 5: The Misplaced

CONCLUSION

The re-charging experience should not be a worrying matter for EV drivers. The use of e-mobility is associated with a range-anxiety-syndrome, presenting hurdles for many potential users to electrify their vehicle use. Even for current users, so far, the EV is still replacing the secondary car in multi-car owning households due to range limitation. This study aims at interpreting the users' data in a meaningful way regarding the data observations, and providing guidelines and recommendations with regard to the design and siting of re-charging facilities based on this. This should be of interest to researchers, planning authorities, policy makers and commercial service providers. From planning perspective, the planners and policy makers would need to have a clear indicative description of the recharging facilities design characteristic and configuration that provides design key elements as well as guidelines for what to expect to get in terms of business need. Among the four clusters, the first one, "The Settled", Fig. 4, is the chosen one to be replicated when designing and planning for RFs while the second one "The misplaced", Fig. 5, needs to be deactivated from current systems and to avoid in new networks. Under the process of assisting in the planning of future EV system, the study's outcomes and recommendations are to maximise the EV system with a nature of "The Settled" cluster. This cluster setup meets the business need of the EV system as it hits the highest number of transactions made by enormous number of users in an ON Street charging points. It is an accessible ON Street facility with a significant value of integration, connectivity and high number of users which reflects suitability.

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APPENDIX

ARCOM Doctoral Workshop Programme

Name	Affiliation	Topic	Time
Dr Alex Opoku	London South Bank University (LSBU)	Registration /Tea	09:15
Martin Lake	Head of Department, Built Environment-LSBU	Welcome Address	10:00
Keynote Speaker:			
Prof. Andy Ford	Director of the Centre for Efficient and Renewable Energy in Buildings-LSBU	Creating our future Built Environment	10:15
Presentation Session 1			
Syeda Zainab Dangana	University Plymouth	Decision support framework (DSF) for the selection of Innovative Sustainable Technologies (IST) for existing retail buildings	10:30
Niloufar Bayat	University of Salford	Exploring Performance Gap in Low-Carbon Housing Retrofitting in England: The Leading Architects' Perspective	10:45
Rosita Aiesha	University of Greenwich	Understanding the drivers, barriers and motivations for energy efficiency housing retrofit	11:00
Nathan Kibwami	University of Leeds	Developing a carbon measurement tool to promote sustainable construction	11:15
Discussions Session: Chaired by Zaid Alwan-Northumbria University Co-chair- Dr Noel Painting- University of Brighton			11:30
Industry Guest Speaker 1			
Kate Terriere	Deloitte Real Estate- Assistant Director Sustainability	Measuring Urban Sustainability – City indices and sustainable development	12:05
Questions and Answers session: Moderation by Dr Alex Opoku			12:20
LUNCH BREAK & NETWORKING			12:35
Introduction to ARCOM: Dr Chika Udejaja-Northumbria University			13:35
Industry Guest Speaker 2			
Robin Brylewski	Sweett Group-Consultant	Passivhaus and Sustainable Built Environment	13:50
Questions and Answers session: : Moderation by Dr Alex Opoku			14:05
Presentation Session 2			
Francesco Pomponi	University of Brighton	A method to evaluate the life cycle environmental performances of double skin façades for office refurbishments in the UK	14:20
Matthew Ozoemena	Northumbria University	A hybrid data quality indicator and statistical method for improving uncertainty analysis in LCA of complex system – application to GHG emission analysis of a small off-grid wind turbine	14:35
Dort Spierings	Radboud University, Institute of Management Research, Netherlands	Scale to fit: Physical scale and social quality of housing in sheltered independent living	14:50
Eima ElBanhawy	Northumbria University	Spatiotemporal analysis of E-Mobility recharging facilities	15:05
Discussion Session: Chaired by Dr Victor Samwinga- Northumbria University Co-chair-Dr Mahtab Farshchi, London South Bank University			15:20
CLOSING REMARKS – Dr Alex Opoku			15:55