Characterising the airtightness of dwellings: its improvement over time and relationship to construction techniques

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Abstract

Purpose: This paper investigates the distribution of dwelling airtightness test results for a developer, between 2007 and 2011. The changes in airtightness test results over time are discussed, and links between the airtightness test results and the construction technique investigated.

Design/methodology/approach: The statistical analysis of a dataset of airtightness test results, applying a probabilistic model of the distribution and inferring parameters using Bayesian analysis.

Findings: The inferred background distributions, those estimated to describe dwelling performance before secondary sealing, suggest an improvement in airtightness between 2008 and 2011, the mode decreases from 5.46±$0.09 m^3/m^2h$ to 4.12±$0.07 m^3/m^2h$, with a corresponding shift in practice towards a more target driven approach. The most airtight dwellings are constructed from reinforced concrete frame, followed by 'traditional' (dry lined masonry), timber frame, and lightweight steel frame.

Research limitations: This study is limited by the size of the available dataset (901 dwellings), and by the fact that the dataset contains a larger proportion of flats to houses; however, the metadata has enabled the exploration of the link between construction practices and airtightness.

Practical implications: Developers need better guidance surrounding how to meet more stringent airtightness requirements through improvements to the primary air barrier, with incentives and support to deliver changes in practice. Furthermore, if a large number of dwellings undergo secondary sealing, this may have implications for the long term efficiency of the dwelling stock.

Originality/value: This analysis investigates two issues that have not previously been studied on a significant number of dwellings: the changes to the distribution of airtightness results over time and the link between construction methods and airtightness.

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1. Introduction

Under the *Climate Change Act* (2008), the UK faces the stringent requirement of an 80% CO_2 reduction from 1990 levels by 2050. Heating and cooling are responsible for approximately 40% of buildings emissions, which are up to a third of total UK emissions (International Energy Agency (IEA) 1998, 2014). Improvement of the building stock is an important component of many countries' plans to reduce carbon emissions (e.g. Department of Energy and Climate Change (DECC) (2011)); greater attention to building envelope performance is therefore necessary (International Energy Agency (IEA) 2014). Indeed, Jones et al. (2015) predicts that up to 5% of total UK energy demand, and 11-15% of total UK buildings energy demand is due to unplanned infiltration. Making buildings more airtight may reduce heating demand by 20% to 30% (International Energy Agency (IEA) 2013), and Lowe (2000*b*) identified airtightness as key to reducing CO_2 emissions associated with ventilation, finding that the lowest level of energy use and CO_2 emissions would be achieved in airtight dwellings with Mechanical Ventilation with Heat Recovery (MVHR) systems.

While there has long been an awareness of the need for the building envelope to be airtight, in the UK there has not been a continuous trajectory of improvement (see eg Roberts et al. (2005)). The need for airtight buildings lead Lowe (2000*a*) to argue for the introduction of testing the building envelope as a means of quality control to deliver increased airtightness. Their key assumption was that if dwellings failed to achieve their airtightness target, builders would be required to undertake remedial work to reduce air permeability. It was assumed that such remediation would be undertaken in a workmanlike fashion, so that permeability would at or close to the test level indefinitely. Lowe (2000*a*) hypothesised that the costs of such remediation would be high enough to persuade builders to adopt building practices that had a high probability of achieving the permeability target without it.

The hypothesis that dwellings failing an airtightness test would be remedied in this way is called into question by new evidence of air tightness test results from the UK (Love et al. 2017), and France (Bailly et al. 2015), suggesting that builders are instead engaging in a practice of iteratively making superficial modifications until a required air permeability is reached. This is of concern because the modifications are not made to the primary air barrier and may not be robust. Seals made with mastic are easily damaged or removed (for example when carpets are fitted), and can crack over time, or if tape is used it may be removed directly after the test occurs. The longevity of interventions to improve the efficiency of the building may therefore be affected, with potentially large impacts on the long term efficiency of the building stock.

This paper examines airtightness test results collected by a private developer between 2007 and 2011. It applies methods developed in Love et al. (2017) and Crawley et al. (n.d.): a probabilistic model of airtightness testing applied to a socio-technical process, with Bayesian parameter estimation. Applied to the developer data, this can be compared to the previously studied ATTMA data. It also facilitates an assessment of yearly changes to the distribution of airtightness test results, which can provide insight into the changing process of generating airtight buildings, and possibly the effect of new legislation on airtightness. Lastly, the effect of different construction methods on airtightness can be examined.

1.1. Building airtightness since c1900

The importance of the airtightness of the building envelope in achieving efficient buildings has long been recognised, although terminology and understanding have developed, with the Research Society of Heating and Ventilation Engineers studying leakage into the building since around 1920 (Houghton & Ingles 1927). An early, but important, work in this field is that of Houghton & Ingles (1927), who investigated air infiltration and heat loss through walls, windows, and doors. They found that air exfiltration/infiltration was a large factor in heat loss through an un-plastered wall, but that wet plastering had the effect of substantially reducing heat loss. Furthermore, they investigated the effect of ageing the plaster. It was found that up until 3-4 months the leakage increased, but after that there was no discernible change.

Lastly, the impact of different wall constructions on air infiltration was investigated. It was found that a wall with furring, and lath and plaster, performed worse than the same wall with plaster applied directly to brick. This was attributed to the more complex construction, where air flow is possible in the furring space as well as through passageways between bricks.

The airtightness of wet plastered masonry was independently confirmed by Lecompte (1987) and Lowe et al. (1994). Lecompte (1987) examined concrete block construction, pointing of joints, and quality of workmanship, and found that of the configurations investigated, a wet plastered wall provided the most satisfactory airtightness. It was also highlighted that accepted literature values used to evaluate airtightness are frequently not useful, because they are not sufficiently reliable: airtightness is considered to be constant (when in fact it is known to vary with pressure difference), joints, workmanship, and regional differences in material properties are not accounted for, and lastly the pressure differences considered are too high for practical purposes in infiltration research. This led Lecompte (1987) to recommend measurement in order to establish reliable airtightness estimates, and to recommend that in order to mitigate the effects of poor workmanship, and challenging constructions around joints, that plaster be applied directly onto brick. Lowe et al. (1994) showed that wet plastered masonry was more than two orders of magnitude more airtight than unplastered, and concluded that this was sufficiently airtight to meet any existing or foreseeable whole-building airtightness standard.

Over the period covered by these two papers, wet plastering as a finish on masonry walls was almost completely replaced in the UK by plasterboard on dabs. Some of the earliest work on the thermal performance of houses with walls finished with plasterboard on dabs was published by Rayment (1995), who measured U values in such walls several times the nominal, as a result of complex air flow paths, and Lowe et al. (1997), who had the opportunity to measure the air permeability before and after retrofit of a group of 12 houses constructed using plasterboard on dabs. This emerging understanding of the role of complex air flow paths, and the relative importance of plastering directly onto brick had no effect on the trend to dry-lined construction, which was driven by production rather than performance concerns.

Analysis of a database of pressurisation tests maintained by the BRE through the 1990s showed that rather than the airtightness of dwellings generally improving throughout the twentieth century, instead, dwellings that were built between 1980 and 1994 were about as airtight as those built at the start of the twentieth century (Stephen 1998). The relative airtightness of wet plastered masonry, compared with plasterboard on dabs is likely to go some way to explain this finding. Measurements taken by the Building Research Establishment on 32 dwellings built post 1995 suggested that they performed marginally better in terms of airtightness than the stock as a whole (Stephen 2000).

However, the range of results was still very wide, and Grigg (2004), in a study of 99 new dwellings found that although approximately two thirds of the studied dwellings achieved permeabilities of $10m^3/m^2h$ at 50Pa, there were still obvious air leakage paths, and disparities between the measured performance of different constructions. It is also notable that although Grigg (2004) discusses common leakage pathways, such as service penetrations, gaps or poor sealing around doors and windows, loft hatches, leaky ventilators, and wall to floor junctions, there is no mention of the potential plenum generated between the plasterboard sheet and the masonry in dry lined masonry wall construction. In this space, air can move freely, and all leakage pathways are effectively interconnected and can be very difficult to access (Lowe et al. 1997). It is also surprising that although several authors have suggested that wet plastering directly onto brick provided superior results in terms of airtightness, a misconception persists that ‘modern’ masonry dwellings, most often comprising of dry lined plaster wall construction, were more airtight than traditional wet plaster constructions (Roberts et al. 2005).

1.2. Airtightness and building performance

The regulatory framework and the guidance provided to prospective developers around airtightness is complex, and a short overview of the topic can be found in Love et al. (2017). The *Building Regulations* (2000) are the regulatory instrument governing most building work in the UK. These are supported by Approved Documents A to R, and Regulation 7 (for example Office of the Deputy Prime Minister (2013*b*)), which provide guidance on how to meet legislative requirements in *Building Regulations* (2000). The Approved Documents are further underpinned by the Supporting Documents, which describe standards for topics such as Gas Safety (Health and Safety Executive 2018).

Airtightness is described within Part F (Office of the Deputy Prime Minister 2013*b*) as the building envelope’s general resistance to infiltration, with planned ventilation closed. It is measured as part of a building’s energy efficiency, with guidance for domestic buildings provided in Part L (L1a Office of the Deputy Prime Minister (2013*a*) and L1b Office of the Deputy Prime Minister (2010)). Research has indicated that uncontrolled air leakage due to adventitious effects is making a substantial contribution to buildings energy use (Lowe

2000*a*), and there is much interest in improving airtightness. However, since there is a trade-off between air leakage rates and maintaining adequate ventilation, the separation of these elements of performance within the approved documents misses an opportunity to optimise for both concurrently, and has potential inadvertent consequences for Internal Air Quality (IAQ) and occupant health.

A further complicating issue in airtightness is that it might increase or decrease as an unintended consequence of construction methods or interventions. For example, engineering design work to prevent water penetrations in timber frame structures led to buildings that were very airtight (Carlsson et al. 1980). However, in development of the previously discussed dry-lined masonry cavity wall technique, attention was not paid to the prevention of gaps that could lead to air flow paths, but instead to cost reduction and available skills (Roberts et al. 2005). Hence, some developments have had the impact of improving airtightness, and some have had the opposite effect. Direct attention to airtightness while considering other aspects of design could help deliver more airtight buildings (Crawley et al. 2019).

When the data used in this analysis was collected, to achieve airtightness, and the required standard of energy efficiency, developers could either follow guidance described in the Accredited Construction Details (Department for Communities and Local Government (DCLG) 2007), or ensure that the building does not exceed 10m^3/m^{2}h at 50Pa (Love et al. 2017). However, some houses are built for social landlords or contractors who may have internal specifications for efficiency in advance of minimum requirements in Part L. Furthermore, funding to social landlords under the Affordable Homes Programme has in the past been tied to specific efficiency specifications (see for example table 12 in the Cost of building to the Code for Sustainable Homes, (Langdon 2011), withdrawn in 2015), which have more stringent efficiency specifications than those in the *Building Regulations* (2000), or in updates to Part L (Office of the Deputy Prime Minister 2013*a*).

Despite the guidance and regulatory standards, there is a performance gap between designed or modelled energy demand of buildings, and that observed in practice (Lowe & Bell (1998), Zero Carbon Hub (2013), Wingfield et al. (2009)). In particular, the performance gap of building elements has been the subject of considerable interest, with a significant differences between the expected and measured performance reported in many studies. For example, in a study of 25 new dwellings built to Part L1A 2006 standard, Johnston et al. (2015) found measured u-values to be approximately 1.6 times greater than predicted. Pelsmakers & Elwell (2017) further highlight disparities between in situ measured and modelled performance for suspended timber floors, with the case study buildings' floors' measured u-values nearly twice those modelled. Hence, heat loss from suspended timber ground floors is potentially underestimated.

Furthermore, the thermal efficiency of a building is not directly measured at the end of the building process. Instead, Standard Assessment Procedure (SAP) calculations are based on specifications for building elements, and the measured air permeability of the building is inputted into final efficiency calculations along with these design specifications, which are either as specified at design stage, or updated to reflect any changes that may have occurred during the build process (Love et al. 2017). This often amounts to the implicit assumption that buildings are built to expected standards, and elements always deliver exactly as expected (Zero Carbon Hub 2013). However, these assumptions are contradicted by Zero Carbon Hub (2013), and Wingfield et al. (2009), who demonstrated a performance gap in a substantial action research project. Wingfield et al. (2009) suggest several possible avenues for improvement, highlighting the importance of on-site practices including communication, feedback, and ensuring the correct building components are installed. They also propose greater scrutiny, including testing and monitoring throughout the building process, because although buildings sometimes met design targets, and performed as expected, there was an overall substantial performance gap between design expectations and measured results.

1.3. Airtightness test results

Love et al. (2017) and Crawley et al. (n.d.) have developed a new approach to analysing airtightness test data. Since airtightness is the only measured quantity at the end of a building process, it is an important measure of quality control. A first analysis of regulatory test results in the UK has been performed by Love et al. (2017), revealing an unexpected distribution of results. Love et al. (2017) suggested that the airtightness, or permeability, distribution of the buildings recorded in the ATTMA dataset does not accurately reflect the true permeability of the new dwelling stock, because airtightness test results may include the effect of temporary sealing in measurement of the building permeability. Some of these measures (described in Love et al. (2017)) are in breach of regulations, and do not improve the true permeability of the building if removed after the test. Measures such as mastic, while allowed under ATTMA (2016) and *Building Regulations* (2000), may not retain the seal as long as measures taken to improve the primary air barrier, which could result in building envelope performance degrading more quickly than it otherwise might. A similar distribution is observed by Bailly et al. (2015), who examine 65,000 test results recorded in the French national airtightness database between 2009 and 2015. Bailly et al. (2015) also hypothesise that the cause of the unusual shape of the distribution is the process of gaps being superficially sealed with mastic at the end of the build process, in order to meet design targets.

If the measures taken to improve the airtightness of a building at the point of testing are not long lasting, it is instructive to establish the ‘true’ permeability distribution of the dwellings upon completion, associated with primary measures for airtightness. Crawley et al. (n.d.) introduces a model that is capable of separating the effect of these secondary interventions from the likely ‘true’ permeability distribution (briefly described in section 2.2). Using this model, and additional metadata associated with a new data set, the likely true permeability of these properties may be estimated. Next, given the evidence described in section 1.1, the data is disaggregated to examine both whether different construction methods are associated with different permeability distributions, but also to establish whether there are any changes in the distribution over time, and in particular, whether design targets become more important.

2. Methods

This paper makes use of the model developed in Crawley et al. (n.d.) and Love et al. (2017) to analyse a new airtightness data set and compare it to the results for the Air Tightness Testing and Measurement Association (ATTMA) data set studied by Crawley et al. (n.d.) and Love et al. (2017). The ATTMA datset comprises approximately 144,000 airtightness test results collected between August 2015 and September 2016 (Crawley et al. n.d., Love et al. 2017). Metadata describing the construction type of tested dwellings is used to investigate the link between construction methods and airtightness, and its extent over five years is used to investigate the evolution of airtightness. The following section describes the data and approach taken in the analysis.

2.1. Data

The data used in this analysis comes from a private developer, henceforth termed ‘Developer data’, collected between 2007 and 2011. It consists of 901 airtightness test results and associated metadata. The metadata includes the year of construction, construction method, ventilation system, and whether the dwelling is a house or a flat. Duplicate results, and data that could identify the dwellings were removed prior to researcher access. The range of results is reasonable (all between 0 and $14\text{m}^3/\text{m}^2\text{h}$, and only two below $2\text{m}^3/\text{m}^2\text{h}$), hence none have been removed on the basis of unlikely permeabilities. Not all of the metadata is available for every dwelling, for example, there are 612 dwellings listed as flats, and 77 as houses, (689 total listings in this column). This means not all permeability measurements can be definitively associated with a dwelling type, however, even if all the remaining measurements were associated with houses, there would still be more flats than the national average, which including London is 33% and excluding London is 26% (National House-Building Council 2017). This suggests that the data set will over represent flats, which is a potential source of bias. Vinha et al. (2015), in a detailed study of 170 single-family detached houses, and 56 apartments in Finland, indicated that flats tended to be more airtight than single unit family homes, potentially due to the different construction methods common to each dwelling type, such as timber frame, or precast concrete block. However, the sample groups were not necessarily representative of the Finnish housing stock, and there were some discrepancies in selection criteria as well as the houses being largely located in a specific region of Finland. Further research is therefore needed to attribute the reason for this difference to specific variables. Finally, the fact that this is a data set taken by a single private developer means that there will be biases in the data set pertaining to the nature of the business it attends to. For example, as described in the literature review, a social house builder may have pressures on them to meet standards for airtightness that are in advance of guidance in the approved documents, whereas house builders for the speculative market may build with other factors in mind.

2.2. Model

Since the distribution of interest is the result of the aggregate effect of independent events, a probabilistic model has been developed. The model used in this analysis has been developed and described in full by Love et al. (2017) (socio-technical) and Crawley et al.

(n.d.) (mathematical). Due to the difference in size of the data sets, there are minor differences in the parameter spaces and the computational approach to estimation. Both the model and the differences are briefly described below.

The complete air permeability distribution is best described as a sum of distributions, each associated with a design target air permeability. For the ATTMA analysis, these design targets were treated as model parameters to be inferred. This is for two reasons. Firstly, some of the design targets declared in the metadata were thought to be unreliable, with some reported, altered, or decided post test, which would account for numbers such as 5.01m^3/m^{2}h. Describing them as "targets" (decided prior to the start of construction) is not necessarily accurate, so design targets were treated as parameters to be inferred. The fact that they are not well correlated with the airtightness test results also supports this proposition (see Love et al. (2017)). Second, the data set is large enough to be able to justify an inferential procedure to identify the most likely target values.

However, for the Developer data, the design targets were not inferred because the data set is small by comparison to the ATTMA dataset. The design target permeabilities reported in the metadata for the Developer data are closer to the measured permeabilities than for the ATTMA data. For this analysis therefore, the design targets are taken from the metadata and used as model inputs. Each design target (t_n) has an associated fraction of dwellings (f_n) aiming for it, which is inferred.

P_{back} (below) is the background 'as-built' permeability (perm) distribution, before any secondary sealing takes place. It is modelled as lognormal, with shape parameters μ and σ.

$$P_{back}(0 < perm) = \frac{1}{\sigma\sqrt{2\pi}perm} e^{-\frac{1}{2}(\frac{ln(perm)-\mu}{\sigma})^2} \tag{1}$$

The Intervention distribution, P_{int}, is modelled as an exponential, and is intended to characterise the process of iteratively improving and retesting the building envelope. This distribution contains those dwellings that would otherwise have had a permeability above a design target permeability, but have been moved from the background distribution to a lower point on the permeability spectrum.

$$P_{int}(0 < perm < t_n) = \lambda(1 + e^{-\lambda t_n})e^{-\lambda(t_n - perm)} \tag{2}$$

λ is the rate parameter, understood here as alluding to the scale of interventions performed. In the more complex model, justified by a much larger data set, it is modelled as linearly related to permeability, and itself has two hyper-parameters: gradient m and y-intercept c. λ is allowed to vary because it isn't obvious that the rate parameter would be the same for different design targets, with it being plausible that a higher design target may have a higher λ, due to a different type of intervention being common to higher (or lower) design targets. However, within this analysis, it was found that the data could not support the additional model complexity demanded by a linear model, hence λ is modelled here as a constant.

The adjustment distribution, P_{adj}, estimates the number of dwellings exceeding their design target permeabilities, and being 'adjusted' to a position of lower permeability. The combined effects of P_{adj} and P_{int} is to create the dramatic build up of dwellings in bins close to or on design targets reported in Love et al. (2017).

$$P_{adj}(t_n < perm) = \frac{1}{2}(1 + erf[\frac{\mu - ln(t_n)}{\sigma\sqrt{2}}]) \tag{3}$$

The distribution for each design target (t_n) is as follows:

$$P_n(0 < perm < t_n) = P_{back} + P_{adj}P_{int} \tag{4}$$

$$P_n(t_n < 0) = 0 \tag{5}$$

Since not all of the dwellings are (reliably) associated with design targets, the model also includes a 'catch all' fraction, $f_c = 1 - \sum_n f_n$. These dwellings are then modelled according to the background lognormal distribution.

The complete distribution is:

$$P(0 < perm) = \sum_{n=1}^{N} f_n P_n + f_c P_b \tag{6}$$

The model parameters are provided in Table 1.

Parameter	Description
μ, σ	background lognormal parameters (ln(m^3/m^{2}h))
λ	rate parameter (m^2/m^{3}h)
$f_1, f_2 ... f_n$	Fraction of dwellings aiming for a design target t_n
f_c	Catch all fraction of dwellings with a design target not included in t_n
t_n	Design targets, taken from the metadata associated with the ATTMA data set

TABLE 1

Model parameters

2.3. Parameter estimation

A Bayesian approach to inference is adopted, as it facilitates the analysis of complex distributions. Further, it allows model comparison, as well as a discussion of the probability that the model represents the data, without unidentified researcher bias and with specified assumptions. Parameter estimation is undertaken by examining the posterior distribution, $P(\theta|y, H)$ of the parameters θ, given the data y and model H. This is given by Bayes theorem (MacKay 2005):

$$P(\theta|y, H) = \frac{P(y|\theta, H)P(\theta|H)}{P(y|H)} \tag{7}$$

The specific approach is very similar to that used for the ATTMA data, which can be found in Crawley et al. (n.d.), and further discussion of Bayesian methods can be found in MacKay (2005), Jeffreys (1948), and Sivia (2006). Discussion of Bayesian methods specifically related to Building Science can be found in Elwell et al. (2015), Biddulph et al. (2014), and Li et al. (2015).

Flat, bounded priors were chosen, which have the effect of assigning equal probability to each possible parameter value within the range, reflecting our initially limited knowledge of the model parameters. The likelihood, $P(y|\theta, H)$, is specified as a binomial distribution (below) because the data is observed as a histogram, and a binomial distribution describes discrete data on a discrete interval. It is also suitable for analysis of relatively small data sets such as the Developer Data.

$$f(x|n,p) = {}^{\mathrm{n}}C_{\mathrm{x}}p^{\mathrm{x}}(1-p)^{\mathrm{n\text{-}x}} \tag{8}$$

The Maximum A Posteriori (MAP) estimate (see MacKay (2005)) was extracted using Minuit numerical optimization software developed at CERN (James & Roos. 1975), and the region around the MAP explored using Monte Carlo Markov Chains(MCMCs). MCMCs sample a distribution, and are intended to converge at the maximum, however, where the distribution is highly complex, the parameter space is high dimensional, or where it's sharply peaked it may not converge, or converge at a local maxima (MacKay 2005). A combined approach is thus adopted, whereby Minuit is used to estimate the MAP coordinates, and the distribution is then explored in the region of the MAP using MCMC. This method mitigates the risk that Minuit had identified a local maxima, and also provides additional insights through illustrating the characteristics of the distribution in the region of the MAP. This facilitates an understanding of how well defined each parameter is, as well as indicating any correlations.

3. Results and Discussion

The results and discussion are presented concurrently, first with the complete data set presented, then the data alongside the modelled distribution with parameters estimated using Minuit. The data is then disaggregated by year of construction and construction method, and the parameters estimated for each subset. The background ('as-built') distributions are then compared. This provides an indication of whether or not construction techniques have changed over the time of the dataset, and whether different construction methods result in different background permeability distributions, whilst attempting to eliminate the effect of late stage modifications to the building envelope.

Figure 1 shows the complete data set which has a similar structure to the much larger, but still not adequately nationally representative ATTMA set (Figure 2) analysed in Love et al. (2017) and Crawley et al. (n.d.). Like the ATTMA data, there is a large peak at 5m^3/m^{2}h, and smaller ones associated with commonly declared design targets. Table 2 shows the number of dwellings declaring each of the design targets in the data set, 5 and 10m^3/m^{2}h being the most common.

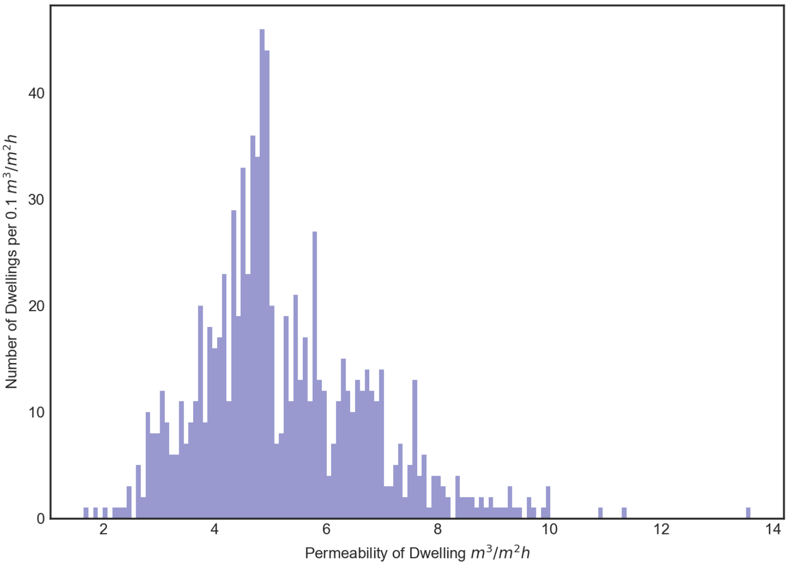

FIGURE 1: Distribution of all airtightness test results in the Developer data set between 2007 and 2011

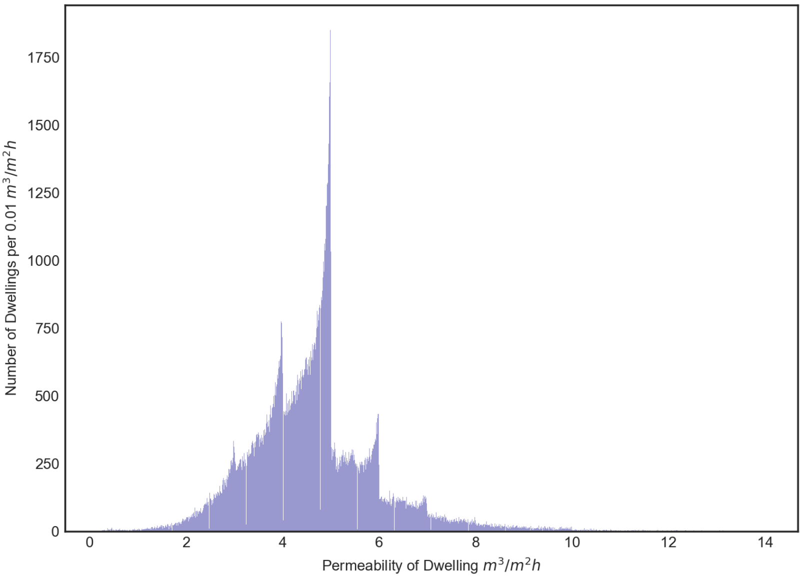

FIGURE 2: Distribution of all airtightness test results in the ATTMA data set between August 2015 and December 2016. Note the much smaller bin width, which is facilitated by the much larger data set.

Design Target (m^3/m^2h)	Number of dwellings declaring it
5.0	283
10.0	266
7.0	103
8.0	94
6.0	24
4.0	21
3.0	6

TABLE 2
Design targets provided by the developer

Comparing Figure 1, and Table 2, whilst there are noticeable increases in the number of test results just below targets at 3, 4, 5, 6, and 7 $m^3/m^2h)$, this is not the case for dwellings with a design target of 10 $m^3/m^2h)$. This is likely due to builders declaring the maximum allowed permeability ($10m^3/m^2h)$), but in general achieving better results through their standard construction practice. Since there are a relatively large number of these dwellings in this data set, this subset could be thought of as a more natural distribution than one centred around a more demanding design target.

3.1. Modelled distribution for complete data set

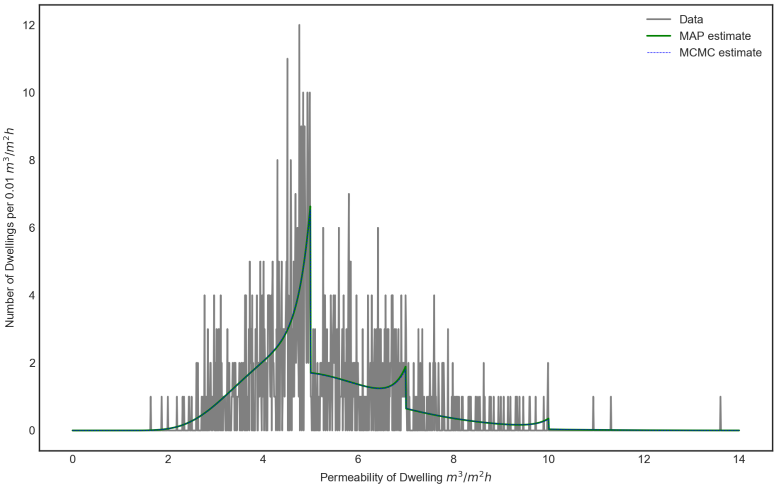

FIGURE 3: The Developer Data shown with the distribution as modelled by Minuit and MCMC. The modelled distribution using parameters estimated from MCMC is a very close match to the Minuit estimate, hence are very difficult to distinguish.

The distribution with parameters estimated by MAP and Minuit is shown in Figure

Parameter	MAP estimate	error	unit
μ	1.67	0.02	$ln(m^3/m^2h)$
σ	0.32	0.02	$ln(m^3/m^2h)$
λ	3.6	0.8	m^2h/m^3

TABLE 3

MAP estimates for the background and the intervention distribution λ, σ, μ

3. Care was taken to avoid overfitting, and to ensure that the data is able to support each parameter in the model. Fitting the distribution using all available design targets did not produce reliable results, with large correlations between parameters indicating that either there was not enough data to distinguish between them, or that the parameters did not exist. Furthermore, MAP estimates, and the distributions modelled by MCMC did not consistently agree on values for the fraction of dwellings at specific design targets (f_n) above three design targets. Hence, it was decided to fit the model with three design targets, which accounts for approximately 70% of the data. This generated the fit shown in Figure 3. It can be seen that the dramatic peak at $5m^3/m^2h$ is present, as well as smaller peaks associated with $7m^3/m^2h$ and $10m^3/m^2h$. The fact that the scale of these f_ns agree with the data supports the model. MCMC and MAP estimates agree precisely, and μ and σ are well defined. λ has a large error associated with it, because the adjustment distribution does not have a lot of data associated with it as a relatively low proportion of dwellings receive interventions. With more data, it is possible that more design targets with associated peaks would be justified.

Table 3 shows the background lognormal parameters, μ and σ, which gives a mode of $4.80{\pm}0.04m^3/m^2h$. These are reasonably close to those of the ATTMA set (μ = $1.60{\pm}0.00\, ln(m^3/m^2h)$, and $\sigma = 0.35{\pm}0.00ln(m^3/m^2h)$), with mode $4.38{\pm}0.01m^3/m^2h$ (Crawley et al. 2019). This indicates that the dwellings in the ATTMA data set perform slightly better overall than the developer data set; the Developer data is taken in the years preceding the ATTMA data. λ is not easily comparable between the different data sets due to the application of a constant λ for this analysis, compared to a linear relationship in previous work.

3.2. Adjustment distribution

Table 4 shows the design targets, with the MAP estimated fractions of dwellings aiming for them (f_n). While the statistical errors are large, due to the size of the data set, the estimated values are close to the metadata values. Table 4 shows the proportion of dwellings that are estimated to have had an intervention after initial airtightness testing to achieve their design target; a total of 18% of dwellings associated with the three most common design targets are affected. Crawley et al. (n.d.) found this proportion to be 39% of dwellings aiming for the most common design targets within the ATTMA data set. Compared with the ATTMA data, this is a strikingly low figure and it is evident from Table 4 that the majority of these dwellings are associated with a target of $5m^3/m^2h$. The smaller proportion of dwelling associated with the adjustment distribution for the

Developer data compared to the ATTMA data explains why the peaks are not so sharp in the developer data set, and why the background lognormal distribution is more visible in figure 3 than that illustrated in Crawley et al. (n.d.). This suggests that builders in the Developer data have not been as driven by airtightness design targets as those in the ATTMA data set, which could be due to the effect of the legislative framework not being as strong between 2007 and 2011, largely before airtightness testing requirements were as much as a focus as when the ATTMA data was collected in 2015-2016. While it became mandatory to conduct airtightness tests on a proportion of dwellings in a development in 2006 (Love et al. 2017), it was not until 2013 that it was suggested in Part L that buildings aim for a permeability of $5m^3/m^2h$ as a means to achieve efficiency requirements.

Design target	% dwellings declaring it	MAP estimated f_n (%)	Adjusted %	% of all dwellings adjusted
5	31	24±3	57	14
7	11	17±4	19	3
10	30	36±11	2.2	1
Total:	72%	77%		18%

TABLE 4
Design targets and percentage of dwellings aiming for them, alongside MAP estimates for proportion of dwellings aiming for each design target

3.3. *Evidence for an evolving distribution*

Analysing independent data within a Bayesian approach can be undertaken by estimating the posterior for all the data together, or updating it sequentially (Sivia 2006). However, the implicit assumption is that the process generating the data is stable in time (the terminal distribution is the same regardless of when the data is collected). However, if the process that generates the data has changed, the final observed distribution could misrepresent the current process. For example, the developer may be responding to different sets of design criteria, or since the testing system is relatively new, and there is learning involved in adapting to a new set of regulations, it is plausible that the distribution is not stable in time (as has been previously noted by Elwell et al. (2015) in the context of boiler efficiency legislation). The developer data set, having been collected over 5 years, allows interrogation of this assumption.

Figure 4 shows the raw data split by year. It is clear that in 2011 (red), there are very few permeabilities beyond 5m^3/m^{2}h, so there is a sharp peak and cut off located at 5m^3/m^{2}h. In contrast, for the preceding three years, the shape of the histogram is much more log-normal, and peaks are not so well defined.

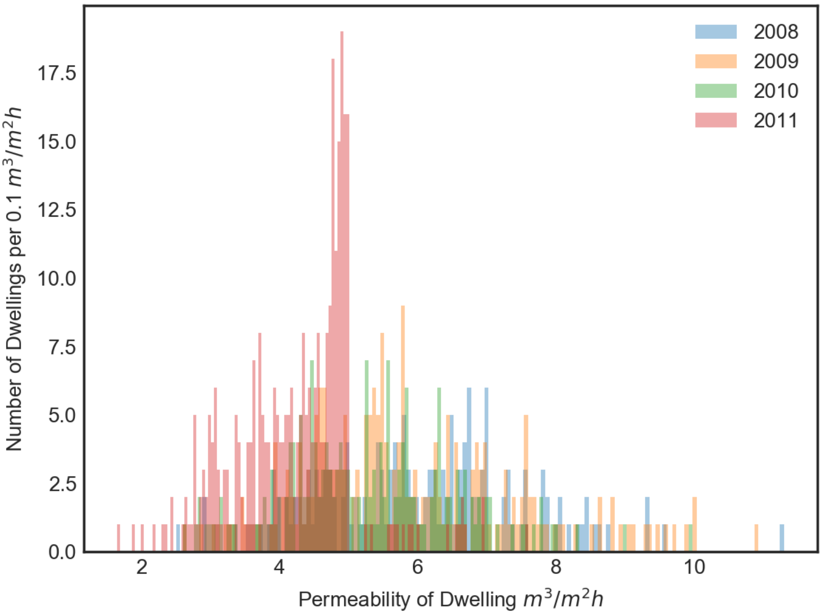

FIGURE 4: Plot showing the data set split by year

This can be seen clearly in Figures 5 and 6 which show the modelled distributions. For 2011 the most data is associated with the targets 7, 5, and 4m^3/m^{2}h, while for 2008 the targets are 10, 8 and 7m^3/m^{2}h. The effect of the target at 5m^3/m^{2}h is very visible in 2011, whereas the peak is much smaller at 7m^3/m^{2}h in 2008, relative to the background lognormal distribution. This suggests that design targets, and in particular the target at 5m^3/m^{2}h, are more significant to the developer in 2011 than in 2008.

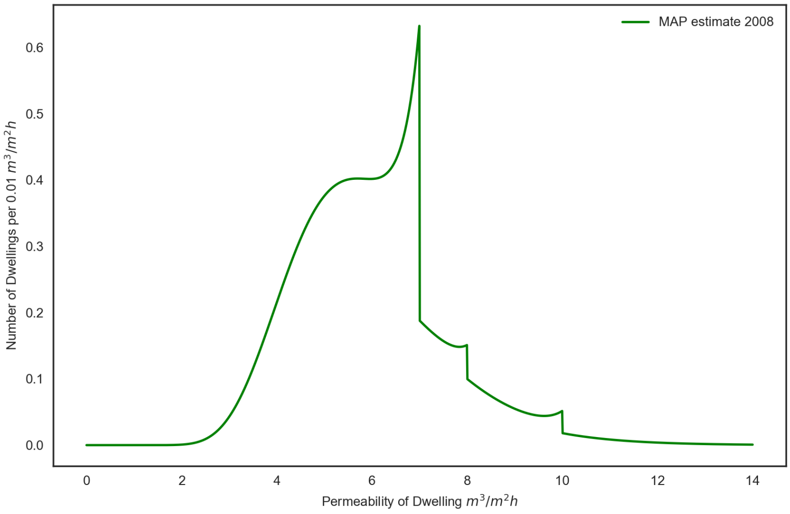

FIGURE 5: Plot showing the modelled distribution for 2008

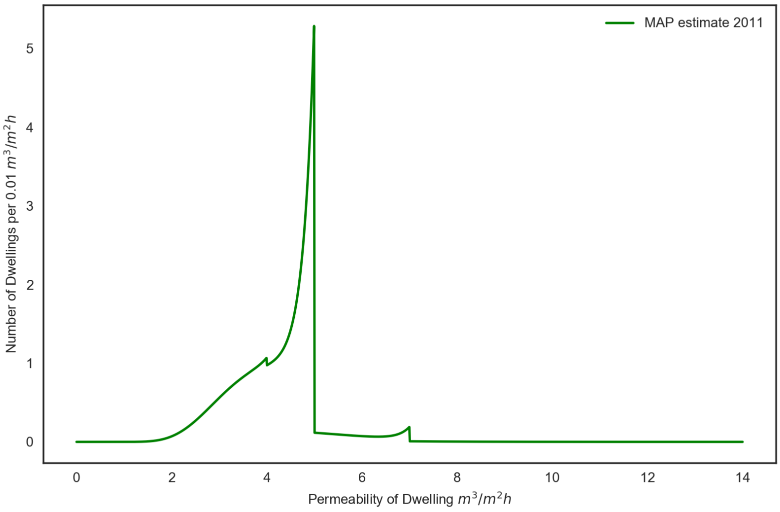

FIGURE 6: Plot showing the modelled distribution for 2011

The potential for changes to underlying construction processes is best gauged by looking at the background distributions for each year, which aims to represent the airtightness performance without the effect of adjustments to the building envelope. These can be seen in figure 7. The mode in 2008 is $5.46 \pm 0.09m^3/m^2h$, and $4.12 \pm 0.07m^3/m^2h$ in 2011. However, the adjustment distribution is much larger, meaning that a larger number of interventions are taking place in 2011.

This suggests that in 2011 the Developer was required to meet a more challenging standard of airtightness than in 2008, and was not able to meet this through improvements in the primary air barrier alone, which lead to a greater number of interventions towards the end of the building process. This finding is consistent with those of Wingfield et al. (2009), who highlighted the need for communication and more robust on-site strategies to manage the shift towards more reliable building methods.

Figure 7 shows the background permeability distributions for the years 2008-2011. It shows that the modes of the background distribution have improved from $5.46{\pm}0.09m^3/m^2h$, to $4.13{\pm}0.07m^3/m^2h$. The quantity of data associated with each year is small, so the final figures should be treated with caution, however it is clear that the airtightness performance of the developer is changing over time, with both a greater proportion of interventions occurring, and an overall better performance in 2011 compared with 2008.

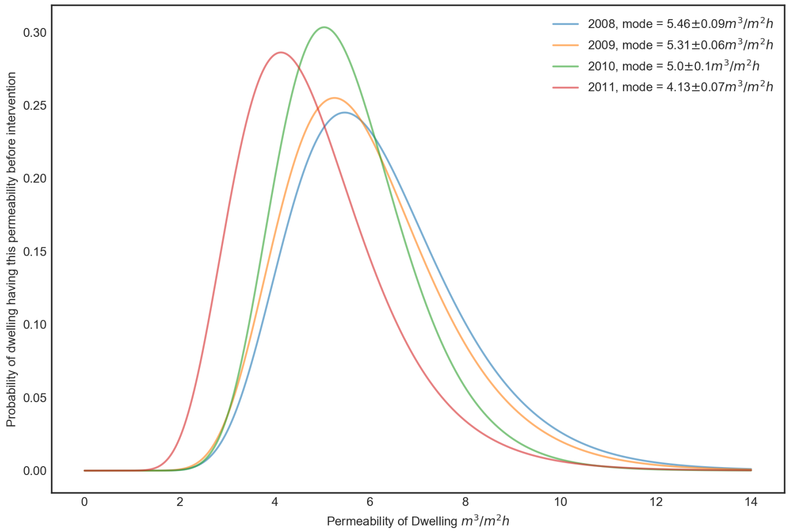

FIGURE 7: Plot showing the yearly background lognormal distributions for the Developer data set

3.4. Construction method

The relationship between construction methods and air permeability was explored. This has been previously investigated by Vinha et al. (2015), Kalamees et al. (2017), Wingfield et al. (2009) and Stephen (1998). The modelled background distribution of airtightness results for the different construction techniques in the developer data, are shown in Figure 8. Reinforced concrete and traditional construction methods perform best, both having a mode in the region of 4 and 4.4m^3/m^{2}h. It should be noted that the terminology adopted is that of the developer, who record dry lined masonry cavity wall as 'traditional', rather than wet plastered masonry.

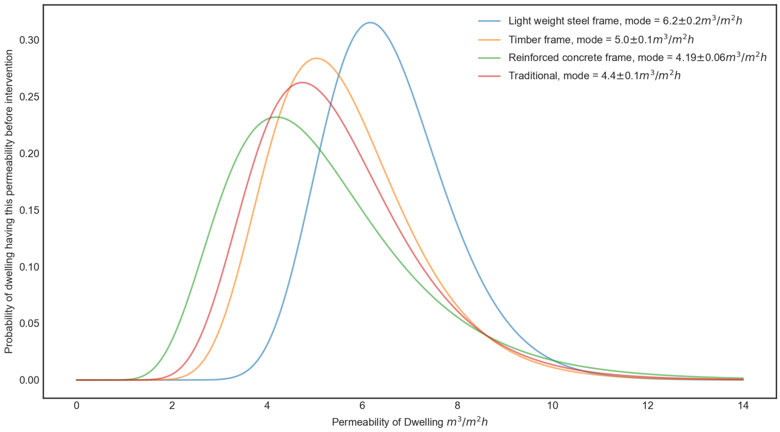

FIGURE 8: Plot showing the yearly background lognormal distributions for the four primary construction methods for Developer data set.

It is notable that 'traditional' construction performs relatively well, because the complexity of the this method has led to it being associated with a possible lack of airtightness Wingfield et al. (2009). Indeed, Wingfield et al. (2009) have shown that techniques such as plasterboard on dabs (which are intended to provide a continuous air barrier) are highly unlikely to result in airtightness because it relies on leaving an air gap to enable levelling of the plasterboard, and rather than builders having the the equipment needed to create a continuous bead, instead, a trowel is used to create the plaster surface.

However, the modelled background distribution for timber framed construction is slightly worse than that of both reinforced concrete frame and 'traditional', whilst that for lightweight steel frame construction has a significantly higher mode of 6.2±$0.2m^3/m^2h$. This is in concordance with findings from Johnston et al. (2011), who showed that steel frame structures had substantially higher permeabilities than wet plastered masonry construction. The reasons behind these differences in airtightness for different construction methods potentially include the familiarity of construction workers with the methods, differences in detailing or design issues across the sample. It should further be noted here that although the data set has been disaggregated by both construction method and year, the interaction between these two effects has not been investigated, because the sample sizes become too small to produce meaningful results once the group is split in this way. It is plausible for example that the type of construction changes with the year, due to the developer taking on different types of project from year to year. This could then have an impact on the annual distributions. Further research is required to confirm whether the differences in airtightness are associated with the construction method itself, or other factors.

4. Conclusions

To meet the 2050 targets of the Climate Change Act (2008), the efficiency of the dwelling stock must be improved. The airtightness of the building envelope is linked to the thermal efficiency of the building (International Energy Agency (IEA) 2013), and airtightness is thus a focus of international efforts to improve performance (Bailly et al. 2015, Vinha et al. 2015). In the UK, Lowe (2000a) argued in 2000 that minimum standards for airtightness, and associated testing, should be required. Furthermore, in order for ventilation systems to operate as intended, uncontrolled ex-filtration must be minimised. In 2006, the UK building regulations introduced a requirement that the airtightness of new dwellings must not exceed $10m^3/m^2h$ at 50Pa, or that the construction must follow guidelines taken from the Robust Details catalogue.

This article follows the work of Love et al. (2017) and Crawley et al. (n.d.), who examined airtightness test data contained in the UK's ATTMA database, which contains approximately 86% of national airtightness test results for new dwellings (Love et al. 2017), finding that the distribution of results was not as expected, with large and abrupt peaks in just within target values. To better understand the permeability of the dwelling stock, the estimated 'as built' permeability of dwellings was separated from the effect of subsequent sealing interventions to pass the regulatory test, as previous research has postulated that secondary sealing may not be as long lasting as the primary air barrier (Bailly et al. 2015, Love et al. 2017). This research uses the model and analysis performed in Love et al. (2017) and Crawley et al. (n.d.), and applies it to data recorded from 2007 to 2011 for a developer in the UK. This facilitated a novel analysis of the impact of construction methods and the evolution of airtightness test results over time.

The model applied to the developer data describes the shape of the distributions well. Comparing the full distribution with that from the ATTMA data, the developer achieves a mode of $4.80 \pm 0.04m^3/m^2h$, whereas in ATTMA the background mode is $4.38 \pm 0.01m^3/m^2h$. 18% of dwellings associated with the most common design targets were estimated to have undergone iterative cycles of modification of the building envelope, as opposed to 39% in the ATTMA data. This is thought to be because the developer had only begun to be more target driven in 2011, with the target of $5m^3/m^2h$ being more challenging and requiring more interventions that dwellings aiming for targets of $7m^3/m^2h$ and above, which were more prevalent in the earlier years. In contrast, the ATTMA data shows that a majority of builders are aiming for a target of $5m^3/m^2h$ throughout, which seem to be associated with a higher number of interventions.

The model further allowed two separate but concurrent effects of the current regulatory regime to be examined. The first was the change in airtightness over time, and it is clear that this developer made improvements, with the modal airtightness decreasing from 5.46±$0.09 m^3/m^2h$ to 4.12±$0.07 m^3/m^2h$ between 2008 and 2011. The second effect is the change in emphasis to a more target driven approach. Targets are more prominent in 2011 compared with 2008, which suggests that the legislation or other development pressures, such as contracts with social house builders or additional planning constraints, may have had an impact, which was increasingly met by secondary sealing rather than airtight construction.

To establish whether different construction methods produced different standards of airtightness, the data was disaggregated. Reinforced Concrete and 'traditional' construction methods produced the lowest as built permeabilities, which was not expected as 'traditional' (dry lined masonry cavity wall) construction methods are sometimes associated with high permeabilities. This is shown in Johnston et al. (2011), and Wingfield et al. (2009), who highlighted the organisation of different processes happening concurrently, as well as access to information for those doing the building, and communication among different actors as critical to producing airtight dwellings.

Further work is required to understand the causes for the differences in airtightness for new dwellings over time, and also that associated with different construction methods, as suggested by Wingfield et al. (2009). The evolution of the distribution suggests that the new building regulation requirements or other design pressures may have improved construction to be more airtight, but also that the changes to the primary air barrier were insufficient to meet stricter design targets without secondary sealing. This is coupled with a lack of clear evidence over the long term reliability of secondary measures, such as the use of mastic, to achieve airtightness targets. The findings of this research, good practice guidance and the results of future research into understanding the changing trends in airtightness need to be shared widely within the building industry to improve the enduring airtightness of new dwellings, as is also suggested in Wingfield et al. (2009). Improving the long term airtightness of dwellings will help reduce the performance gap, improve thermal comfort, and support international efforts to reduce carbon emissions.

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