Techniques for the utilisation and management of Post Occupancy Evaluation data by non-experts

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Acknowledgements

I am very grateful to Prof Peter Larkham for his continuing support, good humour, clear guidance, and encouraging manner during the last steps of this process. I have been working on this for a number of years, but it is Peter's support that helped me see it through. I am also indebted to the colleagues and research collaborators, with whom these papers were produced.

On a personal level, I am ever grateful to my wife for putting up with me. To my sister, for never reminding me she got a doctorate way earlier than me, in a more challenging topic. And to my parents, for remaining stubbornly proud of me, despite the occasional evidence against it.

Declarations

No conflicts of interest, or other declarations to make.

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Paper J2. **Patlakas, Panagiotis**, and Rokia Raslan. 2017. "A computer game to help people understand the energy performance of buildings." In Proceedings of the Institution of Civil Engineers-Engineering Sustainability, 308-21. Thomas Telford Ltd.

Paper J3. Becerra-Santacruz, Habid, **Panagiotis Patlakas**, and Hasim Altan. 2018. "Evaluation and visualisation of Mexican mass housing thermal performance." In Proceedings of the Institution of Civil Engineers-Engineering Sustainability, 9-23. Thomas Telford Ltd.

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Acronyms and Abbreviations

AEC	Architecture, Engineering, and Construction
AI	Artificial Intelligence
API	Application Programming Interface
BIM	Building Information Modelling
BPS	Building Performance Simulation
CAD	Computer Aided Design
CIBSE	Chartered Institute of Building Services Engineers
CSV	Comma Separated Values
DC	Digital Curation
DT	Digital Twin
DCC	Digital Curation Centre
DSS	Decision Support System
EPC	Energy Performance Certificate
HBF	Home Builders Federation
HCI	Human-Computer Interaction
IFC	Industry Foundation Classes
IoT	Internet of Things
I/O	Input/Output
LWJGL	Lightweight Java Game Library
ML	Machine Learning
NHBC	National House Building Council
POE	Post-Occupancy Evaluation
ROI	Return on Investment
UI	User Interface
UX	User Experience
XML	Extended Modelling Language

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1. Introduction

In the past thirty years, the sector of Architecture, Engineering, and Construction (AEC) has been primarily influenced by two major developments: the advent of the information age, and the continually increasing attention paid to sustainability, in the face of what has now been increasingly accepted as the climate emergency. These two developments have run largely in parallel. In addition, the impact they have on the design process has focused almost exclusively on experts: planners, architects, engineers, and other construction professionals, with relatively little attention paid to the contribution non-experts can make in their capacity as building users, consumers, and stakeholders.

So far, the information age has become manifest primarily as the replacement of analogue design and management methods with software. The integration of software in AEC has demonstrated an exponential increase: from the development of SketchPad (Sutherland 1964) as a research project in the 1960s, to the slow introduction of Computer Aided Design (CAD) systems with the mass popularisation of Personal Computers (PCs) in the 1990s, today we have reached an almost fully-digitised workflow, with software packages utilised for all aspects of AEC design and management. The relatively new developments of the Internet of Things (IoT), Artificial Intelligence (AI), and Machine Learning (ML) are expected to further increase the embedment of software and hardware in AEC, and potentially radically transform its conceptual and operational processes (Woodhead, Stephenson, and Morrey 2018).

Sustainability and the environmental performance of buildings have followed a similar path, from a topic of interest only to researchers in the 1970s, to an emerging aspect of building design in the 1990s (Crawley and Aho 1999), to the prominent role it holds today. The construction and operation of buildings and infrastructure are typically considered to account for approximately 36% of global energy use and 39% of energy-related CO_2 emissions, while showing an increase in both emissions and energy use, limited progress on policies, and a slowdown in investment growth (Global Alliance for Buildings and Construction, International Energy Agency, and UN Environment Programme 2019). As the pace of climate change has accelerated, its impact on a global level is becoming clearer. Climate change is now widely referred to as the climate emergency, highlighting its immediacy and importance. It is highly likely that the sustainability and environmental performance of buildings will receive even more prominence in the near future.

However, neither of these revolutions has directly engaged building users. The plethora of software tools for the design, analysis, and management of buildings focuses on practitioners and generally requires expert use. It is characteristic that the few software tools targeted at the general public are either support tools for a specific proprietary commercial aim, such as the IKEA Kitchen Planner, or have failed to gain wide traction, such as Google's brief ownership of Sketchup, now owned by Trimble and again focusing on the specialist market (Constine 2012).

When it comes to the performance and sustainability of buildings, the role of building users is often relegated to that of a passive variable, and one which is difficult to control and model (D'Oca, Hong, and Langevin 2018; Janda 2011). The opinions of building users are often considered relevant by researchers, as a way of measuring the success of a building (Hauge, Thomsen, and Berker 2011). However, there is relatively little attention paid to engaging users directly with the way a building performs, and with how technology can be employed to achieve this user engagement. The communication of building performance data to the building user, and their interaction with the building, appear to be afterthoughts for designers/developers, researchers, and policymakers. What tentative first steps have been taken have, as before, been in the form of supporting tools for proprietary commercial products, such as Google Nest, or due to regulatory requirements, such as the UK's Energy Smart Meter Rollout (Change 2015).

It appears, therefore, that there is a clear research gap with regard to the greater involvement of non-expert stakeholders, be it building users, tenants, owners, or others, in the assessment of the performance of buildings. The potential benefits of greater user involvement at a technological, economic, and societal level have not been investigated in depth. Moreover, the methods through which such an evaluation could happen have not been extensively researched. Finally, the implications of such greater user involvement for data collection and management have also not been investigated. The work presented here intends to address this research gap.

2. Aim and Objectives

The overall aim of the collected works presented here is the development of a framework for the collection, processing, presentation, and archiving of Post-Occupancy Evaluation (POE) data in order to allow its effective use by non-experts, thus acting as a Decision Support System (DSS) and ultimately contributing to the enhancement of building design and performance.

The objectives of the work are:

- O1. An exposition of the importance of data in combating information asymmetries in markets, its applications to the building market with an emphasis on POE data, and the impact it can have on the design and operation of buildings.
- O2. The development of a prototype software application that visualises POE data in a 4D building context, allowing non-expert stakeholders to better understand the results of Post-Occupancy Evaluation surveys.
- O3. The application of this software in a range of real-world scenarios and the evaluation of the effectiveness of this software compared to the state-of-the-art presentation approaches in POE.
- O4. The development of a framework for the long-term archival, storage, and dissemination of such data.

The first Objective essentially forms the Rationale for this work, as well as providing the basis for its potential benefits on a wider societal level. It is addressed primarily below in Section 3, "Asymmetric Information in the Built Environment", and Section 4, "Environmental Post-Occupancy Evaluation Surveys". The observations and corollaries, however, also informed the writing of the published works. Objective 2 is described partly in this section, while summaries of it, at different levels of detail, can be found in Patlakas and Altan (2012) and Patlakas, Santacruz, and Altan (2014). Objective 3 is covered via a number of published works in peer-reviewed international journals (Becerra-Santacruz, Patlakas, and Altan 2018; Patlakas and Altan 2012; Patlakas et al. 2017; Patlakas and Raslan 2017). Finally, Objective 4 is the subject of a more recent paper (Patlakas, Musso, and Larkham 2021).

3. Asymmetric Information in the Built Environment

3.1 Background

The concept of the building as a product is not new; from the Corbusian “machine for living in” of the 1920s (Le Corbusier 2013) to more recent initiatives looking at incorporating concepts from manufacturing (Egan 1998), the buildings and infrastructure that make up the Built Environment have often been conceptualised as different types of consumer items. Yet, contrary to the majority of consumer items, the study of the Built Environment is unorthodox in its treatment of the user of these items, giving little consideration to the possibility that they can understand the design and the performance of a building.

This leads to an interesting, and probably unintended, corollary. The Built Environment has not been a primary topic for mainstream economic research, defined here as the conversation taking place in Economics and Business academic departments and the leading research journals. Reciprocally, the research and conversation taking place in Construction has evolved separately and, while it regularly follows general Business, Finance, Accounting, and Project Management trends and theories, it often appears unaware of the application, developments, and evolution of key concepts in Economics. It is characteristic that a Scopus search of abstracts in the leading AEC journals for “asymmetric information” together with either “construction” or “built environment” over the past ten years leads to only five results relating to the built environment (Fernández-Solís et al. 2015; Owusu-Manu et al. 2018; Xiang et al. 2012; Yao et al. 2020; Ying and Jia 2013); all five focus on the relationship between the contractor and the developer, while some economics concepts show some semantic differences (e.g. “contracts” refer to “hard contracts”). Another paper, in a journal outside construction, engages with asymmetric information concepts between buyers and sellers in the Australian residential sector, in the context of sustainability; however, the focus of the core research is again professionals, namely property practitioners, such as real estate agents and property valuers (Wong et al. 2018). Going back to the last 20 years, there is only one paper engaging with asymmetric information in property markets in the leading AEC journals (Lützkendorf and Speer 2005). While the work did generate some interest (40 citations in Scopus as of May 2020), it had to introduce some fundamental concepts (definitions of basic Economics concepts form a substantial part of the paper) and the authors did not explore the Economics side of the argument in later work.

This section addresses Objective 1 of the work, as described above. It begins by introducing a core concept in Economics modelling, the principal-agent problem, and discusses its implications for the Built Environment, particularly with regard to asymmetric information. It continues by presenting disclosure and transparency as mechanisms for combating information asymmetries, as opposed to “hard” State regulation, and summarises the lessons from other industries. It describes some initial attempts to use disclosure and transparency in the Built Environment and suggests reasons for their very limited effect. It concludes by presenting the concept of brand equity and highlighting how it has received practically no visibility in the Built Environment, in stark contrast to most fields.

3.2 Methodological note

This part of the work engages with concepts that are founding principles of the contemporary theory of Economics, so attempting a “traditional” literature review, via Scopus search terms, would be a fruitless exercise. The core principles are described in all undergraduate Economics textbooks, while the key terms would appear in literally tens of thousands of papers: an analogy from Physics would be to attempt to conduct a literature review on the basic concepts of Newtonian mechanics.

The approach taken here, then, is to develop a narrative based on these core principles, focusing on the aspects relevant to the Built Environment, and the ideas relevant to the work. A detailed discussion of fundamental Economics concepts can be found in undergraduate textbooks, and, where relevant, a small selection of widely popular textbooks is referenced (Estrin, Laidler, and Dietrich 2008; Krugman and Wells 2013; Mankiw and Taylor 2011; Pindyck and Rubinfeld 2015). Outside observers, relying on economists' proclamations in the popular press, sometimes believe that the core principles of Economics themselves are under discussion. While this might apply for more esoteric aspects, and, in some cases, for the emerging field of so-called "Heterodox Economics", economists otherwise largely agree on the course principles taught to undergraduates. As a small example of this, the textbook selection includes the two most popular authors in undergraduate Economics syllabi (Open Syllabus 2022); the first, Greg Mankiw, is a prominent conservative/centre-right economist (The Economist 2009; Mankiw and Taylor 2011), the second, Paul Krugman, a prominent centre-left economist (Krugman 2009; Krugman and Wells 2013). The other two Economics textbooks mentioned are written by prominent academics in the adjacent fields of Finance (Pindyck and Rubinfeld 2015) and Management (Estrin, Laidler, and Dietrich 2008), covering both the US and the UK. It is not felt necessary to cite additional textbooks, as they replicate the same fundamental concepts.

Beyond textbooks, landmark papers have been referenced where necessary. These have been selected via a combination of historical importance and citation count, though the two often coincide; Akerlof's classic paper "The Market for Lemons", for example, currently has almost 35,000 citations on Google Scholar (Akerlof 1970). For more recent developments, or more specialised points, the papers cited have been selected primarily via their citation count as appearing on Scopus and/or Google Scholar. As before, many more papers could have been added to reinforce the same points, and the selection is meant to be indicative, but by no means exhaustive. Often, the relevant part in the cited work is in the introduction, as a statement of the research framework. The mechanisms described in the following sections are taken as standard by the overwhelming majority of economists.

An exception to this rule is the papers dealing directly with Built Environment aspects. There is almost no work engaging with the concepts here. The only relevant papers have been identified via Scopus, using keyword combinations of the various key economic terms described below (e.g. "principal-agent", "asymmetric information", "signalling" etc), with a selection of Built Environment terms ("Built Environment", "Construction", "Real Estate", "Housing"). Typically, the papers appearing in these searches are from a Construction Management and/or Construction Economics background and deal with modelling of actors within the AEC sector. These have been filtered out; there is very little material with asymmetric information with regard to building *users* which is the focus of this work. Any relevant workhas been discussed below. When it comes to framing key Built Environment issues in the UK context, two types of sources have been consulted: landmark government-commissioned reports, and relevant literature reviews.

Finally, the underlying assumption is that this part of the work is relevant in markets that enjoy at least a degree of freedom, and thus can be modelled with classical economic principles, based on incentives. In an entirely centrally planned economy, with no ownership or exchange, this analysis would be less relevant. The rest of the work (Objectives 2-4), however, remains more widely applicable (even in centrally planned economies), at least under the twin assumptions that sustainable building design is an unalloyed good in the context of the climate emergency, and that it cannot be achieved by POE specialists alone.

3.3 The principal-agent problem and its implications for the Built Environment

The principal-agent problem is a fundamental conceptual model employed in Economics for the modelling of transactions. In its most basic form, a single party, the Principal, commissions another party, the Agent, to act on their behalf. Unsurprisingly, the incentives of the agent rarely align fully with the incentives of the principal; more formally, the two parties possess different and independent von Neumann-Morgenstern functions (Ross 1973). As a result, the welfare of the principal is affected by these misaligned incentives.

At first instance, this concept can allow for very simple models. For example, let us assume an owner-occupier who wants a simple house extension. In this, the owner-occupier acts as the principal and the contractor as the agent. The goal of the principal is to have the work completed within a certain timeframe, within a certain budget, and at an aesthetic and functional level that is satisfactory to them. The goal of the agent is to deliver the same work at the highest possible profit (including reputational gain), while avoiding any reputational damage and possible legal repercussions. The misalignment of incentives is significant and the possible repercussions self-evident.

However, the potential and applicability of the principal-agent concept is clearer when it is conceived as a general modelling mechanism. The agency relationship does not have to be restricted either to direct commissioning or to a legal (“hard”) contractual relationship. It can be conceptualised and modelled as principal-agent, even if it involves indirect commissioning by one or more intermediaries for the benefit of an end user. Consider the following, substantially more complex example, of the users of a rented office building. The users, in the form of a firm, act as principals to an owner agent. The building owner acts as principal to a developer agent, who in turn acts as principal a contractor agent (Figure 1). Moreover, each of these conceptual groups have their own principal-agent relationships and incentive dynamics, such as the owners, management, facilities team, and employees of the firm; the shareholder, management, and employees of the developer; the various design and build specialists employed by the contractor, and so on.

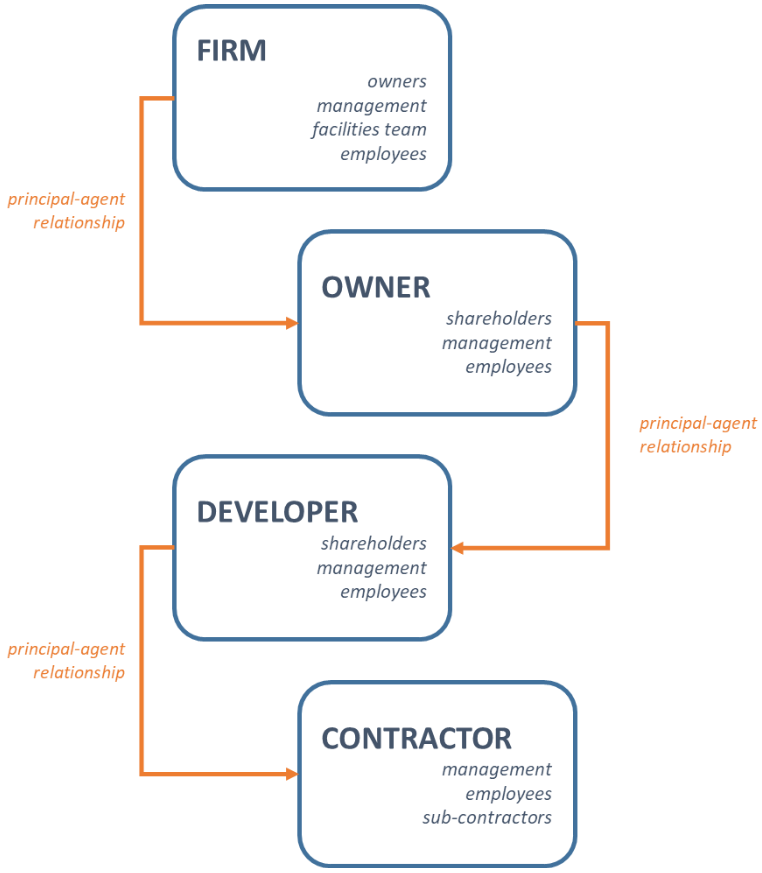

Figure 1: Example of principal-agent relationships in the design and operation of an office building (source: Author)

A major elaboration of the model above comes from the presence of ***asymmetric information***. In a market exchange such as the one described above, one party will typically possess more knowledge of the commodity or service sold than the other. When this is coupled with misaligned incentives, market failure, i.e. a state of non-optimal allocation of the commodity or service, can ensue (Pindyck and Rubinfeld 2015). The term asymmetric information has been used by management researchers for decades (Wilson 1967) but its canonical mathematic formulation is typically attributed to George Akerlof (1970), with further enhancements and major contributions by Michael Spence (1973) and Joseph Stiglitz (1975). Its impact in the formulation of contemporary Economics has been considerable, culminating in the award of the 2001 Bank of Sweden Prize in Economic Sciences (commonly referred to as the "Nobel in Economics") jointly to Akerlof, Spence, and Stiglitz, in recognition of their analyses of markets with asymmetric information, a general theory which the committee considered as having "abundant" applications (Nobel Media AB 2001).

Economics textbooks provide a cornucopia of examples of asymmetric information at a microeconomic level. Occasionally a distinction is made between asymmetries due to a hidden action, such as when an employee knows more about the effort they put in their work than their line manager or a store knows more about the level of post-sale service it will provide than its customer, and asymmetries due to a hidden characteristic, such as when a used car seller knows more about the performance of the car than the buyer, or a restaurant chef knows more about the quality of ingredients than the customer (Estrin, Laidler, and Dietrich 2008; Mankiw and Taylor 2011; Pindyck and Rubinfeld 2015).

The effect of asymmetric information and misaligned incentives on a market are significant and come in the form of problematic resource allocation and lower-quality output (Harris, Kriebel, and Raviv 1982). Effectively, they impede the achievement of Pareto-optimal equilibria (Sharpe 1990).

Economists consider two further aspects in this. The first is ***adverse selection***, i.e. a situation where the buyer recognises the presence of information asymmetry, and responds assuming a worst-case scenario will happen. For example, used car buyers do not hold the same information as the sellers and thus tend to hedge the risk by agreeing on prices corresponding to low-performing cars (Akerlof 1970). Similarly, in the Built Environment, users do not normally hold information on the performance of sustainable technologies. As such, they can hedge the risk by agreeing on prices corresponding to low-performing buildings.

The second aspect is ***moral hazard***, i.e. a situation when an insured, unobserved agent takes actions that are to his benefit and to the detriment of the insurer, which is not in a position to monitor the agent's behaviour (Krugman and Wells 2013). For example, it has long been observed that the value of a machine repairman's effort should ideally be determined according to the time it takes for the machine to break down again, but, if the repairman is unobserved, a Pareto-optimal outcome is not achieved (Holmström 1979). As most aspects of building performance are not communicated to the users, it is not unreasonable to suggest that most aspects of building design and construction are liable to moral hazard.

The conventional response to these deficiencies is considered to be ***signalling***. Signalling typically involves the agent providing credible information about some characteristic of the exchanged subject, which the principal can use as a proxy information device. Typically, the agent will have at least a degree of control over the signal to be revealed to the principal. For instance, college certificates are often considered as a signal provided by a jobseeker (as an agent) for the employer (as a principal) to decide the wages to be offered (Spence 1973). A further elaboration differentiates between a passive response, when it relies simply on existing experience, and active, when the buyer realises the effect the signal has on her decisions and attempts to choose based on this dimension (Spence 1976). A variety of models which take into account multiple signals have been developed (Engers 1987; Quinzii and Rochet 1985).

The consideration of signalling in the Built Environment context remains minimal and almost exclusively concentrated on the relationships between professionals. For example, Ive and Gruneberg (2000) examined the relationship between AEC services providers, while Spencer and Winch (2002) considered the users as passive consumers, who do not engage in the design and performance management process.

Lützkendorf and Speer (2005) is the only work so far to conceptualise building quality as a consumer signal. However, their proposed solution of an all-encompassing "building information system" assumed an extremely extensive collection of information, without an attempt to model the costs or suggest methodologies for the collection of this information. Moreover, the concepts of quality and performance were left somewhat ambiguous. The authors considered the (then new) European Commission Directive of the indication of expected energy performance ("energy pass") of a building as a prime example of such information. It is now well understood that such simulations are hardly representative of the actual building performance (De Wilde 2014) and that their actual effectiveness is limited (Amecke 2012), facts recognised by one of the authors in a later paper (Lützkendorf et al. 2012). Thirdly, Lützkendorf and Speer recommend aspects that are either difficult to measure in a definitive accounting manner, or model effectively econometrically, such as "social performance". Finally, they set a requirement for a disclosure of the financial gain or loss from the investment, which is arguably in conflict with the concept of information as an asset for the function of a market (Arrow 1996), and thus undermines somewhat the fundamental supporting argument.

From an empirical perspective, there is very limited signalling in order to address the asymmetries in the Built Environment. Typically, Built Environment agents do not invest heavily in elaborate signalling. Instead, the end user is expected to assume that the price is an accurate reflection of quality, while state ("hard" or "direct") regulation is understood to provide coverage of the more technical aspects of build quality.

3.4 Disclosure and Transparency as Mechanisms of Improved Signalling

The imposition of directly intervening regulation may appeal to the public and have political benefits for lawmakers, but mainstream economists typically dispute its efficiency. A classic, broad review by Hahn and Hird (1991) surveyed the impact of regulations in a range of sectors including telecommunications, agriculture, transport, and energy. While acknowledging that they have some social benefits, the researchers found that regulations also induce significant costs such as additional overheads for compliance and extra burden for innovation and technological development for compliance. More recent reviews in sectors such as broadband internet (Cambini and Jiang 2009) and chemicals (Mahdi, Nightingale, and Berkhout 2002) again deliver a mixed message, providing both benefits and costs.

By contrast, using disclosure and transparency as correction mechanisms for market failure is much less controversial, regardless of it being a result of policy or the goodwill of an agent. From an economic perspective, they serve as fundamental tools to address the principal-agent problem by reducing the information asymmetry between the two parties. From a political perspective, they can act as a response to popular sentiment, such as the post-Enron Sarbanes-Oxley Act (Zhang 2007) in the USA. Imposing disclosure and transparency through regulation is often referred to as informational regulation, which has been an important pillar of policymaking in recent decades (Sunstein 1998). Its importance and effects have been studied extensively in a range of business aspects, such as marketing (Lev 1992), corporate social responsibility (Spicer 1978), corporate governance (Hermalin and Weisbach 2012), accounting (Lambert, Leuz, and Verrecchia 2007), and finance (Yosha 1995).

Disclosure, however, is hardly a panacea as collecting and disclosing information comes at a cost. It has long been accepted, however, that this cost can be justified on a macro level if the gain in the societal utility exceeds the societal cost of the disclosure (Coffee Jr 1984). There is considerable literature studying the cost-benefit ratio from the enforcement of information disclosure in a number of industries in the past decades from both a theoretical (Cheong and Kim 2004) and practical perspectives (Adrem 1999; Depoers 2000; Francis, Khurana, and Pereira 2005; Liu and Anbumozhi 2009).

Beyond purely economic aspects, there is a growing realisation that psychological mechanisms are also in play. An extensive literature review by Loewenstein *et al.* (2014) examined information transparency in industries as varied as credit cards (Agarwal et al. 2015), schooling (Jensen 2010), cars (Allcott 2011), household appliances (Allcott and Greenstone 2012), utilities (Allcott and Rogers 2014), fast food restaurants (Bollinger, Leslie, and Sorensen 2011), and health (Lansky 2002; Pope 2009). They identified a range of unintended consequences resulting from mechanisms well known to psychologists, which have an adverse impact on the effectiveness of information disclosure. These mechanisms, from limited or motivated attention, to biased probability judgments, to social pressure and moral licencing, need to be taken into account in order for transparency to act as a corrective to information asymmetries.

3.5 Regulation, Disclosure, and Signalling in the UK Built Environment

The United Kingdom offers a good case study of a combination of regulation, disclosure, and signalling in the Built Environment. During the past three decades a series of government-commissioned reports and frameworks has highlighted issues such as counter-productive tendering practices; poor design and build quality; inefficiency and low productivity; lack of innovation; failure to deliver value to clients and other stakeholders (Cabinet Office 2011, 2016; Egan 1998; Latham 1994). The emergence of sustainability as a major issue in the past two decades added new challenges for building designers: however, the extent to which those are addressed is questionable. It is now generally accepted amongst researchers that in the key environmental concern, energy use, there is a considerable gap between the intended and the actual performance of new buildings (De Wilde 2014; Cozza et al. 2021; B.Ozarisoy and Altan 2022).

At the same time, building users usually have very limited input in building design ("bespoke" buildings, constructed for a known user with substantial user input remain the exception, not the rule). The need for greater user involvement and engagement in the Built Environment is widely accepted and the way to achieve this has remained a subject of debate for decades (Arnstein 1969; Jones, Petrescu, and Till 2013; Udall and Holder 2014; Leyden et al. 2017; Wilson et al. 2019; Woods and Thomsen 2021). However, most housing is designed and built speculatively, without input from the eventual residents (Barlow et al. 2003), despite the fact that resident satisfaction is directly tied to the design aspects of the space (James 2007; Da Silva et al. 2020). Beyond housing, building users report problems in other building types whose design they cannot control. In contemporary offices, problems have been reported both in layout (Kim and de Dear 2013) and environmental (de Kluizenaar et al. 2016; Kwon et al. 2019) aspects. User satisfaction is not a trivial matter and can have a substantial effect on users. In a prominent example, it has been suggested that greater user satisfaction with hospital design can have a physiological effect, affecting health and recovery outcomes (Lawson and Phiri 2000; Liddicoat et al. 2020).

It is interesting to observe that the progress made in the past two decades, such as improved environmental performance or increased uptake of Building Information Modelling (BIM), seems to have occurred primarily as an industrial response to government legislation rather than out of the industry's desire to innovate and improve its output. The amount of government regulation and intervention in a sophisticated market is, of course, a core concern in political economy, with the debate tracing back to the extremes advocated by Lange (1937) and von Hayek (1945). Mainstream economic opinion today, however, generally accepts that the use of directly intervening regulations, often referred to as "hard" regulations, has adverse effects on productivity and investment (Conway et al. 2006) and risks a re-engineering of the industry towards rent-seeking by those who lobby the regulators (Grossman and Helpman 2001). Naturally, the Built Environment sector offers clear examples of hard regulations, such as the parts of the building codes that deal with safety-critical issues. While a debate does take place about the nature of those (Meacham et al. 2005), this unavoidably tends to be confined to the realm of the experts. There is generally little progress in the use of either soft regulations (in the manner of encouragement of disclosure), or a combination of hard and soft regulations that enforce some quantifiable aspects while requiring the builder to disclose performance-related characteristics. The two main exceptions to this rule are the disclosure of user satisfaction in new housing, as a signal of overall performance, and the disclosure of energy ratings, as a signal for energy performance. However, neither has been particularly effective, as will be described below.

3.6 Disclosing user satisfaction as a signal for overall performance of new housing

The National New Home Customer Satisfaction Survey, commissioned annually by the UK Home Builders Federation (HBF) as a response to the Barker Review of Housing Supply (2004), is a typical example of disclosure as soft regulation. These annual surveys often have high response rates (typically at least 35% and at times exceeding 50%) and big samples (above 25,000, with 45,000 in 2016). They include collective statistics in various categories for all homebuilders, and a "star rating" for individual builders. However, they seem to affect neither industry performance, nor consumer perception. Between 2010 to 2017, a year-on-year average 92.75% of new homeowners had to report at least one problem (defined as "snag, defect") to the builder; 55.86% reported at least 6 problems, 28.63% at least 11 problems. Despite the disclosure, the number of problems seems to show an increase year-on-year. Specifically, the percentage of respondents with at least 11 problems has shown a steady upward trend in recent years, from 20.93% in 2013, to 40.18% in 2017 (Figure 2).

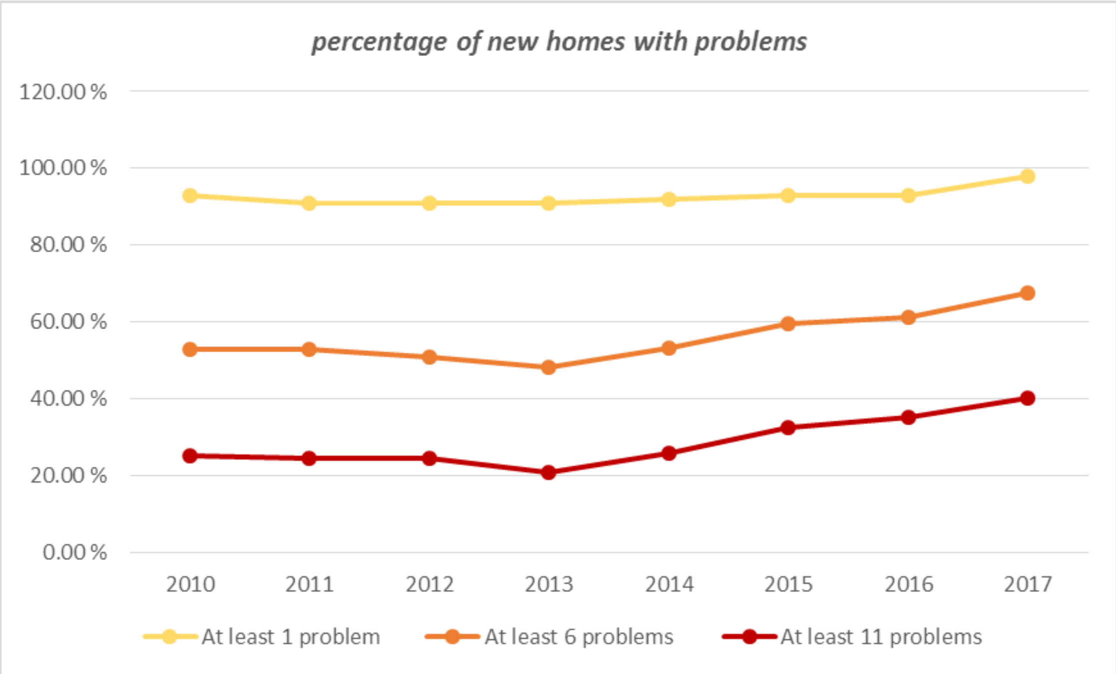

Figure 2: Percentages of new homes with problems (source: Author, derived from HBC 2010-2017)

One could argue, of course, that homeowners with problems are more likely to respond to the survey. However, the observation pertinent to this discussion is that the customer satisfaction is remarkably high: on year-on-year average, 87.5% would recommend their builder to a friend, and 69.63% reported the number of problems being at the level they were expecting or lower (HBC 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017). This could suggest that UK consumers are not able to recognise the quality a product can or should achieve.

One factor for this could be the effectiveness of marketing. Researchers have long highlighted the effects of relationship marketing on consumer satisfaction (Crosby and Stephens 1987). A similar effect is likely to apply here as, since National House Building Council (NHBC) started collecting such data in 2012, there is a year-on-year average 77.17% of respondents who are fairly or very satisfied with the service provided by the builder after they moved in. While the crisis in the UK housing market is well documented and explains the price inelasticity, it does not explain the satisfaction of new homeowners in the face of such a performance by the UK building industry. It is more likely that this is a case of severe market failure due to information asymmetry. More simply, it is possible that UK house owners might be unaware of how a building is meant to perform or are resigned to low expectations. Alternatively, it could be that builders pre-empt criticism by allocating resources to respond promptly to customers, which could ameliorate the image of the provider to the consumer. The fact that the reporting of building performance happens at one or two points in time, as opposed to a continuous monitoring, incentivises builders to respond accordingly.

3.7 Disclosing energy rating as a signal for energy performance

The environmental performance of buildings, instead, is an example that combines hard (e.g. minimum U-values) and soft (e.g. disclosure of an energy-related certificate) regulation. The evidence of the impact of such certifications, such as Energy Star or Energy Performance Certificate (EPC) is mixed, with some studies showing a positive correlation between certification and willingness-to-pay (Eichholtz, Kok, and Quigley 2010; Fuerst et al. 2015) and others little or no impact (Amecke 2012; Fuerst and McAllister 2011; Murphy 2014). However, the weaknesses of the certification processes are well known (De Wilde 2014; Tronchin and Fabbri 2012), and there are examples where certification does not correspond to a low ultimate energy use (Eichholtz, Kok, and Quigley 2010), thus suggesting that the actual impact of such disclosure is small. Its effectiveness will also reduce further if consumers find discrepancies between the suggested ratings and actual consumption.

3.8 Brand Equity as an incentive for performance improvement

This limited use of signalling in the Built Environment can perhaps be explained in part by an anomaly that prevents buildings for being conceived as products. For the vast majority of markets, the importance of branding is unquestionable (Bristow, Schneider, and Schuler 2002). The term “brand equity” is commonly used to describe how a brand name functions as a signal for the product quality used by consumers to assign commercial values to a producer. Effectively, this acts as an incentive for producers to improve quality in order to improve their brand names (Cobb-Walgren, Ruble, and Donthu 1995; Dawar and Parker 1994; Gürhan-Canlii and Maheswaran 1998; Jacoby, Olson, and Haddock 1971; Kamakura and Russell 1993; Maheswaran, Mackie, and Chaiken 1992).

By contrast, the concept of brand name in the Built Environment is not particularly apparent, especially for development by individual developers and contractors. While the developer’s name will appear during construction and in promotional literature during the sales of a new build, a layperson end user, or even a buyer, of a building such as a store or a house generally does not link it with a general perception of a quality of built, or specific characteristic (it is indicative that the leading property websites tend not to mention the developer in advertisements for either sales or lettings). Even if an above-average informed consumer is assumed, it is likely that any attempt to seek information will be based on anecdotal stories from a close network and, in any case, it is very highly unlikely to involve any technical characteristics on performance. A comparison with the car market here is particularly striking; a rough analogy would be to advertise a car stating characteristics such as horsepower and fuel consumption, but omit the carmaker, or, similarly, present the carmaker but the buyer having no perception of the brand characteristics linked to the carmaker.

A possible counter-argument for this application of signalling in the Built Environment is that buildings are very complex products, with a range of companies involved as sub-contractors, and the control by developers or contractors is limited. However, many products, such as cars and mobile phones, involve highly complex supply chains with a very wide range of companies; yet it is widely accepted by manufacturers that their brand is tied to the quality of the end product, and it is their responsibility to select appropriate suppliers. The construction industry, however, is unique in placing a considerable burden on the commissioning client, which results in high complexity in coordination and communication (de Blois et al. 2011), thus increasing the potential information asymmetries.

Institutional clients, which theoretically have the resources to build brand equity profiles as institutional knowledge, tend to have a transactional mind-set (Smyth 2014) that makes capital cost as the reference to measure project success. As a result, there is a lack of incentive to collect data relating to the lifecycle performance of buildings and assess the life cycle cost implications in general. The implication is that incomplete operational datasets are collected, which are either not taken into account or are used on a heuristic basis for decision making, with exceptions typically involving cases of dispute regarding buildings that perform significantly poorer than anticipated.

This is particularly striking given the consensus on the importance of the whole lifecycle performance of buildings. Institutional clients of the construction industry began to appreciate the importance of whole lifecycle analysis and costing as early as the late 1970s (Boussabaine and Kirkham 2008). More recently, the topic has generated interest in the context of energy consumption, sustainability, and the environmental performance of buildings (Cabeza et al. 2014; Gluch and Baumann 2004; Khasreen, Banfill, and Menzies 2009; Ramesh, Prakash, and Shukla 2010; Zabalza Bribián, Valero Capilla, and Aranda Usón 2011).

The systematic collection, analysis, and dissemination of whole lifecycle building performance data could thus have a transformative effect. Linking such data to the developer would effectively build brand equity. Overall, this would not only address various information asymmetries, but would also significantly increase the incentive of agents to provide principals with a high-quality product.

This, naturally, raises a number of new issues. What data is needed? How can this data be collected and analysed? How can the results be communicated effectively to non-expert end users and other stakeholders? What costs are involved in this process, particularly with regard to long-term storage? The work presented here attempts to provide some initial answers to these questions.

4. Environmental Post-Occupancy Evaluation Survey Data

Lützkendorf and Speer (2005), inspired by similar concerns on Asymmetric Information, have tried to build an extremely comprehensive framework, called a “Building Information System”. This covered areas as disparate as structural safety, biodiversity, impact on community well-being, quality of planning and design, and deconstruction and disposal costs – to name but a few. The intention was certainly laudable: however, the fact that there has been no progress on this more than 15 years later, and that the authors themselves appear to have abandoned that line of inquiry, suggests that the scale of ambition was perhaps above what could have been realistically achieved.

Data collection is also a central tenet in Post-Occupancy Evaluation. In the third paper in a seminal series on the subject, Bordass and Leaman (2005) identify a range of techniques, from questionnaires, to discussions, to standardised assessment methods (such as the CIBSE TM22), highlighting the very diverse types of data that can be collected in a POE context. Conceptually, however, POE surveys can be considered along two axes: if data collection is automatic or not, and if the data collected is objective or subjective. Some examples along those two axes are given in Figure 3. (Unsurprisingly, collection of subjective data requires some user involvement, so it is difficult to have subjective data collected automatically.)

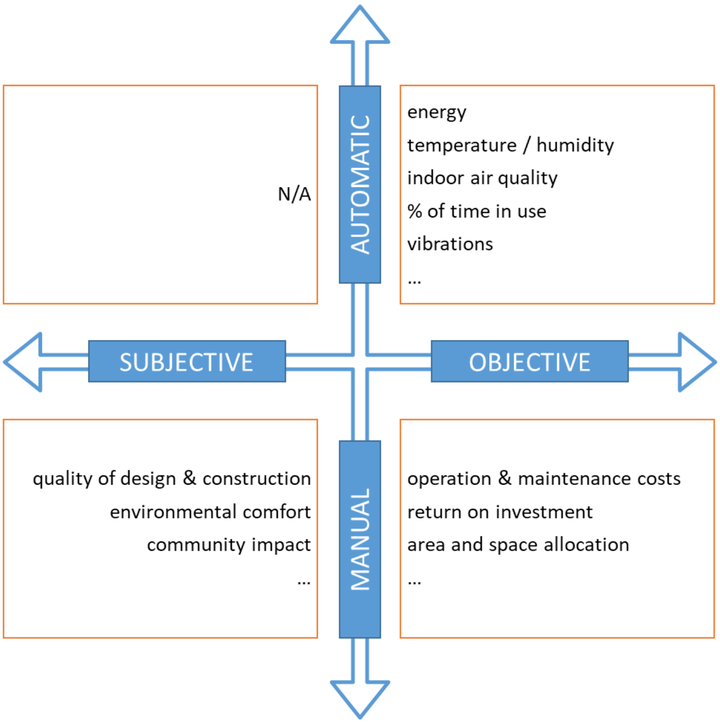

Figure 3. POE Data classification (source: Author)

While it can be argued that all data is important, in order to make effective use of resources and maximise the benefits, it is important to prioritise the data whose collection and analysis is the most efficient and can make the most impact. Avoiding data overload and focusing on key issues has been identified by researchers as important in order to overcome the barriers to wider POE implementation (Hadjri and Crozier 2009).

For the purposes of the work presented here, the focus has been on objective environmental performance data that can be collected automatically. The advantages of such types of data are many: they are not subject to user opinion, thus providing quantifiable results that can be analysed further; once the monitoring equipment has been installed, they can be collected automatically; they provide information about the environmental performance of the building, and thus its energy use, the most important aspect in the context of sustainability and the climate emergency. Such data can also be used to address the performance gap, thus further facilitating the sustainable design of buildings (Menezes et al. 2012). In most of the work presented here, Temperature and Relative Humidity (T/RH) have been the key properties monitored. These are the key parameters of thermal comfort, which typically has the biggest impact on energy use. However, the research approach adopted can be easily generalised to all other types of objective data collected automatically.

The methods of collection and analysis of such data are well established, with a number of literature reviews published on the topic (Heinzerling et al. 2013; Khodakarami and Nasrollahi 2012; Park and Nagy 2018; Rupp, Vásquez, and Lamberts 2015). The focus of those studies, however, is on the specialists and professionals. A key new contribution of the body of work presented here is that the focus is on communicating this information to the layperson.

The mode of this communication was a key decision early in the work. The project started from the observation that POE measurement were presented only in the form of raw data (typically in spreadsheet format) or, usually post-analysis, in two-dimensional (2D) graphs. This type of presentation has a number of limitations. Firstly, and as graphs have a small amount of available space, especially on a printed page, it can only show measurements over either small periods of time, or by summarising results (such as showing averages), which is likely to miss the effect of fluctuations. Secondly, only a limited number of spaces can be juxtaposed at the same time, while keeping a graph, or a small collection of graphs, readable. Thirdly, interpreting even basic graphs requires some amount of familiarity with this type of presentation, and an understanding of the underlying principles. Medical professionals, for example, have long observed that lay readers have difficulty understanding statistical graphs (Muscatello et al. 2006). Even individuals with some training in a field can find interpreting graphs difficult when they are intended to interpret those in the context of a specific domain (such as Physics), compared to abstract mathematics (Planinic et al. 2013). Moreover, building these graphs effectively requires a degree of training and expertise in statistical graphics. Yet most Built Environment researchers are unlikely to have received formal training in the statistical graphic design aspects, and would probably rely on standard software, such as Microsoft Excel. It has been observed, however, that the default options of such software rarely lead to effective graphs for the communication of scientific concepts (Su 2008). The volume of raw data in POE makes the use of 2D graphs problematic, as even a basic survey will have hundreds of thousands of readings: a single temperature logger, set at 10’ intervals over one year (the typical minimum monitoring period) will result in 52,560 data points.

Besides the data volume, there are other, more important, challenges to consider. Typically, a single data property does not communicate adequate information. In the most common example, thermal comfort depends on two variables: temperature and relative humidity. More importantly, POE data typically refer to Built Environment *spaces*. Presenting the information without any spatial context is rarely useful. The 2D graphs in POE reports are meant to be complementary to extended technical texts analysing a specific space, where other graphical media (e.g. 2D plans or 3D models) might be used to communicate aspects of the building. Overall, however, the usual intention is for these to be technical reports, written by experts and intended, primarily, for a similarly qualified audience. There is little or no consideration about communicating this data not just to lay readers, but even Built Environment professionals without POE expertise.

The advantages of more expressive modes of data visualisation have been well established. As a general rule, it can be said that effective visualisation of large datasets allows better comprehension of such data in different scales, it enhances the identification of emergent system properties, it facilitates hypothesis formation, and it highlights issues with the data itself (Ware 2012). Beyond those broad benefits, however, specific data visualisation techniques find applications in individual disciplines. In the AEC context, it has long been observed that three-dimensional (3D) visualisation allows for a more intuitive understanding of spaces, especially among those without training in reading 2D technical drawings (Peng 2011). For professionals, 3D visualisation can provide improved accuracy in design and construction, as in the case of Building Information Modelling (BIM) (Eadie et al. 2013). These advantages extend beyond basic graphic representation: there is the potential to overlay other information layers too. Time (“4D”) and cost (“5D”) are currently the most common, though researchers have described the potential for visualising more layers (“nD”) (Ding, Zhou, and Akinci 2014). Beyond BIM, 3D in-context visualisation can be beneficial, i.e. within navigable virtual worlds. This creates a gamification element, which has been used by researchers both for design education and for understanding more about the use and function of space (Armenakis and Sohn 2009; Brown, Knight, and Winchester 2005; Peng 2011; Sourin 2005).

The advantages of communicating information with static (3D) or dynamic (4D) visualisations are well recognised by software manufacturers. It is telling that leading packages such as Autodesk Revit (and, previously, Ecotect) incorporate 3D visualisation as a key communication mechanism for their Environmental & Energy Analysis results (Autodesk 2021). However, and while standard tools like Microsoft Excel or R can be used for the statistical analysis, there is still no comparable software for visualising the results of POE studies. This, to an extent, is to be expected. The software vendors that have in-house knowledge and expertise to develop such software typically focus on the lucrative market of developing analysis tools. As pointed out earlier, however, these analyses are widely problematic: this is the accepted “performance gap” (De Wilde 2014). Software vendors who sell simulation tools have little incentive to develop tools that highlight the simulation failures more starkly; POE monitoring hardware manufacturers might not necessarily see the Return on Investment (ROI) of developing such software. In order to communicate effectively the results of POE data, a custom software application needed to be developed and its effectiveness measured via application in a range of scenarios, with users of different levels of expertise.

Another element of contemporary POE studies, as covered in a range of literature reviews (Heinzerling et al. 2013; Khodakarami and Nasrollahi 2012; Park and Nagy 2018; Rupp, Vásquez, and Lamberts 2015) is that data is collected on an ad hoc basis. Specifically, data is collected for a particular project and analysed with regard to the period studied; the long-term data storage and lifecycle are not considerations. As a result, there is limited potential for reuse and sharing of such data. However, if POE surveys are to be expanded to a large scale, the archiving, storage, and dissemination of the data will be major issues, as the data volume become substantial. The work presented here recognises these issues and attempts to engage with them, setting up an initial framework to address issues of data lifecycle, management, access, and dissemination.

5. Methodological Framework

The interdisciplinary nature of the work meant that a range of methodologies from different fields had to be applied. The work combines aspects of building monitoring, nD visualisation, software development, gamification, and digital curation. The present section provides an overview of the methodologies employed, and the rationale for their selection. Further details are provided in the published works included in the Appendix (Becerra-Santacruz, Patlakas, and Altan 2018; Patlakas and Altan 2012; Patlakas et al. 2017; Patlakas, Musso, and Larkham 2021; Patlakas and Raslan 2017; Patlakas, Santacruz, and Altan 2014).

5.1 Software Development

The development of the software consisted largely of three parts: Requirements Engineering, i.e. identifying the minimum required functionality, including Input/Output (I/O) aspects; User Experience (UX), i.e. developing the User Interface (UI) and Look and Feel of the application; and core development, i.e. the programming of the application.

Requirements Engineering

The main required functionality of the software was to visualise POE data in a 3D building context, using both static and dynamic (4D) visualisations. The intention was to develop an application that would have minimum learning requirements and be simple enough to be used by non-expert users.

As this was intended as a proof-of-concept, prototype application (“app”), considering only one POE aspect was considered adequate. Measurements related to thermal comfort, i.e. temperature and relative humidity, were selected. A Pass/Fail criterion was also considered necessary, in order to allow the user to perceive immediately if the thermal comfort standards of the space were met. The thermal comfort criteria provided by the Chartered Institute of Building Engineers were taken as the default (Armstrong, Butcher, and Rowe 2003), but the option of user customisation of those criteria was also to be provided. In addition, the adoption of a Pass/Fail criterion was also deemed useful as an indication of the potential of the application to combine various input data types to provide new insights.

A second required element was for the software to be as intuitive and easily accessible as possible (flat learning curve / no learning overheads), in order to allow effective use by laypeople and combat “app fatigue”, i.e the resistance users have in engaging with new apps in a saturated digital environment (Morris and Morris 2019). This necessitated a simple User Interface and a minimum number of interactions needed in order to achieve the required outcome.

A third requirement was that the application would fit with contemporary AEC digital workflows, and have minimal involvement with proprietary formats and software. This was necessary in order to both minimise the costs of preparing suitable data for it and demonstrate that such an application could be integrated into current practice.

For this purpose, the COLLADA format was chosen as the 3D model input format, and XML as the data logger information format. XML is a very common option for data exchange, as it is simple, flexible, extensible, and non-proprietary (Bray et al. 2000). COLLADA is a non-proprietary 3D asset exchange schema, based on XML, which allows diverse tools to be combined into the graphics production pipeline (Arnaud and Barnes 2006). Both formats are open while they are supported by freely available software applications. XML files can be edited in any text editor, such as Notepad++, while export to COLLADA is supported by free and popular 3D modelling applications such as Trimble (previously Google) SketchUp. Support for Microsoft Excel was added in later versions of the software. Though proprietary, Excel has an overwhelming market share and it is a common file format in which POE data is collected. Users of alternative spreadsheet packages can easily convert the native format, typically Comma Separated Values (CSV), to XML as this is supported by all major vendors.

User Experience

In order to serve the User Experience requirements described above, the following principles were applied:

- Single-Screen App. The core functionality of the software would be included in one screen, with only optional information, of secondary importance, requiring second-level interaction such as pop-up windows (Figure 4)
- Industry-standard navigation. The navigation within the 3D models followed the common industry practice of mouse-based navigation (pan with left mouse button/zoom with the mouse wheel/ rotate with the wheel pressed)
- Intuitive colour maps. Gradient colour maps were used for numerical data and single-colour maps for binary data (Figure 5).
- Minimum number of actions. The standard app usability can be achieved in only five steps:
    - input three-dimensional volumetric models of the buildings
    - input the source data from the data loggers
    - select from/to dates of interest
    - select a real-to-model time ratio
    - run the visualisation

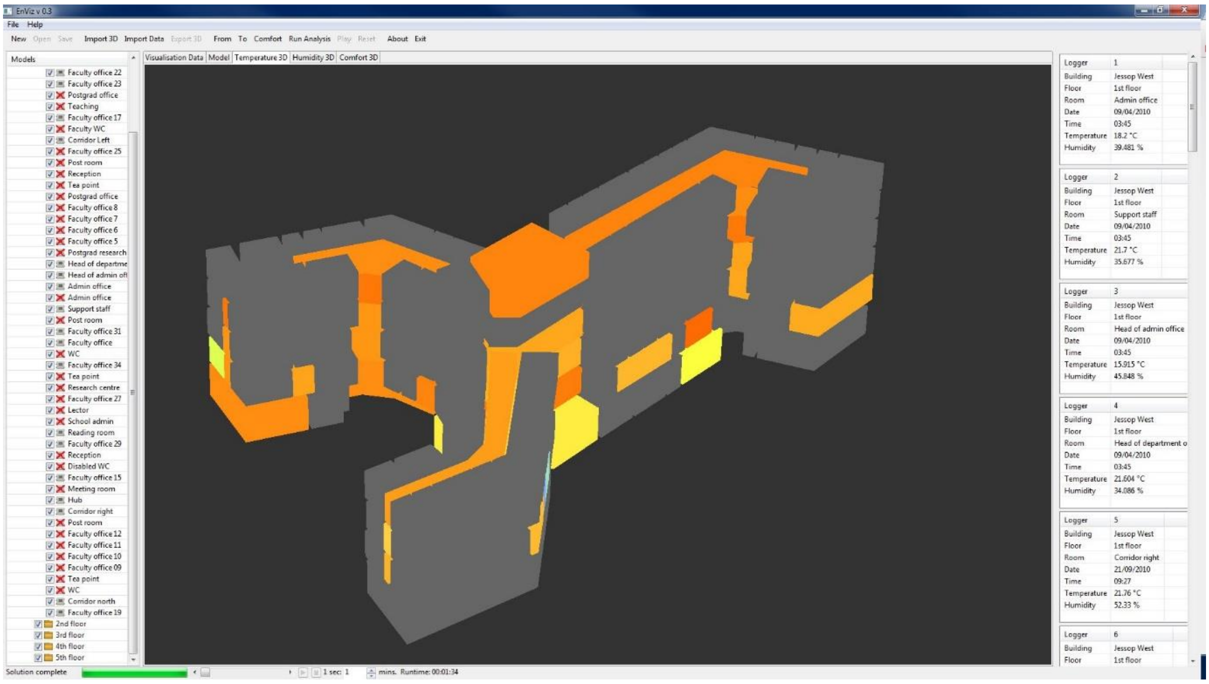

Figure 4. Screenshot of the main screen of the application

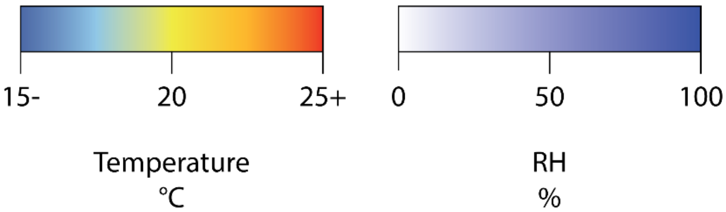

Figure 5. Temperature and Relative Humidity Colour Maps (source: Author)

Further usability, such as setting thermal comfort criteria is optional, but also achieved with a minimum number of actions. Additional information on the particulars of the UI is given in the papers in the Appendix that cover the technical development in detail (Patlakas and Altan 2012; Patlakas and Raslan 2017; Patlakas, Santacruz, and Altan 2014).

Technical Development

The software, named EnViz for "Environmental Visualisation", was developed in Java SE 7, utilising the OpenGL programming interface for 3D graphics. This was implemented via the freely available and open source Lightweight Java Game Library (LWJGL) (Tsakpinis 2015). Other freely available libraries and Application Programming Interfaces (APIs) were used, as per standard programming practice. The application is currently stand-alone and runs on the Windows operating system.

The process diagram of the app of the metadata binding is given in Figure 6 below.

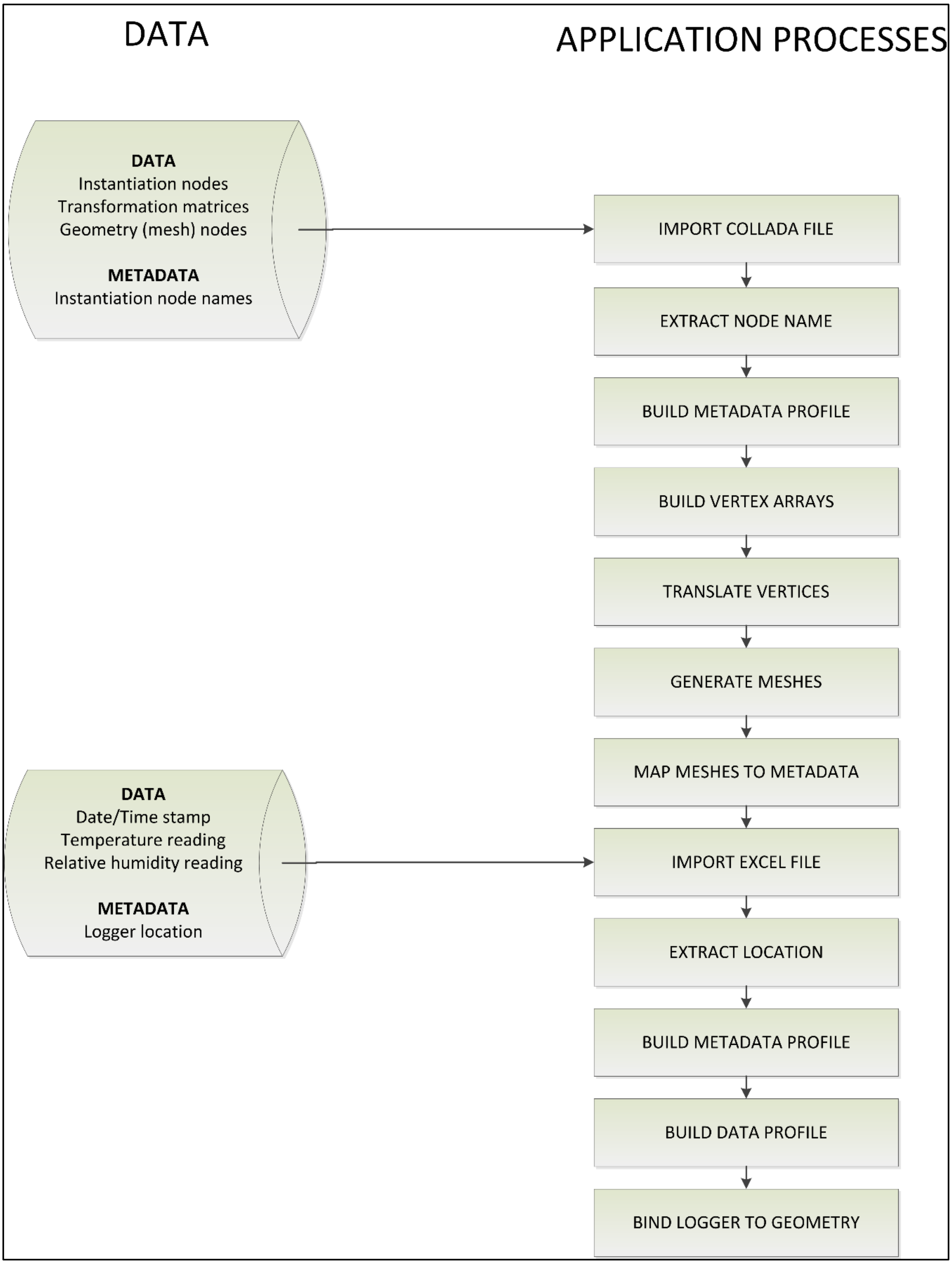

Figure 6. Process diagram of software function (source: Patlakas, Santacruz, and Altan, 2014)

Further information on the application development can be found in Patlakas, Santacruz, and Altan (2014).

Application Versions

Three major versions of the application were developed. The first was intended as a beta version and was evaluated via a Pilot Study (Patlakas and Altan 2012). The main differences to the final version were that only a single building was evaluated, the user had to place each logger manually, and T/RH gradation equations were used for the visualisation of each space.

The first full version expanded the usability in order to accommodate multiple buildings and data filtering to allow user comparison of specific spaces. In addition, the entry of logger positions was automated via the introduction of appropriate metadata in the POE data files. Finally, this version introduced Pass/Fail thermal comfort criteria. This version is used in two papers (Becerra-Santacruz, Patlakas, and Altan 2018; Patlakas and Raslan 2017).

A final version introduced POE data importing directly from Excel, improved the 3D model parsing, and added some bug fixes. This was utilised in Patlakas et al (2017).

Limitations

Developing even a prototype application for research purposes comes with significant software development overheads. As a result, the app had a number of feature limitations, the most important of which is that the input data requires some manual preparation to be compatible with EnViz. The POE data needed the addition of the logger space in the same name as the model. The COLLADA models need to be developed specifically to allow visualisation, i.e. they need to be volumetric models of the space without details (details can be included in the model, but they will ignored by the model parser). From a practical perspective, this meant that the input data for the evaluation exercises were prepared by the author. This, however, does not have an impact on the proof of the concept, as extending the app to accommodate standard models is simply a matter of building in the software intelligence, which can be done following standard practices.

A second limitation is that the software is not integrated directly in a BIM workflow. At the time of the conception of the software (2010), Building Information Modelling was not as prevalent as today, and none of the models of the case studies were in BIM-compatible software. However, BIM actually *supports* the concept of the app. A variant of EnViz could easily be implemented within a contemporary BIM framework, simplifying substantially the metadata process given in Figure 5.

5.2 Software Effectiveness

Several activities were organised in order to evaluate the software effectiveness. The work was split into two main phases. In the first, the effectiveness of the 3D/4D visualisations was compared with the effectiveness of the state-of-the-art, i.e. 2D graphs, via standardised evaluation activities. In the second, the effectiveness of the software as a decision support system was evaluated via a gamified process. Supplementary activities followed providing additional data in support of the effectiveness of the application.

Visualisation Effectiveness

The measurement of the effectiveness of software applications falls within the domain of Human-Computer Interaction (HCI). Such effectiveness is typically measured via field trials, where empirical methods are utilised to collect qualitative and quantitative data (Te'eni, Carey, and Zhang 2007). In order to assess the efficiency of an information visualisation system, such as EnViz, or 2D graphs, a common practice is a workshop environment where participants are asked to perform certain tasks; parameters such as the participants' response accuracy, response time, and mental effort are measured (Huang, Eades, and Hong 2009). Such tasks should mimic the actual intended functionality of the application (Nielsen 1994).

Over a two-year period, eight workshops were organised, with a total of 89 participants, 72 of whom completed the tasks in full. Four workshops took place in the UK and four in Mexico. The workshops featured participants of varied backgrounds, with their expertise in POE methods classified as 'no expertise' (undergraduate students in built environment disciplines), 'low expertise' (graduate architects or engineers, with 0–3 years of professional experience and/or a post-graduate qualification in sustainable design) and 'high' (architecture or engineering professionals and environmental design researchers). The users were given tasks which required them to comprehend, assess, and compare information, first with the standard practice of source POE data and 2D drawings, then using EnViz. The response time was kept constant for both tasks and the response accuracy was measured quantitatively. The users' mental effort was assessed qualitatively, via an anonymous questionnaire provided at the end, in which users were asked to evaluate the two methods in the following aspects:

- easy to learn
- easy to use
- user productivity
- effectiveness of communicating the data
- capacity to compare different spaces and/or buildings
- usefulness in sustainable design

Users were also asked to identify their preferred method, while additional informal feedback was collected via discussion.

Additional information, and the results of the study, are provided in Patlakas, Santacruz, and Altan (2014).

Gamification

Gamification has seen an increased interest in recent years, with applications in various fields (Bajdor and Dragolea 2011; Huotari and Hamari 2012; King et al. 2013; McCallum 2012; Pedreira et al. 2015; Abou-Shouk and Soliman, 2021). However, a precise definition remains elusive (Huotari and Hamari 2012), as the concept of a Game has important philosophical implications. Drawing on the work of Koster (2013) and Salen *et al* (2004), Patlakas and Raslan (2017) defined gamification as "the development of a system in which players engage in a set challenge with defined rules, aiming to arrive at an identifiable outcome; the underlying aim of the system is for the developers to achieve specific results from the players' engagement, unrelated to the outcome, which might or might not affect the players".

Huang and Soman's (2013) framework for the development of games for educational purposes was utilised in order to develop a game based on POE data. In this game, the players assumed the role of facilities managers whose aim was to "fix" different areas of a building that failed to achieve its required performance. They were provided with a fixed budget and awarded points based on the effectiveness of their intervention. They also used two different systems: firstly, the current state-of-the-art of 2D drawings Excel files, and then EnViz. Thus the game served two different agendas: for the players, the aim was to understand better the issues relating to building performance, POE surveys, and facilities management; for the researchers, the objectives extended to collecting evidence regarding the respective effectiveness of EnViz vis-à-vis the current method of visualisation of data (2D drawings/Excel files). A pilot study was undertaken, following which the rules of the game were streamlined, and an interactive game environment was designed in Excel to make the logging of the points more straightforward (Figure 7).

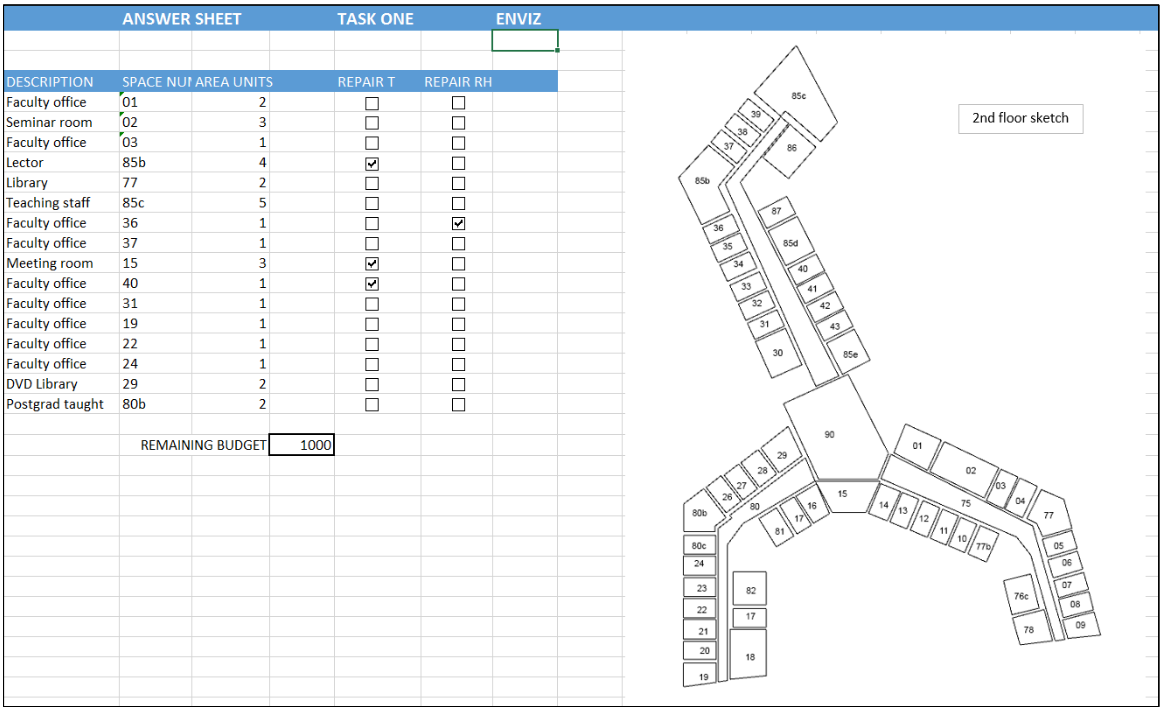

Figure 7. Snapshot of the interactive game environment (source: Patlakas and Raslan, 2017)

As before, the comparison between the 2D & 3D methods was undertaken both quantitatively, by comparing the points scored by the players, and qualitatively, by issuing the players with a questionnaire. Further details, including the analysis of the gamified system using the Dubbels matrix (Dubbels 2013), are given in Patlakas and Raslan (2017).

Additional Uses

EnViz was applied in additional POE cases, which were used as case studies to provide further evaluations of its effectiveness. In Becerra-Santacruz, Patlakas, and Altan (2018) it was employed by the researchers in order to enhance their understanding of POE data, in a study of 12 houses built with industrialised mass housing methods in Morelia, Mexico. In Patlakas *et al* (2017) it was employed by the researchers to compare simulation data with POE data, and the methods described above were used to provide quantitative and qualitative evaluations of EnViz vis-à-vis the standard 2D visualisation.

Limitations

The methodology described above had three main limitations. Firstly, the two approaches (2D/Excel and 3D/4D with Enviz) were compared at the macroscopic level, i.e. one approach versus the other, in the same scenario. Naturally, this generates a very wide range of variable factors that might influence the users' performance and opinion of the approaches tried. While the core tenets of usability engineering were applied, this was done at a general level. In the field of HCI, doctoral theses can be written for identifying the performance of a single feature or a single UI component. The ambition here was not to delve into such fine detail or provide decisive answers on an isolated component, but gauge the general effectiveness of, and response of users towards, a 3D/4D in-context visualisation system. As such, the results should be interpreted as an indication, as opposed to definite scientific proof.

A second limitation was the previous experience of the users. All participants in the laboratory exercises were familiar with Excel, and the majority were also familiar with 2D drawings. In contrast, their experience of EnViz was only a brief introduction prior to engaging with the app directly. This potentially penalises the effectiveness of the app and does not capture potential gains once users become more accustomed to its use. However, this can be considered a positive: if anything the app is likely to be *more* useful once users engage with it further.

A final limitation was the incentives of the users. Where possible, this was contextualised as a learning experience, thus increasing somewhat the users' commitment. However, this does not simulate fully the interest and commitment "real-world" users would have. Combined with the users' familiarity with Excel and 2D plans mentioned above, this would again penalise the effectiveness of the app. As before, this can be considered a positive, not negative.

5.3 Digital Curation of POE Data

The mass collection of POE data will bring challenges with regard to the storage, archiving, management, recovery, and utilisation of such data. These, however, are not new challenges; they have been faced by many disciplines which collect so-called "Big Data". An emerging term for addressing these challenges is *Digital Curation* (DC), defined by the Digital Curation Centre (DCC) as the "maintaining, preserving and adding value to digital research data throughout its lifecycle" (Digital Curation Centre, 2022). For the purposes of the work presented here, an initial Digital Curation Framework for POE data was developed.

Currently, a small range of data formats exists for Building Performance Simulation (BPS), typically built around the XML markup language. The gbXML schema (2022) is particularly popular, originating in widely used Autodesk software, even though researchers have identified substantial limitations with it from a practical perspective (Alshehri et al, 2019). McCarty and Rysanek (2019) proposed extending this to an XML file (DEPSxml) that would include energy and POE data. However, as of the time of writing, there appear to be no further developments on it, and no actual applications in real-world projects to gauge its applicability. An alternative approach has been developed in the BuildingSync XML schema (2022), which aims to systematize the energy audits undertaken in the US under the local regulations. On a more conceptual level, the Building Energy Data Exchange Specification (BEDES, 2022) has attempted to provide a common dictionary of terms for building characteristics and performance. While these approaches have merit for their specific applications, they fail on general DC principles. BuildingSync is constructed around the specific use case (energy audits); gbXML/DEPSxml are software-driven and their connection with building geometry generates substantial ontological complexity and does not allow for porting and encapsulation; BEDES is useful as a frame of reference for physical attributes, but includes substantial semantic overheads for specific assessment programmes, with negative cost-benefit results. Thus, substantial potential exists for an approach that focuses on POE data as individual properties of an encapsulated framework, as opposed to sub-elements of a specific application.

The work presented in this section started with a two-part Literature Review. Firstly, the fundamental literature of Digital Curation was reviewed and the main DC models presented. Secondly, POE literature of the past five years was reviewed, in order to identify the types of POE data that researchers currently use. The abstracts of a total of 429 papers were read, and narrowed down to 40 that were considered relevant: 37 research papers, 2 literature reviews, and 1 dealing with building monitoring ontology.

Following standard practice in Digital Curation research, a questionnaire was sent to the researchers of these papers: 30 questionnaires were sent out and 21 responses were received. The questionnaire investigated the current DC practices of POE researchers and the impact they considered various aspects of POE had on the value proposition of this research.

The results of the literature review and the questionnaire were used to identify the requirements of a suitable DC framework. The key objectives of the framework were for it to be lightweight, generic, extensible, human-readable, machine-readable, self-contained, software and data structure agnostic.

The framework was developed in XML, while linkages to BIM were also explored. Further information can be found in Patlakas, Musso, and Larkham (2021).

6. Contribution to Knowledge

The work presented here is a multi-disciplinary, independent, and original contribution to knowledge in the AEC field. This contribution is on three levels: reconceptualising the relationships between users and buildings, by thinking of buildings as other consumer products; demonstrating the feasibility and potential benefits of communicating POE data to non-expert users, via a specialised app; and developing a Digital Curation framework for the storage, archiving, management, recovery, and utilisation of POE data.

6.1 Building as a Product

The work presented here is supported by the conceptualisation of the Building as a Product, and the Building User as an economic Principal. Traditionally, AEC has conceptualised the Built Environment as an object of study by specialists, typically designers (including engineers), developers, and regulators. As such, Building Performance is typically considered a subject of interest for specialists only, with hard regulation set by the State being the main mechanism for improving Building Performance.

This work inverts this paradigm by reconceptualising the relationship of the user to the Built Environment. The Building (and, by extension, Infrastructure) User is considered a Principal who, directly or indirectly, commissions an Agent to deliver a suitable Built Environment element to them. The lack of information the User has on the building performance is considered a typical case of Asymmetric Information between Principal and Agent. Section 3 presented an exposition of this problem, based on fundamental Economics theory. It considered the impact of Disclosure, Transparency, Regulation, and Signalling, as mechanisms to alleviate this information asymmetry. In addition, it discussed Brand Equity as an incentive for Agents that deliver Built Environment products (designers, engineers, developers, managers), to improve Building Performance.

While a (very limited) number of authors have discussed asymmetric information in buildings before, to the author's knowledge, this is the first conceptualisation of the Built Environment in such terms, taking into account all the mechanisms stated above. The originality of this is important: the Built Environment is arguably the only major area of human industry where the user is expected to be a passive recipient, the silent assumption being that either the user is unable to appreciate the technical nuances, or these nuances are too difficult to measure and/or communicate.

What is more, the potential of this paradigm is difficult to be overstated. Reconceptualising the relationship between building user and building producers in Principal-Agent terms and associated concepts opens a wide array of possibilities, with substantial implications for research, industry, and society. Contrary to popular belief, Economics theory, while hardly flawless, is concerned with addressing market failures, as opposed to creating them (the theory itself is politically agnostic). The current situation in the Built Environment is an ostensibly free market, which is highly distorted and is in a state of permanent market failure. The conceptualisation of the user as a Principal who is lacking suitable information as a partial cause for this market failure is important; it can also generate momentum towards empowering the user and providing them with appropriate information. This can be achieved via mass scale building monitoring, effectively rendering Post-Occupancy Evaluation a permanent aspect of building operations. Moreover, the outputs of this permanently running POE would need to be in a format that would allow laypeople to derive key insights. Combined with the concept of Brand Equity for developers, this has the potential to revolutionise the way the Built Environment is designed, valued, and operated.

From a technical perspective, mass building monitoring and permanent POE has the potential to improve vastly our scientific and engineering understanding of Building Performance. The potential of Machine & Deep Learning and Artificial Intelligence in making sense of Big Data has been proven in a number of fields: releasing this potential in the Built Environment can have particularly beneficial effects, and a major impact on the future design and operation of buildings and infrastructure.

Finally, from a societal perspective, beyond the market failures discussed above, improved building performance can be a major driver to reducing the environmental impact of the Built Environment, which is a major factor on humanity's effect on the planet. As the Climate Emergency is highly likely to be the key challenge of this century, the importance of this cannot be overestimated.

6.2 Feasibility and Benefits of Communicating POE data to non-experts

The conceptualisation described above, while promising, would be of little use if the implicit assumption made today was correct, and POE data was indeed impossible to communicate effectively and thus only useful to experts. The work presented here demonstrated that employing alternative methods of communication, such 3D & 4D in-context interactive visualisation, can have a beneficial impact in allowing non-experts to understand POE data. In addition, the work demonstrated that developing software applications tailored to such data is feasible with minimal overheads: the core application was developed by two individuals, a software developer and the author, in the space of six months, with additional bug fixes and development work by the author over a period of two years, on a part-time basis. The total software development budget of the project was below £20k, a minimal amount which further highlights the potential of developing such applications if taken up by the commercial software industry.

The originality of the work remains important. A recent literature review of POE state-of-the-art found only a handful of projects engaging in visualisation of all types of POE data, with EnViz being the only software application visualising environmental POE data in a 3D/4D context (Li, Froese, and Brager 2018). It is also important that the same review found no other research engaging with trying to communicate POE data to non-expert building users. Other literature reviews on POE and building monitoring conducted over the past 10 years show the same picture (Guerra-Santin and Tweed 2015; Olivia and Christopher 2015; Vásquez-Hernández and Restrepo Álvarez 2017).

Moreover, the research presented here is the first that tries to assess the effect of different ways of presenting POE data can have on understanding, comprehension, and engagement. This is an important contribution to knowledge: if Post-Occupancy Evaluation is going to be expanded and become a permanent fixture of the Built Environment, identifying the optimal way to communicate this information is of paramount importance.

6.3 Digital Curation for POE Data

If POE is expanded to a mass scale, this will lead to an exponential growth of the collected data. So far, as POE studies are conducted largely in an ad hoc manner on individual projects, there has been no engagement with the management of the digital assets that mass collection of POE data will generate. The final element of this work is the first, to the author's knowledge, development of a Digital Curation (DC) framework for POE data. It is also the first attempt to query POE researchers on their digital asset retention and management strategies (or lack of them), as well as the impact the data collection has on the POE value proposition. Simultaneously, it is the first work to try to integrate POE data in the current state-of-the-art in Digital Curation and the associated theoretical frameworks.

The contribution to knowledge is substantial. The identification of the state-of-the-art in digital asset management in the POE field is important in order to understand the issues faced by POE researchers and how the field can go forward. The contextualisation of POE data within the Digital Curation theoretical frameworks allows POE experts to benefit from the experience of researchers and practitioners from other disciplines with substantial experience in handling vast amounts of data. Finally, the development of a Digital Curation framework demonstrates that the storage, archiving, management, recovery, and utilisation of Big POE Data is both feasible and can be achieved with relatively low overheads in time and cost. It is an important first step towards large-scale, systematic Digital Curation practices for POE data.

6.4 Position in the current research context

Despite the presented work covering a period of more than 10 years, it is firmly positioned in the current research context. From a technical perspective, were EnViz to be developed today, it would likely be implemented within a BIM-compatible application, adhering to open protocols. In recent years, a shift has been observed within BIM standards such as openBIM (BuildingSMART, 2022), focusing equally on project delivery and asset management throughout the building lifecycle, for which POE is a major element.

The work is even more relevant to what is emerging as the new dominant concept in AEC research, that of the Digital Twin (DT) (Boje et al, 2020). A recent review by Opoku et al (2022) identified some of this work's key themes, such as real-time data visualisation, enhanced decision making, enhanced environmental monitoring, enhanced energy management, and continuous monitoring of assets, as key drivers for the adoption of DT.

It is also notable that a full, real-time integration of, and comparison between, simulated and actual performance remains elusive. Recent work by Agostinelli et al (2021), for example, conceptualises the building as a cyber-physical system in order to improve energy management, but the monitoring aspect focuses on energy consumption, not on actual environmental conditions within the monitored spaces, suggesting the relevance of the work presented here is important for the development of the Digital Twin concept.

Another important element is the conceptualisation of POE data as an encapsulated, lightweight, and independent data structure, as opposed to a segment of an all-encompassing data schema. The tendency towards the latter was an inherent weakness of schemas such as the Industry Foundation Classes (IFC). Instead, the identification of a framework-agnostic approach, such as the one presented in Patlakas, Musso, and Larkham (2021), is consistent with LinkedData principles (W3C, 2022), utilisable in the semantic web. Achieving the Digital Twin paradigm would require exactly this linked data approach (Boje et al, 2020).

7. Conclusion and Directions for the Future

This document, and the accompanying published papers, describe a body of work that aimed to develop a framework for the collection, processing, presentation, and archiving of Post-Occupancy Evaluation (POE) data so as to allow non-expert users to make effective use of them, thus acting as a Decision Support System (DSS) and ultimately contributing to the enhancement of building design and performance. This was accomplished via four objectives described in Section 2, which draw from a wide range of disciplines, combining Economics, Software Development, Human-Computer Interaction, Gamification, and Digital Curation, in order to present a comprehensive and cohesive whole. The range of disciplines highlights also the complexity of the undertaking. Building Monitoring and Post-Occupancy Evaluation might appear a relatively narrow technical challenge; in reality, it is a complex multi-disciplinary undertaking, with important implications for research, industry, and society. At the same time, it is a major opportunity to address some of the greatest challenges of contemporary Built Environment: market failures; user satisfaction, involvement, and engagement; building performance; and environmental impact.

Overall, the work presented here has an important corollary. It suggests that it is both feasible and beneficial to expand Post-Occupancy Evaluation to a mass scale, monitoring buildings comprehensively, constantly, and permanently. Moreover, the true potential of mass-scale POE will be achieved by looking at the building scale, but at the neighbourhood, town/city, country, and international scale. The technical challenges of such an undertaking might be considerable, but are certainly not insurmountable. The produced data can be collected, stored, and organised with suitable Digital Curation strategies, following the paradigm established by other disciplines. This data can also be communicated to the public via appropriate digital analysis and visualisation platforms. Collecting this information is not outside the capacity of what is considered the state-of-the-art in other fields. Analysing substantial amounts of data, and gaining valuable insights, might be an arduous process. However, the contemporary revolution in Machine Learning and Artificial Intelligence in other fields suggests that this is also feasible – and valuable.

A perhaps more challenging paradigm shift, however, is required on the societal and economic side. For centuries, buildings and infrastructure have been considered outside the mainstream market mechanisms, which revolve primarily around the value of the land. Viewed dispassionately, and without preconceptions, this can appear peculiar for what are arguably the most technically complex and certainly most widely available products: buildings. The reconceptualization of building as a product, whose users can assess its performance, assign brand equity to its designers and builders, and make informed market decisions can lead to a radical overhaul of our expectations from, and relationship with, buildings.

The limitations of the work presented here are primarily a reflection of its overarching nature. The approach taken is a "big picture" one, identifying key steps that demonstrate the objectives of the research agenda are addressed. Inevitably, this means that these individual steps are not as in-depth as in highly specialised theses. This has been clearly stated in Section 5, as well as in the published papers, where appropriate.

There are two main directions for further research that follow logically from the work presented here. The first is the technical one. The work has demonstrated the potential of digital visualisation of POE data in contemporary projects, which are of a small scale, as is typical. The next step is to try to demonstrate this in an intermediate scale, e.g. at a complex of at least 100 fully monitored buildings. On the digital side, any software or platform should aim not only to visualise the collected data, but also to proceed to analysing them, drawing inferences, and suggesting connections: effectively a more advanced Decision Support System that does not simply report data, but analyses it using state-of-the-art AI techniques. Naturally, a more advanced system also brings the potential for substantial research on Human-Computer Interaction, building on what has been presented here.

The second direction is the socio-economic one. The conceptualisation put forward in Section 3 lays the fundamentals of an Economics model of the relationship between the User and the Building. Expanding this to an actual model on par with the state-of-the-art in Economic theory is a major intellectual undertaking, but one that can be both rewarding and have a major impact in research and society.

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