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Closing the performance gap in the delivery of zero-carbon homes: A collaborative approach

Andrew Dainty¹, Derek Thomson¹ and Scott Fernie¹

1. School of Civil and Building Engineering, Loughborough University, UK

ABSTRACT

The UK government has mandated that all new homes achieve ‘zero-carbon’ status by 2016. This policy introduces challenging targets for reducing carbon consumption and emissions. Achieving these standards requires, among other technologies, advanced fabric solutions and high quality workmanship to provide air tightness, high levels of thermal insulation, micro-generation technologies, and feedback of building performance to occupiers. Although such technologies have been proven under controlled conditions and in small commercial developments, consistently delivering zero-carbon housing at scale presents considerable technical and institutional challenges. Evidence from initial, small-scale UK schemes suggests that design intentions are difficult to achieve in practice. Novel approaches must now be developed to close the gap between predicted and as-built performance of eco-homes. This paper reports a novel collaborative research project which is developing process and governance solutions to address this performance gap. An action-learning methodology is presented that uses process mapping to model, evaluate and re-engineer design, construction and commissioning processes around the delivery of c. 400 homes in the UK’s first ‘eco-town’ development. The approach integrates expertise from the entire construction supply chain around the achievement of producing zero-carbon homes at scale that reliably fulfil design intentions.

Keywords: eco-town, zero-carbon homes, performance, collaboration

1. INTRODUCTION

As one of the largest contributors to carbon emissions, it is now widely accepted that buildings provide a substantial context in which to achieve broader objectives to reduce carbon emissions (see Sorrell 2003, Ürge-Vorsatz and Novikova 2008, Sodagar and Fieldson 2008, Oreszczyn and Lowe 2010). This is reflected in the need to attend to several aspects of the construction process, not least in relation to low-energy housing performance (Oreszczyn and Lowe 2010). The UK faces unprecedented economic and technological challenges in addressing the energy performance of its housing stock. Its aged, thermally inefficient pre- and post-war housing requires upgrading and refurbishment (Dowson et al. 2012, Killip 2011). For the new build sector, the challenge comes from the suppressed demand of the financial crisis and the pressure on house builders, traditionally seen as slow to innovate (Ball 1998, Barlow 1999), to design and construct better performing homes to meet increasingly stringent performance standards. In recent years the performance imperative has been enforced by changes to the Building Regulations (Lowe and Oreszczyn 2008) and particularly the energy section of Part L requirements, which now stipulate a Target Emissions Rate (TER). Beyond this, pressure to meet the targets of the Code for Sustainable Homes (CLG 2008) also exist, which are themselves being mandated through further Part L revisions as a ‘zero-carbon’ target for 2016 (Osmani and O’Reilly 2009).

The need to reduce the carbon emissions of houses is set against a backdrop of a significant downturn in the sector’s output, despite on-going housing shortages (Office for National Statistics 2010). Current annual production stands at around 120,000 units per annum (see Gorse et al 2012): an inadequate capacity given the apparent housing shortage (Hall 2012).

The sector must innovate to meet these demand forecasts, especially if new homes are to remain affordable to the first time buyers that are essential for market fluidity. It must also address dissatisfaction with quality and service among new house buyers (Ozaki 2003). Despite these needs, there is growing evidence to suggest that buildings in many countries fail to satisfy their respective regulations (Pan and Garmston 2012), and that a ‘performance gap’ is opening up between the specified and actual performance of new homes specifically (Bell et al. 2010, Gorse et al. 2012a, 2012b). Such problems have been variously attributed to issues with procurement, complexity, design, product substitution and construction process issues (Bell et al. 2010). Meeting the energy reduction and carbon emission targets of the Code for Sustainable Homes (CLG 2008) is, therefore, particularly problematic given the fragmented nature of the industry and demands on house builders to produce high quality homes and to do so at scale.

In light of these drivers, UK Government has recently challenged house builders to develop systems and techniques to address zero-carbon targets under its Technology Strategy Board collaborative research programme (TSB 2012). This paper reports on a new four-year research project funded under this programme which aims to address the performance gap in eco-home (i.e. homes intended to satisfy zero-carbon intent) construction. The study will implement a novel, action-learning approach founded on sustained collaboration between participants in what is probably the UK’s most significant zero-carbon development to date: the NW Bicester eco-town. The associated research will develop innovative build process solutions using iterative learning and collaboration in the first scheme phase (c. 400 units).

This paper is structured as follows. First, the carbon context of the UK housing sector is explained, particularly in relation to the Code for Sustainable Homes which has become the *de facto* standard for new home performance in the UK given the 2016 zero-carbon target. Next, the challenges in achieving zero-carbon houses are outlined, especially in relation to fabric performance. This section explores a broad range of influences on performance concerns, explaining how they combine to present a problematic landscape for zero-carbon house building. The paper then outlines an innovative collaborative approach to ensuring zero-carbon performance and the production of a novel toolkit – BEPIT – to provide benchmarks and performance tools for future zero-carbon developments.

2. THE DRIVE FOR ZERO-CARBON HOUSING IN THE UK & THE CODE FOR SUSTAINABLE HOMES

There is no doubt that the drive for low and zero-carbon housing has become increasingly prominent in the UK over the past 10-15 years. The late 1990s in particular saw the onset of environmental policies aimed at lowering energy consumption in the housing sector (Lovell 2005). In 2006 the Government of the time introduced a target to reduce CO₂ emissions by 25% by 2010, by 44% by 2013 and to then achieve zero-carbon by 2016 (Greenwood 2012). This is largely in recognition of domestic housing accounting for over a quarter of the country’s total energy consumption (BERR 2007), and some 27% of the total carbon emissions (DTI 2003). Although business drivers and cultural issues have played their role (Osmani and O’Reilly 2009), regulation has undoubtedly been the most profound influence on the low carbon housing agenda in recent years.

Greenwood (2012) charts the policy transition towards low carbon homes, including policy around the reduction of CO₂ emissions within the Building Regulations energy section (Part L), the Standard Assessment Procedure (SAP), and the energy and water sections of the Code for Sustainable Homes. The Building Regulations provide a Target Emissions Rate (TER) based on a notional building archetype. The estimated performance of the design of buildings must be equal to or better than this standard. The Code for Sustainable Homes (CLG 2008), on the other hand, is an assessment method for evaluating new home performance against a flexible framework of carbon measures. By 2016, all new houses will have to achieve the ‘zero-carbon’ standard defined by the code (Heffernan et al. 2012). The definition of what this means in practice has been subject to revision since the introduction of the code, partly because of the difficulties of delivering against such targets.

Originally, the Code for Sustainable homes stipulated that the zero-carbon definition encompassed both regulated (energy used for heating, cooling, hot water etc.) and unregulated energy (which includes appliances), but this was later dropped in favour of including regulated energy only given the difficulties of meeting such targets (Heffernan et al. 2012). The Code covers nine aspects of sustainable design including Energy and CO₂ Emissions, Water, Materials, Surface Water Run-off, Waste, Pollution, Health and Well-being, Management and Ecology (CLG 2010). One of the key features of the Code is that it represents a flexible assessment framework. As such, aside from a set of minimum requirements, developers can choose which aspects to implement to obtain ‘credits;’ the more of which a house accumulates, the higher its rating under the code. The achievement of Level 6 is considered by the Code to be a ‘zero-carbon’ home, but this can be met in a number of different ways, including the offsetting of some of the requirement against ‘Allowable Solutions’, or methods of offsetting carbon which are either local to the site, nearby, or off-site (see Zero-Carbon Hub 2011).

The transition to the low and zero-carbon standards enshrined within the Code for Sustainable Homes demands a radical rethink of the ways in which the house building sector operates, especially in relation to fabric technologies. The achievement of the highest levels of the Code – Levels 5 and 6 – demands the novel combination of technologies and techniques. As will be explored below, realising these standards is far from simple given the rapid design transition and new construction techniques required.

3. CHALLENGES IN MAINSTREAMING ZERO-CARBON INTO THE HOUSEBUILDING SECTOR

There is growing acknowledgement of the difficulties of ensuring the performance of zero-carbon homes against their design specifications, especially in relation to thermal performance. Closing the ‘performance gap’ has become the focus of considerable research attention (Bell et al. 2010, Gorse et al. 2012) and the subject of a major government-sponsored research programme (TSB 2012). Given the complex socio-technical context of the industry, embedding new processes and technologies is inherently problematic (Murray and Langford 2003). Thus, it is not simply a focus upon innovations that is required, but also an examination of the existing systems and structures in which innovations to achieve zero-carbon homes are developed and diffused. If the role of these broader contextual factors is more fully understood, then the implementation of novel approaches in high-performing low carbon buildings can be better managed. These factors are explored below.

3.1 Core technological challenges

The integration of novel technological innovations to new house construction has proven especially difficult, particularly given the need to coalesce such technologies with more traditional techniques. Recent evaluations of new houses have revealed commonly occurring concerns over design and construction processes and their resulting effects on the performance of technologies, systems and buildings (Gorse, et al. 2012a). This work has shown how poor quality workmanship, insufficient monitoring, buildability issues, poor adherence to designs, adverse consequences arising from design changes and the incorrect use and installation of technology adversely affect performance. Similarly, Pan’s (2010) exploration of influences on air tightness revealed broad technological challenges in the area of build method and dwelling type, particularly in relation to those constructed using masonry and reinforced concrete. Recent studies have also exposed failure modes in existing technology such as significant heat loss in cavity walls due to inadequate consideration of air flows (Lowe *et al.* 2007). Indeed, it is not unusual for the associated transmission heat loss to be twice that predicted (Gorse et al. 2012b).

Overcoming some of these challenges may have to engage with Slaughter’s (1993) argument that construction innovation is largely rooted in site operatives’ activities. Much of their

decision making is ad hoc, causing problem solving and innovation to remain largely uncontrolled, unrecorded and unexpected. As well as having the potential to reinforce the problems of meeting performance predictions (Gorse *et al.* 2012a), failure to recognise this makes scaling-up the reliable and affordable delivery of zero-carbon homes problematic, especially as any departures from formalised design enacted during construction cannot be easily monitored or explained. Overcoming these problems requires effective and appropriate data collection during construction. Such data are more reliable if they are collected from live sites rather than laboratory experiments and complemented with further data that describe the performance of interconnected technologies and entire build systems (see Bell *et al.* 2010). To date, such exhaustive and embedded data collection and analysis is rare, and systematic testing and learning from attempts to deliver zero-carbon homes is limited.

3.2 Management and procurement challenges

The nature of traditional commercial procurement systems and methods (for example, tendering processes) is argued to militate against investment in innovation and research and development (R&D) in the construction sector (Ball 1996, de Valence 2010). Specifically, main contractors' levels of innovation are argued to be highly dependent on the speed with which their suppliers and project supply chains can innovate (Ko and Ferrer 2007). The industry's capacity to deliver zero-carbon homes is thus argued to depend on novel forms of procurement that encourage cross-organisational collaboration and deepen interdependencies (de Valence 2010, Gambotese and Hollowell 2011, Rutten *et al.* 2009, Dulaimi *et al.* 2002). These forms largely draw upon familiar concepts such as early supplier involvement, alternative governance structures and supply chain learning. Carefully considering and revisiting these concepts in the context of zero-carbon housing is arguably fundamental to construction sector performance (Osmani and O'Reilly 2009, Lowe *et al.* 2008) and can be seen as an integral aspect of the renewed focus on supply side innovation within the sector (Wolstenholme 2009).

3.3 Skills challenges

Clearly the drivers for, and impediments against, delivering zero-carbon homes extend well beyond the technical challenges already described to include the intersecting institutional influences on the market for sustainable homes. Key amongst these concerns is the need for developing new skill sets and extending existing ones (Heffernan *et al.* 2012). However, the development of skills within the UK construction sector is deeply problematic, with the vocational, education and training system poorly positioned for reproduction of high quality skills (Chan and Dainty 2007). In addition, as Berker and Bharathi (2012) suggest, buildings are becoming more complex, creating a need for improved integration of multiple kinds of expertise. This undoubtedly places a greater pressure upon existing designers, managers and construction workers to work together more effectively to deliver zero-carbon homes; yet they lack the skills to do so (Heffernan *et al.* 2012).

3.4 Scaling challenges

In addition to the skills issues discussed above, the technical feasibility of mass producing zero-carbon homes is a concern given the very high performance standards required. Recent efforts to reduce natural resource inputs have focused on ecologically sustainable development principles and have been variously applied in so-called 'eco-home' demonstration schemes and projects (Horne and Hayles 2008). Although such demonstrators have shown that these designs can perform to very high levels of thermal efficiency, it remains to be seen whether such technologies and designs can be scaled to large development projects, especially given the attention to detail and workmanship they require. Indeed, achieving 2016 targets requires that learning from 'niche' developments is embedded, or mainstreamed, to inform the mass construction of future eco-homes (Greenwood 2012). This will likely prove difficult. For example, lessons from retrofitting insulation to buildings on a large scale and in the absence of close supervision suggest that workmanship and completeness are problematic (Dowson *et al.*

2012). Moreover, the professional skills required to oversee sustainable housing are in short supply (Heffernan et al. 2012) themselves. Skills shortages can, as has often been argued, be offset to some extent by off-site fabrication. Indeed, the Code for Sustainable Homes targets may provide objectives for reengineering construction processes in housing. However, the absence of clear goals has hitherto been a significant barrier to adoption of new working methods, technologies and systems in housing (Roy et al. 2003).

3.5 User behaviour

Realising low carbon performance predictions must also address occupier behaviours. Peuportier et al. (2013) have found sustainable housing performance to be highly sensitive to user behaviour. Modelling 'spendthrift' and 'economical' behaviour patterns, they found the heating load energy use of the former to be ten times that of the latter in an eco-home, yet only twice the latter in a traditional design. This sensitivity is compounded by Pilkington et al.'s (2011) discovery that user behaviour is highly variable and difficult to predict. When retrofitting energy performance improvements to existing UK housing stock, for example, considerable shortfall in predicted gains has been caused by occupants' "thermal comfort take-back" (Vadodaria et al. 2010, Dowson et al. 2012). Similar behavioural phenomena could emerge when eco-home technologies are scaled to the mass market.

Behavioural challenges are of particular concern because the deployment of sustainable technologies to meet zero-carbon policy targets at scale requires all homes to become eco-homes, fundamentally changing the nature of the housing supply. Given that UK market demand for eco-homes remains limited (Osmani 2009a), even if marketed by their 'green credentials', most of these homes will be occupied by users unwilling to alter their behaviours to fit the tenets of eco-home philosophy and design, as Hostetler and Noiseux (2010) observed in the US. If users do not exhibit expected patterns of home use, the influence of their behaviour over energy consumption may mask any shortfalls in carbon reduction performance caused by delivery process deficiencies. For example, Pilkington et al. (2011) found that permaculturalists occupying traditional homes have a personal ecological footprint only 62.5% that of eco-home residents who do not share these ecological values. A key challenge will therefore entail distinguishing between shortfalls caused by process deficiencies and those caused by user behaviour. This may be achieved by thorough field testing of building fabric performance prior to user occupation, although this will not provide an understanding of occupied buildings as a holistic system.

3.6 Cost challenges

Finally, but perhaps most importantly, the cost of building zero-carbon buildings must not necessitate a price premium relative to standard buildings. Indeed, the UK Government has decreed that industry must reduce the current construction costs of low carbon buildings by 10-30% to match the costs of traditional designs (Innovation and Growth Team 2010). Yet, compliance with a prescriptive code – of which mandated 'zero-carbon' performance is one – has historically increased housing costs as a consequence of an attendant improvement in quality (Muth and Wetzler 1976). The limited cost data available for eco-homes reinforces this assertion. For example, Rodrigues et al. (2012) report a 26.4% increase in construction costs when designing for compliance with Level 4 of the Code for Sustainable Homes rather than Level 3 on a recent, small UK sustainable housing development. Interestingly, they report that the Code 4 houses "are attracting a premium [market] price" (p. 206) of around 20%. Nevertheless, if the mass-market consumer indifference to green housing technologies observed in the US by Hostetler and Noiseux (2010) also emerges in the wider UK housing sector, delivery process transformation will become a prerequisite to profitability as a market premium will simply be untenable.

4. CLOSING THE PERFORMANCE GAP IN ECO-HOME DELIVERY: A COLLABORATIVE APPROACH

As the above discussion suggests, the challenge of delivering eco-homes at scale, in compliance with their design specifications, and at standard market prices poses considerable challenges. Overcoming technological and process innovation challenges will require sustained collaboration between all the parties involved including developers, designers, consultants and contractors. The process revisions required to successfully deploy eco-home technologies, and to routinely meet Levels 5 and 6 of the Code for Sustainable Homes, must depreciate traditional demarcations of design and construction expertise. Most importantly, a highly integrated delivery process will be required, supported by appropriate metrics to enable performance evaluation at all stages of the development process. This must be supported by a sustained collaborative learning environment in order to yield insights with immediate benefit for the delivery of the homes throughout the development process.

Given that the effectiveness of many new eco-home technologies is contingent on the workmanship and minute attention to detail at the work site, traditional process models – which tend to stop upon the delivery of information to site (e.g. Austin et al. 2000) or the movement of materials around the site (Ballard 2000) – have insufficient scope and resolution. An appreciation of the housing delivery process that starts with design detailing, spans the organisation of site work, and extends into the act of handling the new technologies as they are installed is required, as it is at this last stage where many defects can occur. Moreover, site operative expertise and experience must be recognised as legitimate sources of learning and insight into process completeness and accuracy. This will determine how, where and why existing processes must be revised to reduce the risks of defects, and rework and shortfalls in performance in use.

4.1 The NW Bicester Eco-Town Project

An action research project will be enacted in the NW Bicester Eco-Town development in Oxfordshire, UK. As well as being the UK's largest Code 5+ development to date, this scheme is meeting much higher eco-town standards by delivering true zero-carbon homes without using allowable solutions. The development will trial innovative low carbon technologies, build system designs and fabric technologies to offer an ideal test bed for determining how processes must be revised to realise innovations and ensure their performance in high volume schemes. By engaging the entire supply chain in the co-creation of innovative products and processes that demonstrably perform to specification, and which can be delivered at or below standard costs, the resulting processes should provide a model for future eco-home developments.

4.2 The BEPIT Research Programme

The research aims to develop, test and document interconnected and mutually supportive process models and measures. These tools must provide process benchmarks for the industry. The research will adopt an iterative, action learning approach where research and development activities examine, develop and trial novel products and processes. The performance of the tools and approaches developed will be continually evaluated by stage-gate reviews and subsequent co-learning processes. The following discussion outlines the steps being taken to combine its learning to develop the Bicester Eco-town Process Improvement Toolkit (BEPIT).

Modelling the building delivery processes

Focussing on the first batch of designed and delivered homes, three mapping methodologies – BPMN2 process mapping (information flows), value stream mapping (timing and sequences) and social network analysis (sources of expertise) – will continuously map initial and ongoing refinements to design, construction and procurement processes. An embedded researcher will be permanently located on the construction site to concurrently monitor activity, attend progress and project management meetings and liaise with the academic team to understand

procurement path, incentivisation schemes, project risks, supply chain configurations and installation issues. Problems occurring with elements of the design and construction, and the solutions developed to overcome them, will be systematically captured, catalogued and flagged for discussion within the collaborative meetings.

Developing solutions via ‘collaborative camps’

The modelling work will reveal technological and process challenges that must be addressed to ensure that the buildings perform to design specification. The informal learning captured during the modelling and construction phases will be brought together in a series of formal workshops known as ‘collaborative camps’. These will form a series of learning situations for the exploitation of strong weak ties (see Granovetter 1983) between actors from different communities of practice. Exploring these connections, and their differing perspectives of process, will encourage workshop participants to challenge and revise past solutions to refine and improve them for later construction phases. The collaborative camps will also provide a social setting for the free exchange of insight into the nature of problems and for the negotiation of process revisions. The full housing delivery process is too big for exhaustive consideration by these camps. Moreover, the new technologies of eco-home construction will only impact upon certain systems and situations. Thus, the camps will focus on specific process elements revealed by predictive deliberation and emergent site activity as particularly problematic pinch points for collective attention, or those which relate to design and/or construction elements which have been shown to be problematic in other eco-home schemes. The resulting stream of refinements can be instantly and continuously applied and scaled.

Evaluating build system performance

The actual, as-built performance evaluation of the technical build systems will be measured. A series of insitu tests will characterise any gap between intended and actual building performance. This will be an ongoing activity as homes are delivered so that refinements – supported by delivery process revisions – can be made. Evaluations will include coheating and air tightness tests, thermal performance surveys, zero-carbon performance evaluations, embodied carbon assessments, construction defects analyses, energy use monitoring and construction cost reviews. Post-handover monitoring of user behaviours in technology use will also take place. Evaluations will characterise performance so that, with the support of experienced site staff and design consultants, FMEA can prioritise shortfalls for response by process revisions and those revisions can be informed from both theoretical and practical viewpoints.

Developing the toolkit

A suite of exemplar tools to support as-built compliance with Level 5 (or higher) of the Code for Sustainable Homes will be developed. These will include refined process models, stage-gate review processes, key performance indicators (KPIs), procurement and governance frameworks and specifications for operating manuals (to assist with user behaviour issues). Detailed build system specifications will also be produced to guide the deployment of technologies emerging from the learning loops. These will meet environmental performance standards required, will be deliverable at cost and will be scalable to high volume schemes.

4.3 Developing a co-learning culture

Success in the above four components will require sustained co-learning between individuals and organisations that are normally separated by ingrained and contractually-defined roles and responsibilities. Villar and Albertín (2010) established that a collaborative culture of trusting relationships is a prerequisite to learning. A key role for the embedded researchers will be the nurturing of a sense of collaborative learning to build trust. This is a prerequisite to the collective construction of understanding by: taking social risks (that may expose lack of understanding); exploring conflict between individuals’ understanding; and engaging in debate to resolve such conflict (Blumenfeld et al. 1996). The mutual accountability that trust

brings to relationships can make individuals feel responsible for their peers' and their own learning (Johnson and Johnson 2009). These positive cultural traits bring socio-emotional benefit to learners (Gundeson and Moore 2008) and will be sought by the project.

Following Morris and Matthiessen (2007), a pivotal work component will nurture an appropriate climate for open collaboration to occur within a commercial project setting. To assist with spanning discipline boundaries, a learning mechanism will be developed to provide a "human action system" (Aken 2005) that recognises the "thoughts and feelings" of designers *and* site operatives as they consider the processes through which zero-carbon technologies are realised in actuality. Accounts of their experiences will be a central source of insight into required process revisions. Well-established workshop facilitation principles will promote collaborative camps as 'safe' contexts for the social construction and negotiation of common understanding (Mlecnik 2012). Recalling one of Morris and Matthiessen's (2007) success factors, workshops will adopt value management principles to promote common understanding of explicit learning goals (Liu and Leung 2002). Each stakeholder will be helped to debate conflicting perspectives using methods from participatory design traditionally found in front-end master planning (e.g. Jenkins and Forsyth 2009). Mutual accountability will be established by promoting the concept of the 'internal customer' and the need for value system alignment around process stage interfaces.

5. CONCLUSIONS

Despite the significant investment in technological innovation to meet the challenging standards of Level 5 and 6 of the Code for Sustainable Homes, building performance continues to fall short of design intent. The deployment of innovative technologies is not a panacea to achieving step-change performance improvement. Rather, new technologies create a need for concurrent rethinking of design and build processes, and a need for performance evaluation to inform continuous, cross-disciplinary learning. In this paper, we have argued that this requires a deeply collaborative approach to modelling the construction process and finding the novel technical and process solutions that will ensure the scalability of low carbon housing solutions.

As Lowe et al. (2008, 4479) suggested, such knowledge should be developed through "*a demonstration programme ... large enough to provide an exemplar development in every community, to cover all main dwelling types and to demonstrate a wide range of construction systems.*" The first phase of the NW Bicester Eco-town development has ground-breaking environmental performance ambitions and is constructing zero-carbon homes at a scale not seen before in the UK. To meet performance standards at speed, at volume, at cost and with low defects, this research is facilitating the radical rethink of the delivery processes necessary to achieve its ambitious goals. At the heart of the work lies the need to collaborate throughout the supply chain. To this end, an iterative approach based on learning mile-stoned by intensive 'collaborative camps' will bring the partners together around radical innovation challenges. If proven successful, such an approach could provide a blueprint for the mainstreaming of zero-carbon housing construction as required by current UK government policy.

6. ACKNOWLEDGEMENTS

This research is partially funded by the Technology Strategy Board under their *Rethinking the Build Process* programme. We are grateful to them for their financial support, and to our industry partners A2Dominion, BioRegional, Willmott Dixon, PRP Architects and Silver DCC, each of whom is contributing significant resource and expertise to this project.

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