VISUALISING URBAN ENERGY USE: The potential value of remote sensing & LiDAR data in urban design and energy planning

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ABSTRACT: *LiDAR (light detection and ranging) is an optical remote-sensing technique that uses laser light to densely sample surfaces, producing highly accurate measurements. It is primarily used in airborne laser mapping applications. However it offers a huge potential for improving the data input available for modelling urban energy systems and visualising urban carbon emissions. This paper explores this potential and highlights some of the limitations of the information that can be obtained from LiDAR data and how these limitations can be ameliorated. To do so it presents an example of the use of LiDAR data and aerial imagery to provide input data for building geometry and building physics models to develop an energy model of a mixed-use inner urban area in the North East of England.*

The work presented highlights the significance of data accuracy for the assessment of heat-loss parameters, orientation, shading and renewable energy micro-generation; and the limitations of remotely sensed data and how these can be ameliorated using a combination of open-source property data, such as building age, occupancy, tenure and existing stakeholder data sets, including building services and measured energy performance.

The paper concludes that there are significant benefits in the use of LiDAR data for improved accuracy in, and visualization of, urban energy use and carbon emission calculations. However it also highlights that further work is required to reduce the data manipulation required if the potential of Lidar data is to be fully exploited to inform urban energy modeling.

KEYWORDS: *Remote sensing, LiDAR, energy modeling, urban planning.*

1. INTRODUCTION

There is a challenge of managing urban change within the paradigm of the ‘information city’ (Kraemer & King 1988). Municipalities and their partners require a supporting information infrastructure that helps a broad range of urban stakeholders to both understand and reinforce geophysical communities within urban neighbourhoods and localities (Doheny-Farina 1996). The city map and urban model remain the most intuitive ways of structuring and accessing this urban information.

“The ability to routinely access the infinity of global archives of own and other experience provides a tool for exploring own identity and for better understanding … through virtual technologies … technology can be used to reconstitute as well as to fragment” (p10 Little et al 2000).

In this changing environment, issues of sustainability and energy efficiency are among the most significant challenges of urban planning with regard to accessing, mapping and visualising digital data. Typically energy use in buildings is around half of all energy consumed and it clearly has a strong spatial component that relates to individual buildings, neighbourhoods, districts and ultimately municipalities. It is within this context that the value of remotely sensed data and its role as part of the city’s strategic information infrastructure has been examined in the research presented.

Appropriate and accurate data is crucial to understanding the viability of both substantive urban systems and the decision-making procedural systems that manage the urban system (Grossmann & Watt 1992). In effect there are complementary requirements from both technical and non-expert urban stakeholders in the use of urban energy information, its collection, analysis, sharing and visualisation. Here there is real potential for LiDAR data; collected remotely at the neighbourhood or city scale; to simultaneous contribute to both the technical and political decision-making requirements for better data.

Initially LiDAR is ideal for information directly relating to building geometry. This geometry or 'property-based' data can be the basis for integration with data related to the wider and 'softer' aspects of urban planning and sustainability.

Early European Commission funded work found that "... remote sensing (is) technically suited to the collection of information needed for certain types of area planning ... that require systematic collection of certain statistical information" (p31 Cardoso 1996). In this context, it should clearly include energy and emissions planning. Yet, to date, there has been little practical use made of remotely sensed data at the scale of individual buildings and their levels of energy efficiency and carbon emissions.

There have been a few research-specific applications of remotely sensed data addressing the challenge of understanding the energy performance characteristics of a large building stock, using city-wide data sets and simplified calculation processes. For example, a recent demonstration project based in Milan involved the development of a GIS based city buildings database (Caputo et al 2013) and a Toronto case study used LiDAR data sets as input data for building energy calculation (Tooke et al 2014). In addition, there have been specific use of LiDAR to understand the potential for the application of large scale solar PV panels (For example see Borfecchia et al 2014, Jacques et al 2014) using assumptions around roof space of different property typologies. However, many of these current approaches are concerned with assumed input data from a LiDAR survey for existing commercial energy calculation software, albeit data that is based upon limited number of sampled properties and the use of building archetypes. In most cases of modelling the energy performance of the existing building stock, there is an emphasis on a simplified calculation process using the best data available given the costs of collection and calculation - what can be described as the 'Best Available Data Not Entailing Excessive Costs'. While these methods are generally pragmatic and appropriate to the level of decision-making relating to local policy making and / or capital investment into building improvements, the results are an estimate, where the accuracy of the estimate is largely dependent upon the quality of the data used. Underlying each method and application is the quality of the input survey data used in the calculation process.

This paper suggests that the real benefit in pursuing a simplified calculation process using semi-automated data sets, such as LiDAR scanning, is the ability to make better strategic decisions on the existing building stock. For example, in this project researchers assumed the adaptation of a standardised data collection process (RdSAP) that has certain requirements for necessary input data. In such a simplified method of energy calculation, the data quality and accuracy has to be fit for purpose, rather than over specified. Practical pragmatism has to balance the complexity of the model against the quality and availability of the urban data sets.

Recently this has been recognised in project work looking at the development of a theoretical framework for energy modelling at the urban scale (Keirstead et al 2012) that could be supported by appropriate big data sets and cloud computing. This research suggested the potential development of new models or the successful integration of one or more existing models (mix of geometry, building uses / activities, transportation etc.) and the potential of LiDAR data extraction for specific building elements such as facades details (Kan and Sun 2014) in addition to building geometry. Yet recent research also contains a common acknowledgement of the intrinsic difficulties of acquiring good quality data, and of integration different models at the right resolution (Kedzierski and Fryskowska 2014) to make this practicable.

This limited use of remotely sensed data to fill such a gap in requirements for good quality data is despite the importance of the collective level of carbon emissions from the domestic property sector, where estimates are often at best a mix of modelled usage. This modelled use of energy efficiency has a common acceptance of the use of the property assessed independently from the variations of occupancy (Boardman et al 2005) and grounded in the basic attributes and parameters of the building. Hence it is possible to generate an estimation of an individual property energy use based on the attributes of the building (age / method of construction, geometry and services) and 'standardised' behaviour of the typical occupants. It is these property attributes that are well suited to the integration of LiDAR data on geometry with other open-source and publicly available data sets that record the building performance characteristics. For example, the use of open source database on the age of construction of the property, the use of stakeholders' own asset management database, systems upgrades to social housing as part of decent homes programme.

As part of an EU 7th Framework funded research project, the potential of a variety of publicly accessible and open-source data sets were explored through a series of European case studies. These case studies identified data that can be edited, integrated and visualised to support energy efficiency within urban design and planning. The focus of one of these case studies was on identifying the refurbishment options for an inner-city residential area in Newcastle upon Tyne in the UK. The study area contains different housing typologies, including single family properties and multi-story and multi-occupancy properties. A lack of accessible and affordable property data available for the area led to the commissioning a LiDAR survey, primarily to provide accurate building heights.

The remainder of the paper explores the collection, editing and use of this LiDAR data, its potential application and the practical limitations. This is presented as a series of discussions that follow the sequential steps needed from specification of the survey through to data integration tasks within an urban energy model. It concludes with a discussion around the potential value that LiDAR data can provide and some of the key issues that need to be resolved in order to fulfil this potential.

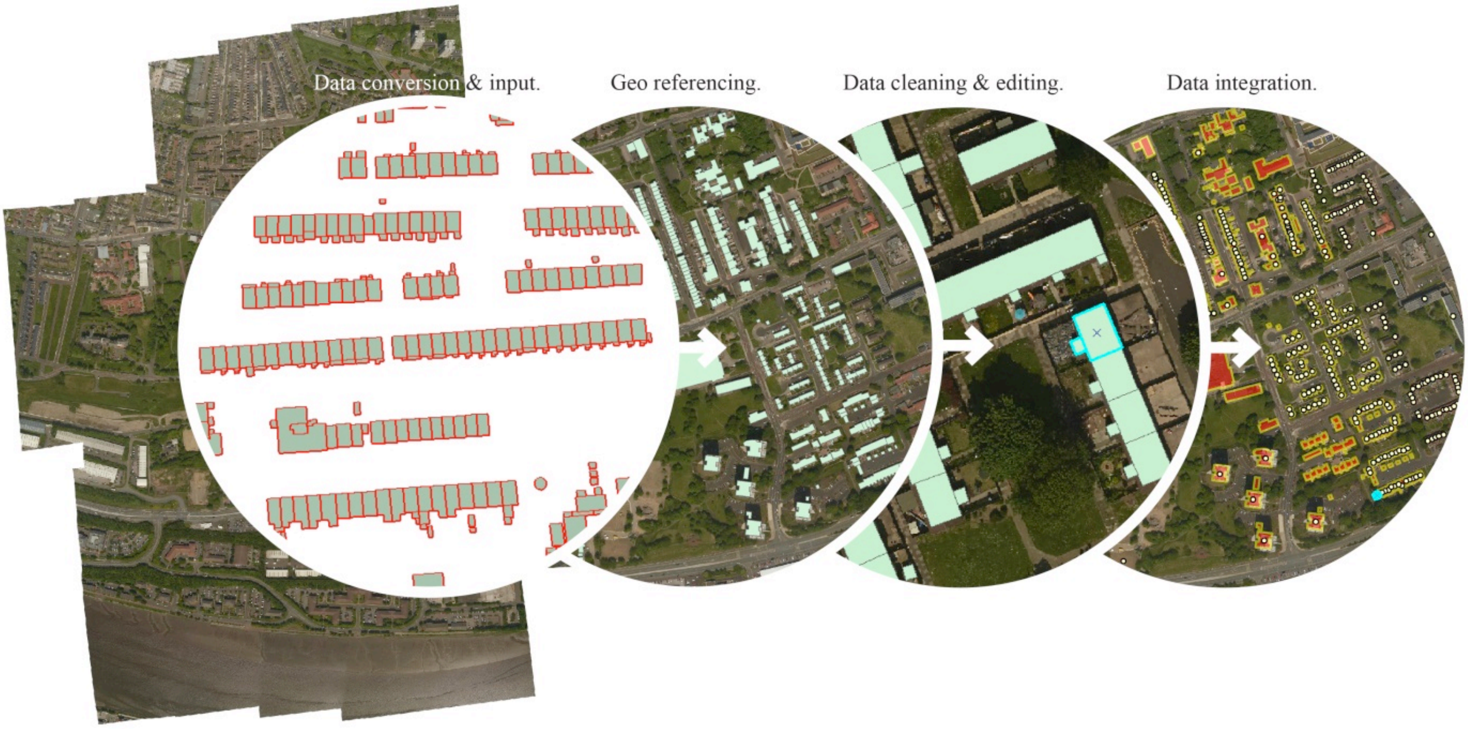


Fig 1: Key steps in data handling.

1.1 Building geometry data and user-defined mapping

LiDAR data was required to provide accurate measurements of building geometry to inform the estimation and modelling of urban energy systems. The commissioned LiDAR data also had the advantage that it includes the copyright required to allow its integration with other data sets as part of an online energy modelling and decision-support tool (Madrazo et al 2013). The rights to share this data and demonstrate the potential functionality when combined with other data sets was also a key advantage. This allowed an open-ended approach to the use and adaptation of the data set without time-limitations or legal restrictions on its use.

DATA SPECIFICATION & COLLECTION

A commercial provider (BlueSky) conducted the LiDAR Survey and supplied the LiDAR Data. In retrospect, much was learnt regarding the specification of the data collection processes. Most significantly there is the lack of any standard specification for the format, resolution and cleaning of the data. It became clear in the case study that the end-use or application of the data should have informed the format of data from LiDAR survey in the tender from the outset.

1.2 Data conversion & input

The data was provided in CityGML and Collada formats that are readable within many different standard software packages. Over a square kilometre of the inner city was surveyed with two separate scans that provided a terrain model and ‘partially’ auto-rectified structures.

Typically LiDAR has over specification of details in certain areas and significant gaps regarding surface materials and varied dimensions of solid / opaque surfaces. There are some recent demonstrations of the application around the detail available and transferring or ‘tracing’ (Kimpton et al 2010) CAD polylines over a polygon surface model / point cloud data. This is effectively a manual task to reduce the level of detail within the model. It turned a set of point cloud data into closed polygons – polygons with properties suitable for adding attributes and for visualisation. A similar approach was required at the neighbourhood scale to make the data usable for the purposes of estimating the energy use of individual properties.

Disconnected polygons for single properties arising from irregularities in the scanning. Distortions and separations reflecting the angle of scanning.

Additional extraneous vector lines arising from edges of external plant on the roof of multiple occupancy properties.

Inconsistencies in the recording of porches, extensions and attached outbuildings.

Unnecessary vector points recorded along the boundary even following the merging of multiple polygons.

Additional extraneous vector points along property roof ridge-line causing distortion along property polygon edges.

Discrepancies in boundaries become evident with rear property additions showing the edge of the party wall between contiguous properties. This is different from the change in height at roof level effectively showing the other edge of the party wall.

Irregular gaps between contiguous structures requiring new vectors to simplify and join the adjacent polygons.

Fig 2: Highlighting the initial LiDAR data errors.

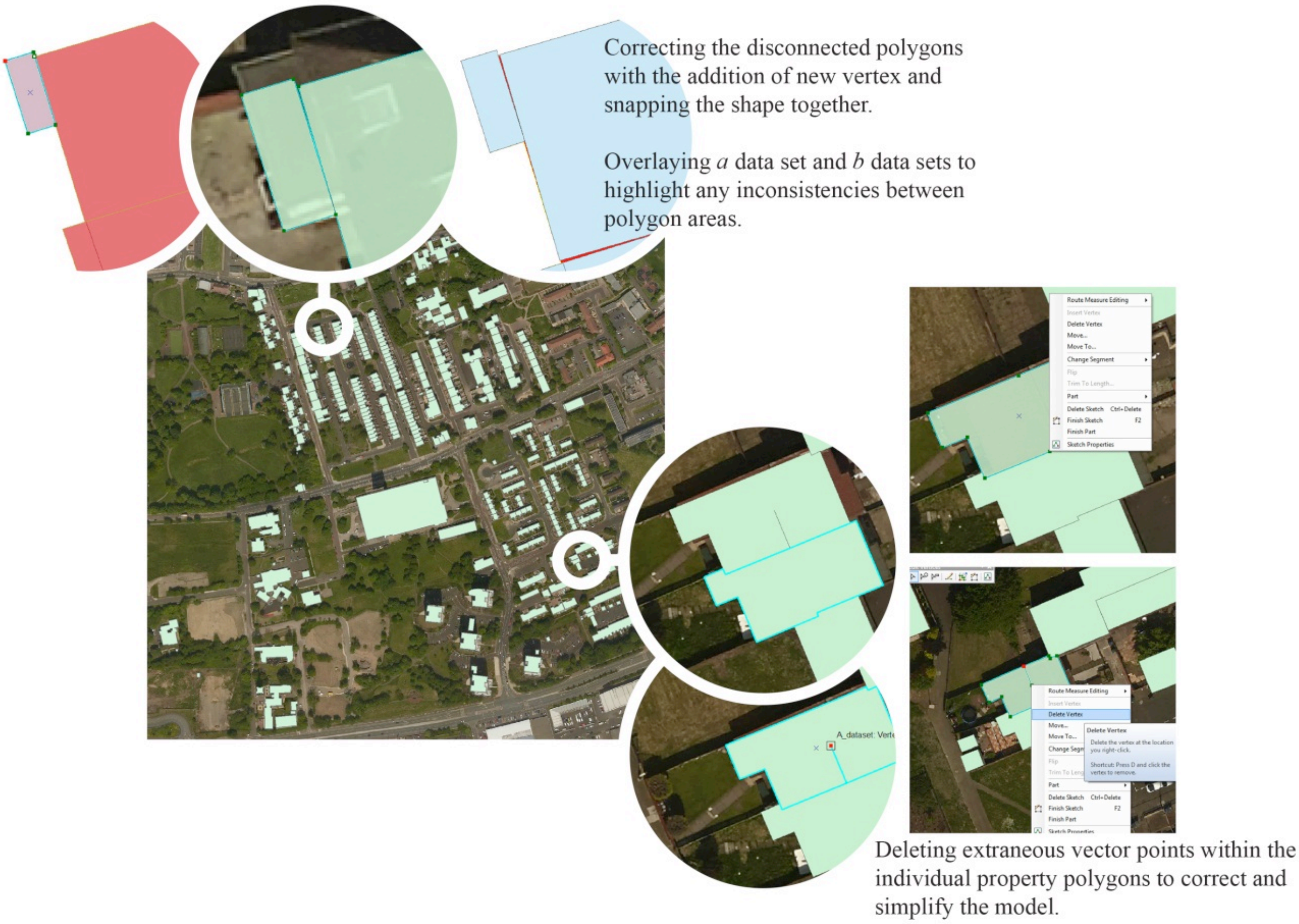
Ultimately the data had two significant geometry values that needed to be maintained as input measurements into a reduced data standard assessment procedure (RdSAP) or estimated SAP calculation process as the normal UK energy model. This input geometry is (a) the shape of the property; measured as the gross external footprint of the individual dwelling unit; and (b) the height of the property. Together these two input parameters allow an accurate calculation of heat-loss parameters around the extent of internal heated living space relative to the exposed surface areas as made up from the ground floor, external walls and roof. While there are limited opportunities for changing the shape (simplifying) and size (reducing) of homes to affect the heat loss parameters (Friedman 2005), building fabric interventions (typically internal or external insulation) can improve the thermal efficiency of specific building elements to reduce the heat loss. In most cases, improvement work to the building fabric will also be dependent upon the same geometry in terms of cost of treatment per square metre. Further interventions relate to possible upgrades to building services or the provision and connection to renewable and / or decentralised energy systems. These can also be attached as attributes to the property-based data. Consistent with similar scoping and qualitative assessments of stakeholder requirements (National Refurbishment Centre 2012) and those responsible for property management and maintenance, there is a practical focus on cost-effective and technically trusted approaches to refurbishment that requires good evidence based on accurate data.

To obtain accurate building geometry data it was necessary to identify any significant errors inherent in the original format of the commercially provided data and undertake some data editing.

1.3 Errors within data collection

There were several kinds of errors arising from the initial data collection (fig. 2) that had to be addressed in advance of having useful data sets for energy modelling. These are almost exclusively issues of ‘bad geometry’ arising from a combination of the angle of scanning of the terrain and properties together with the level of ‘noise’ within the LiDAR data. The ‘noise’ included errors from building overhangs, shadows, trees / vegetation and became more pronounced in areas where there were more complex geometries and structures.

The best strategy for dealing with the mix of geometry errors was to create two separate data sets that held discrete input data. The first dealt with building footprints and the second with building heights.



Delete the vertex at the location you right-click.

Shortcut: Press D and click the vertex to remove.

Correcting the disconnected polygons with the addition of new vertex and snapping the shape together.

Overlaying *a* data set and *b* data sets to highlight any inconsistencies between polygon areas.

Deleting extraneous vector points within the individual property polygons to correct and simplify the model.

Fig 3: Examples of correction of data errors.

1.4 Data cleaning and editing

In advance of this, the basic errors in the data had to be cleaned up as the first step in data handling. Editing was undertaken using the edit functions within ESRI’s ArcGIS (fig. 3).

Overlapping polygons in the commercial data set were clear errors as they represented two properties occupying the same building footprint. These were merged and then split along an estimated property boundary. Disconnected polygons or ‘gaps’ in between terrace properties were similarly impossible structures. These had their vertices snapped to match.

There were several instances of vertices existing within polygons that seemingly picked up variations in roof structures, chimneys / ventilation or in some instances of larger multi-occupancy properties and non-residential units mechanical and engineering services plant on the roof. These were merged into single polygons with all extraneous vertices deleted. The result was (a) data set that held accurate footprint data.

1.5 Identifying individual properties

The next step was to separate the contiguous polygons / structures into individual properties. It was helpful that the LiDAR data was effective in picking up changes in external building heights. In an area of exaggerated topography in the west end of Newcastle where contiguous properties / terraced housing step up and down the slope, this suggests division between properties. However in looking in detail, it failed to make a distinction between property boundaries because this boundary is in reality the thickness of a party wall between the individual properties. The change in roof heights coincided with the end (or in some instances the roof overlap) of the party wall and not the middle of the party wall. This becomes more evident when rear extensions have to be attributed to a particular property polygon. This could only be corrected manually using 'best-guess' information (Fig. 4) based on equidistant polygons to create properties of equal sizes as a typical property typology or using external clues to property boundaries.

The use of external boundaries as the basis for the 'splitting' and subdivision of source data into individual property polygons.

Complex constructions and groups were simplified into single polygons to be attributed with a unique property identity.

Combination of external property boundaries and equidistant vector points were used in the creation of individual property polygons.

Assumptions made in the 'splitting' and subdivision of polygons into individual property polygons included the use of midpoints to create new vectors points.

Fig 4: Data editing to create individual property polygons.

There had to be an acceptance that additional errors were introduced at each of these discrete stages in data cleaning and editing. Maintaining two separate data sets holding the footprint and height details separately was the best strategy to reduce the number of stages in data handling and thus reduce the potential to introduce any new errors from data handling.

2. INTEGRATION WITH OTHER DATA SETS

Thinking around the value of city models is rapidly changing in response to the power of computing but more significantly, the quantum of big data that now exists digitally.

Planning practitioners are entering into a world where everything is data. Planning has to deal with the scope of different sources of supporting evidence each using a variety of methodologies. There has to be an understanding of limits, unpredictability and allied to this are the procedural issues around irrationality, objectivity and political / cultural perceptions and definitions of qualitative aspects of behaviour, knowledge, attitudes and perceptions. Maps are clearly a useful way to explore data. But ultimately they are didactic tools. They are abstractions of reality and designed primarily for exploration and understanding at strategic scales and early stages of decision making. They will contain errors and have to be treated as tools for understanding rather than predicting energy usage.

Planning practitioners are currently experiencing the development of the ‘map’ or ‘model’ from physical to digital, a paradigm shift in urban design and planning “… that hold(s) the potential for allowing the designer to move directly from concept to full scale construction” (p8 Porter & Neale 2000). In order to achieve this, there has to be the development of new methodologies to support the analysis and integration of large data sets (Aiden & Jean-Baptiste 2013). Real ‘big data’ can be considered a replacement for intuition or guesswork where there are strategies in place for harvesting and mining every possible source (Baumgartner et al 2012).

2.1 Stakeholder data and user-defined mapping

Big data tends to be messy data. One of the key support tasks is to organise, structure and make sense of this big mess. This is generally done using one or more of the industry standard software packages, ArcGIS, AutoCAD / Revit, Sketchup and to a lesser degree, GoogleEarth. There is also open-source mapping software and data, for example in the ESRI sponsored crowd-sourced mapping (Medeiros 2013). Building energy data is just another element of this big data. Building energy use and carbon emissions have to be understood in the wider policy context and the complexity of the real world. We have to provide the ability for users to export, import and connect with their own datasets to build on the functionality of the basic building geometry.

The significance of remotely sensed data is that it provides accurate building geometry. This geometry has value as input data for the calculation of the energy efficiency of buildings. When shared online it also has a range of additional functionality where other data can be linked to the individual property address or when there is a requirement for accurate measurement. For example, in the calculation of property refurbishment and renovation costs where building geometry is linked to a cost database or cost estimations.

Seperate data sets for property (a) footprints and (b) heights next to Google eart screen shot of the same area and using the same BlueSky data.

Example screen shots of the case study area from Google Earth, showing the variety of property typologies. Visualisation but without functionality to export and manipulate the geometry data.

Fig 5: Data compared to Google Earth.

The availability of open-source three-dimensional data is both limited and controlled. The impressive representation of the same case study area of Newcastle in Google Earth effectively uses the same data from the same commercial supplier (fig. 5). Yet the functionality of this is limited to basic visualisation and the virtual exploration of the urban environment. Any export functions are limited to two dimension aerial imagery, creating a level of frustration in the level of accuracy available through open-source data compared to the knowledge of the existence of accurate geometry. Yet this data is still currently just a collection of shapes without property specific tagging. Beyond the visualisation of the data are extractable geometry models that can be used for a variety of purposes, including acting as input data for more detailed urban design and architectural modelling.

Although it is a significant way short of BIM standards, this is potentially the next step in the use of open source LiDAR information. Format and specifications in line with emerging standard BIM protocols, such as Cobie, and which can be useful at the earliest stages of a design or construction plan of works. At present ISO 1006-2 sets the specification standards for ICT in construction projects and includes a detailed ontology for construction and building elements. This standard also sets out the design responsibilities between different professional stakeholders and the minimum requirements for technical / digital information change between the professionals. The standard has overlaps with Cobie standards for data exchange which sets out the specification of element properties in the form of an industry standard data language with specification properties.

As an increasing range of software packages use Cobie standards for data input and integration, the challenge is to allow the use of remotely sensed LiDAR data on building geometry to be useful and time-saving as input data into these design software packages. Here the best versions are mostly automated from Revit or similar Solibri compliance checking software. When remotely sensed data can be used with confidence at an early project stage and form part of the initial information exchange it will have significant new functionality. It has to be remembered that while most design packages and protocols are intended for new construction, around 80% of all construction projects still include existing structures for renovation, refurbishment, adaptation or conversion (Itard & Meijer 2009). An accurate representation of existing structures with a usable database containing the attributes and parameters of these structures will be a hugely valuable addition to the initial business planning stages of many urban planning and regeneration projects.

3. THE IMPORTANCE OF VISUALISING ENERGY DATA

“To an architect, a plan is a drawing; to a planner it is a written document. From such small but vital distinctions, the two professional have grown apart dramatically … however, incursions by architects into the field of planning … are returning to its roots in physical design” (p19 Walters 2007).

Lessons from practitioner reflection (Schön 1982) suggest that learnt experience is actually limited by the view of the role and function the planner has of themselves – in effect of ‘title (or job description) dictating behaviour’. Stakeholders acknowledged that too much evaluation of successful urbanism is based on quantitative measurements, and often aggregated measures that fail to understand aspects of scale on design quality. Yet they also accepted the need for ‘smart measurement’ to increase the understanding of the site or project in the appropriate context. Urban planning and regeneration is complex. It brings together a broad range of stakeholders, as a mix of technical professionals and many different non-expert stakeholders that have their own personal and organisational experiences. Urban planning and management has become a two-way educational mutual learning process (Wals 1996) that have connections between many consultation / participation exercises.

These urban planning processes require the development of an evidence base and information provision that is interoperable, exchangeable, accessible and understandable to the broad scope of project stakeholders. Indeed, Castells (2000) suggested that that the appropriate sharing of urban data assists with the reform and legitimisation of local democracy and governance. Data, including energy data, with all of its errors is best shared in a manner that is accessible to multiple stakeholders. It should be understandable to non-technical users, but also extractable and editable for technical users. It is in this planning context that the research project is currently testing the functionality of the edited LiDAR data sets through an on-line platform that allows the full range of stakeholders to use the data (Fig. 6).

174

Surface	144 m²
Height	6 m
Number of floors	2
Volume	864 m³
Use	HOUSE
Year of construction	1916
Indicators	
SAP rate	66.6966
CO2 emissions	5,336.17 tCO2
Energy consumption	25,774.9 kWh

Indicator: SAP rate

● Year
○ m²/year

🟩	92 / 100 (A)
🟩	81 / 92 (B)
🟩	69 / 81 (C)
🟨	55 / 69 (D)
🟧	39 / 55 (E)
🟧	21 / 39 (F)
🟥	1 / 21 (G)

1 buildings selected

Fig 6: Screen shots of the online Semanco platform. Selection of properties within a suitable range for the SAP (estimated property energy efficiency) and the potential improvements following changes to the building fabric.

This is still work in progress and subject to continual review regarding the visualisation of the date, the design of the interface and usability of a number of decision support tools. The intention is that this interface is designed to aid intuitive understanding. There are well-established examples of graphic representation of mapping (Tufte 1983) and visualisation being the manner in which complex data is accessible. As the on-line platform is explained and demonstrated to stakeholders outside of the initial case studies, the importance of the visual three-dimensional interface as a common language (Madrazo et al 2013, 2014) for a range of stakeholders becomes more apparent.

4. CONCLUSION

The research shows that there are clear potential significant benefits in the use of LiDAR data for improving the accuracy of input data into urban energy models. However, this potential benefit is matched by a clear need for more accurate data relating to existing building geometry within even the most simplified building energy models. Accurate geo-referenced building footprints, heights, roof areas and orientation are a critical starting point for integration with other performance attributes of the building relating to the fabric, systems and occupancy. When these input measurements improve, the standardised energy estimations also improve.

Yet at present the regular application of LiDAR or remotely sensed data for district or city-scale energy modelling is limited. It is likely to remain so until the mixed issues of data quality and translational errors can be resolved. As discussed, these errors are a combination of data collection / data editing errors that have tended to become exacerbated with issues of interoperability between software packages, platforms and human errors.

Yet a better understanding of the end-use application of the data that is typically beyond the visualisation of the physical building form would help in addressing some of these limitations. At the collection stage, the survey specification has to be informed by the end-use of the data as it relates to the level of resolution in the scanning reflecting the urban or building scale being modelled. At the editing and processing stages there are aspects of simplification that would go a long way to improve the accuracy and associated functionality of the data. Processing can be improved by informed assumptions about the geometry of real-world buildings and structures, for example in understanding the nature of contiguous properties and correcting unrealistic gaps between buildings and impossible overlaps of different structures. If these assumptions can be automated as part of the initial data conversion and auto-rectification stages it would allow for large scale use of LiDAR without significant additional time or cost and hence make the use of the data attractive for energy modelling.

It could be argued that many of the simplified building energy calculation processes used throughout the European Union are defined around the availability and cost of acquiring meaningful input data. As the availability of more accurate data on the geometry of existing buildings increases, it is likely that it can be matched with better input data for building characteristics. This in turn will help to make better energy calculations and predictions, guide better investment decisions through better visualisation of the energy efficiency at a variety of different scales of operation.

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6. REFERENCES

Aiden, Erez and Michel, Jean-Baptiste (2013) *Uncharted: Big Data as a Lens on Human Culture* (Riverhead, New York).

Baumgartner, T. Hatami, H. and Vander Ark, Jon. (2012) “Find Big Growth in Big Data” pp31-48 in; *Sales Growth: Five Proven Strategies from the World’s Sales Leaders* (John Wiley & Sons, New Jersey).

Boardman, B. Darby, S. Killip, G. Hinnells, M. Jardine, C. Palmer J. and Sinden, G. (2005) *40% House* (Environmental Change Institute, Oxford).

Borfecchia, F., Caiaffa, E., Pollino, M., De Cecco, L., Martini, S., La Porta, L. Marucci, A. (2014) “Remote Sensing and GIS in planning photovoltaic potential of urban areas”. *European Journal of Remote Sensing* **47** 195-216.

Caputo, P., Costa, G., Ferrari, S. (2013) “A supporting method for defining energy strategies in the building sector at urban scale”. *Energy Policy* **55** 261-270.

Cardoso, Fausto (1996) “Mapping urban areas by remote sensing”. *Sigma* Summer pp31-33.

Castells, Manuel (2000) ‘Urban sustainability in the information age’. *City* 4(1) pp 118-122.

Doheny-Farina, Stephen (1996) *The Wired Neighbourhood* (Yale University Press, Newhaven).

Friedman, Avi (2005) “Ideas for the Home Front” pp307-322 in; Heintzman, Andrew and Solomon, Evan (Eds.) *Fueling the Future* (Anansi Press, Toronto).

Grossmann, Wolf Dieter and Watt, Kenneth EF (1992) ‘Viability and sustainability of civilisations, corporations, institutions and ecological systems’. *Systems Research* 9(1) pp 3-41.

Itard, L and Meijer [2009] *Towards a Sustainable Northern European Housing Stock: Figures, Facts and Future* (Sustainable Urban Areas) [IOS Press, Amsterdam].

Jacques, D.A., Gooding, J. Giesekam, J.J., Tomlin, A.S., Crook, R. (2014) “Methodology for the assessment of PV capacity over a city region using low-resolution LiDAR data ad application to the City of Leeds (UK)”. Applied Energy **124** 28-34.

Kan, X., Sun, J. (2014) "Application of LiDAR and oblique photogrammetric technology in digital real city model". *Journal of Geomatics* **39**(3) 43-46.

Kedzierski, M., Fryskowska, A. (2014) "Terrestrial and aerial laser scanning data integration using wavelet analysis for the purpose of 3D building modelling". *Sensors* **14**(7) 12070-12092.

Keirstead, J., Jennings, M., Sivakumar, A. (2012) "A review of urban energy system models: Approaches, challenges and opportunities". *Renewable and Sustainable Energy Reviews* 16 3847-3866.

Kimpton, Graham, Horne, Margaret and Heslop, D. (2010) *Terrestrial laser scanning and 3D imaging: Heritage case study – The Black Gate, Newcastle Upon Tyne*. In: ISPRS Commission V Technical Symposium: Close range image measurement techniques, 22 June - 24 June 2010, Newcastle upon-Tyne.

Kraemer KL and King JL (1988) 'The role of information technology in managing cities'. *Local Government Studies* 14(2) pp 23-47.

Little, Stephen., Holmes, Len and Grieco, Margaret (2000) 'Calling up culture: information spaces and information flows as the virtual dynamics of inclusion and exclusion'. Paper presented at IFIP WG9.4 Conference *Information Flows, Local Improvisations and Work Practices* Cape Town, May.

Madrazo, L., Gamboa, G., Nemirovskij, G., Sicilia, A., Crosbie, T. (2014). *SEMANCO Deliverable 8.4 Implementation effectiveness*.

Madrazo, L.; Sicilia, A and Nemirovski, G (2013) "Shared Vocabularies to Support the Creation of Energy Urban Systems Models". ICT for Sustainable Places International Conference, Nice 9th-11th September.

Medeiros, João (2013) 'Maps made by millions' *Wired* August pp48-49.

National Refurbishment Centre (2012) *Refurbishing the Nation: Gathering the Evidence*. (Watford, National Refurbishment Centre).

Porter, John and Neale, John (2000) *Architectural Supermodels: Physical Design Simulation* (Architectural Press, Oxford).

Schön, Donald A (1982) "Some of what a planner knows: A case study of knowing-in-practice". *APA Journal*, Summer pp351-364.

Tooke, T.R., van der Laan, M., Coops, N.C. (2014) "Mapping demand for residential building thermal energy services using airborne LiDAR". *Applied Energy* **127** 125-134.

Tufte, Edward T (1983) *The Visual Display of Quantitative Information* (Graphics Press, Cheshire Connecticut).

Wals, Arjen EJ (1996) 'Back-alley sustainability and the role of environmental education'. *Local Environment* 1(3) pp 299-316.

Walters, David (2007) *Designing Community: Charrettes, masterplans and form-based codes* (Architectural Press, oxford).