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Making good decisions: avoiding alignment problems and maladaptation in retrofit and construction

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ABSTRACT

The current approach to retrofit has failed to deliver the promised reductions in energy use in the built environment, but it has exposed many historic buildings to maladaptation, and is threatening many more. This paper argues that the problem rests in a classic misalignment between the intentions behind retrofitting, and the means being used to assess retrofit options. Underlying issues include a poor understanding of how buildings were designed and operated before the Industrial Revolution radically changed our approaches to materials, construction, and use. This pre-carbon past still has much to teach us, with lessons that can be integrated with the best of the modern tools. But this requires careful planning for the long term, together with a much more flexible approach to modelling and assessment. This paper suggests a simple approach that might be used to unlock whole-life energy or carbon assessment, encouraging feedback and sharing of knowledge to achieve the rapid improvement needed to tackle the climate emergency.

KEYWORDS

climate change; historic environment; adaptation; carbon; climate emergency; lifecycle costing; alignment problems; building performance; retrofit

Introduction

> *"… I think part of the danger that we have at the current moment is that our models are wrong in the way that all models are wrong, but we have given them the power to enforce the limits of their understanding on the world."*
> *Brian Christian*[1]

We have now had rather more than two decades of retrofit programmes aiming to reduce energy and carbon in the built environment worldwide, and the kindest thing that can be said is that the results have been disappointing. At best many retrofits have failed to achieve meaningful reductions,[2] and at worst they have led to serious problems for the building and its occupants.[3]

Those who are familiar with the history of construction suspect this failure is rooted in the connections between the sources of energy available to us, and the ways we have constructed and then operated our buildings. There are many differences between the 'traditional' (solid wall) and 'modern' (hollow wall) approaches to construction and operation,[4] that can essentially be traced back to the sudden availability of cheap energy in the form of coal and other fossil fuels.[5] This alone suggests that, when it comes to understanding how to make a zero-carbon low-energy built environment, we may have much to learn from the pre-Industrial past.[6] Nonetheless, at present we continue to base climate-change decisions on the assumption that pre- and post-Industrial buildings need to be run in exactly the same high-energy way; and that, by extension, older buildings are the problem rather than the solution to sustainability.

Currently, buildings are mostly constructed with carbon-intensive (and often short-lifespan) materials that are expensive to produce and transport, using systems that make maintenance difficult, if not impossible. Many of the resulting buildings are not usable without mechanical services: deep floor plates and tall structures demand lifts, pumps, mechanical ventilation, and artificial lighting even during the day (*Figure 1*). Designs are usually highly specific to particular tasks, and can therefore be very difficult to adapt to changes of use (for example from office to residential) without major reconstruction. All these factors then contribute to a very short lifespan.[7]

Figure 1. The cloud forming above this glass building in London on a cold winter's day shows its cooling tower is running. The design and materials of many modern buildings mean that overheating is a serious problem, requiring air conditioning to be run even in the coldest parts of the year. It is not clear what will happen with such buildings as the climate emergency becomes ever more serious. (Photo: Robyn Pender).

Against all these considerations, 'traditional' construction fares very well. Most old and especially vernacular buildings were made using local materials, and if kept in good repair (using those same materials) can function for hundreds if not thousands of years. Their designs, which were many and varied, all grew out of the need to rely on natural lighting and ventilation. Thermal discomfort was dealt with passively, largely by exploiting the radiation of body heat into the interior surfaces and controlling air movement, rather than by space heating or cooling.[8] Mass structure and simple plan-forms meant they could be altered easily and adapted to new conditions, as evidenced by the many ancient buildings still in daily use. With minimal care and maintenance, and the replacement of weathering details and renders as they erode, traditional materials such as earth, brick, stone and even timber can survive indefinitely (***Figure 2***).

Figure 2. The Jews Court and Jew's house buildings on Steep Hill in Lincoln dates to c.1170, and have been in continual occupation throughout, though with many different uses and many alterations. (Photo: Robyn Pender).

On the other hand, traditional buildings are dogged by a general perception that they are fundamentally uncomfortable; and, in truth, many are currently characterised by sub-optimal indoor environments. For the most part, this can be traced to poor care and maintenance, sometimes because of neglect, but often because the way older buildings perform is no longer widely understood.[9] Modern materials and modern operational practices are therefore imposed onto older buildings that were designed to be run on entirely different principles, with inevitably poor results. On top of this, the rather random introduction of modern services – especially plumbing – has introduced new moisture problems where none previously existed. It is instructive that traditional construction did not use any form of damp-proof coursing, and that the first mentions of 'rising damp' appear in mid-nineteenth century patents for systems intended to deal with leakage into cellars from the brand-new London sewage system.[10]

Simply returning to a purely pre-carbon approach to building performance would, however, be neither possible nor desirable. Although the introduction of plumbing certainly led to a plethora of problems, and electrical wiring similarly greatly increases fire risk, both plumbing and wiring provide too many benefits for building usability to be simply abandoned. The answer not is to lose these services, but rather to learn to do them better (something that will greatly benefit newer buildings as well).

When it comes to the ways we have of producing liveable interior environments, though, there is undoubtedly much to learn from the pre-carbon past. By steering away from the emphasis on air temperature as a marker of comfort and usability, and thinking once again of exploiting radiant heat loss, ventilation and air movement, we will not just reduce energy and carbon, but also improve conditions for occupants. The figures for body heat loss given by the thermal physiologists suggest these should deliver a good baseline of comfort, which could then be enhanced with occupant-centred equipment that was not available in the past, such as electric fans and personal heaters.[11] Although these may use some energy, by heating or cooling the occupants rather the building, they greatly reduce waste.

Perhaps most importantly, it would also mean there was no longer a compelling need to seal buildings tightly and insulate heavily to prevent energy loss.

The fundamental question is: to deliver a truly sustainable and usable built environment in the face of a changing climate and rapidly changing population dynamics, which of the myriad tools and approaches, old and new, should be favoured to adapt, construct or run our buildings? How do we make good choices that actively counter the environmental problems we are facing, and avoid maladaptation (for example using measures that take more energy and carbon to produce, install and operate than they save over the longer term)?

Where the problem lies

Current approaches to retrofitting represent a classic case where the means chosen to meet an end conflict with the desired outcome; as described by Brian Christian in his book *The Alignment Problem: Machine Learning and Human Values*.[12] The term 'alignment' originally described the difficulties of trying to reconcile the very different interests of stakeholders in businesses (the staff, the managers, and the share-holders). More often than not, the systems of incentives, goals, or indices devised by well-intentioned managers ended up not leading the business towards its target, but rather revealing loopholes that could then be 'gamed' by individual stakeholders. Worse still, all too often there were serious unintended consequences. As Christian points out, it is extremely difficult to design any self-governing system that will internalise the goals and the behaviour people are trying to produce,[13] which is why alignment problems are particularly common wherever models are used to try to simplify decision-making.

As Christian notes, there are a number of critical reasons for this, most importantly:

1. All models must begin with a set of assumptions and simplifications, and if these are not correct or suitable, the projections made by the model will also be wrong.
2. Models are very often 'black boxes', where the underlying assumptions and calculations are invisible or unclear to the user. This makes it almost impossible to track down the root cause(s) of poor projections.
3. The more complex the system being modelled, the greater the risk of misalignment between the projection and reality.
4. Most models require numerical input, but the factors that are easy to measure or otherwise enumerate are rarely the factors you wish to know (this is an alignment problem in itself).
5. Every measurement and calculation in a model will have some level of error, and moreover errors compound. Very few models take these errors into account, so their projections may end up being very wide of the mark.

Unsurprisingly, given the fundamental complexity of all aspects of buildings – physics, materials, use, occupation – alignment problems are common in modelling of the built environment. This is especially true of the models that are being employed to predict energy use or the impact of retrofits. The factors involved in energy consumption are poorly understood, leading to poor predictions, especially in buildings of traditional construction.[14] In particular, since the occupation is almost impossible to measure or model, it is not incorporated into the energy assessment: this despite the fact that it is in operating buildings that most of the energy is being used.[15] Therefore the actions suggested by retrofit modelling rarely deliver the promised energy savings.[16]

An obvious example of an alignment problem is the use of computer models such as the Building Research Establishment Domestic Energy Model (BREDEM), and its suc-cessors the Standard Assessment Procedure (SAP) and RdSAP, to try to predict energy use in buildings. BREDEM was originally developed in the mid-1990s to estimate the broad-brush energy use of a large estate of identical 1980s houses, but in 2006 largely for political reasons it was adopted by the UK government as its preferred methodology for assessing individual buildings of all types and periods. It has been well established that the predictions of SAP and RdSAP are notoriously different to measured energy use.[17] Some obvious sources of error have been much discussed, including oversimplified building physics, misunderstandings about certain types of materials and structures, and the neglect of occupancy and appliance usage.

What is more, sustainability is not all about energy. It is critical that we reduce carbon outputs, but the energy models may suggest actions that increase the use of carbon over the medium and long term (such as installing 'energy-saving' products that have short lifespans: for example double-glazing, or insulation systems that must be replaced after 20 years or so).

The climate emergency is demanding that we make major changes in how we construct, adapt and manage our buildings, and make them quickly. We must accept that we can no longer rely on old familiar ways of doing things; but how can we start making better decisions: decisions that truly cut carbon and energy over the long term?

Problems with the current approaches to reducing energy and carbon

To begin with, it is worth examining some of the intrinsic sources of the current problematic approaches to retrofit.

The 'fabric-first' approach to retrofit

It is in day to day use – heating, cooling, lighting, operating appliances – that the bulk of the energy and carbon is being used: that is evident from records of the use of energy and carbon since the 1980s. The buildings themselves have changed very little, except perhaps by being given more insulation, but their carbon and energy footprints have grown considerably.[18] Although the enquiry into the devastating fire at Grenfell Tower in London (in which 72 residents died) has yet to report on its findings, but it appears to be an example of just how badly things can go wrong with a 'fabric first' approach to retrofit (*Figure 3*). Evidence has been revealing deep alignment problems between the goals of all the stake-holders: the residents, the local authority, the building management, the retrofitting architects, the materials manufacturers, and the testing authorities. The evidence being presented makes for painful but instructive reading.[19]

Figure 3. The fire at Grenfell Tower killed 72 residents, and the subsequent inquiry has uncovered a welter of mistakes, many stemming from self interest or short-term thinking on the part of numerous stakeholders. (Photo: Dan Lemieux, Wiss Janney Elsner).

To deliver a sustainable built environment, we need to be thinking of not just of reducing carbon and energy, but of many other factors: biodiversity, land use, and adapting to a climate that will be changing. It is critical to understand the potential synergies and potential conflicts in these different aims, and to not act on one area without thinking through the likely consequences in others.

Difficulties in assessing carbon and energy

Since measuring carbon use and energy use is by no means straightforward, even establishing baselines against which to judge the impact of retrofits has proved challenging.[20] For example, whole-life carbon costs are notoriously difficult to determine even for materials in current production. It is widely understood that estimating future carbon is complicated by the assumptions that must be made about changing energy sources; but it is just as difficult to quantify the carbon embodied in older buildings. How do you assess the carbon used to construct and operate a building before the use of fossil fuels, if you are trying to fully understand its whole-life impact on the environment?

Misunderstandings about occupant comfort

Most of the action around reducing energy, especially in heating climates, has tended to begin with a fundamental misconception: the presumption that for a building to be comfortable and usable, it requires some form of space heating or cooling. If this were indeed the case, saving energy and carbon would require action to prevent conditioned air being lost. Essentially, the building envelope would need to be sealed.

In reality, thermal comfort is dominated by other factors, including occupant control.[21] The critical importance of radiant body heat loss was well understood in the past, and dealt with using radiant breaks (simple passive interventions such as cloths hung on the wall and made into partitions and canopies, or wooden panelling, which stop body heat being absorbed by the building fabric) (*Figure 4*).[22] Currently, energy and heating models incorporate radiant heat loss by

Figure 4. Although contemporary images demonstrate that wall cloths to reduce body heat loss by radiation were once ubiquitous (as in this fifteenth-century illumination), tangible remains are few, and usually overlooked. (Illumination from *La Gest ou histore du noble roy Alixandre, roy de Macedonne* (Folio65r, BnF Archives et Manuscrits) ark:/12148/btv1b6000083z). At Exeter Cathedral, there is a rare hint in the painted stone screen of the c.1320 sedilia to the south of the main altar. This is sculpted and painted to resemble hanging cloth, and decorated with bronze hanging pins very like those used to fix the cloth in the manuscript. They may indeed have been more than purely decorative, perhaps being used to support cloths during the colder months. (Photos: Robyn Pender, with thanks to the Dean and Chapter of Exeter Cathedral).

translating an estimate for Mean Radiant Temperature (the average surface temperature 'seen' by the occupant's body) into a contribution towards the air temperature. In other words, they assume that:

- comfort requires there to be no radiant heat loss into the surroundings, whatever the occupant is doing;
- to prevent body heat being lost the wall surfaces must be heated to body temperature;
- that the heating mechanism for the walls is thermal transfer from heated air (a highly inefficient mechanism, not least since heating the air creates convection currents).

This fundamental error is shared by all the models commonly used in retrofit. It is linked to the third and fourth 'alignment' issues listed above: air temperature has been chosen because it is easy to measure with some accuracy; whereas comfort, radiant body heat loss, air movement, and occupant activity are not.[23]

Lack of understanding of how pre-eighteenth-century buildings were meant to be operated

With the loss of this deeper understanding of comfort, we have also largely forgotten how buildings designed for a world before industrial exploitations of fossil fuels were originally intended to function (*Figure 5*). Even many vernacular buildings are poorly understood, poorly maintained, and poorly operated. With the purpose of weathering details such as lime renders, hood mouldings and cills no longer understood, when these eroded, they were removed rather than being repaired or replaced. Most older buildings are now missing at least some of the features that once kept them in good condition, and ensured dry and comfortable interiors. Worryingly, the impact of many of these losses on comfort may not be appreciated; it is merely assumed that 'all old buildings are cold and damp'. Such problems are not intrinsic, but are now all too likely to be thought of as a inherent drawback of older buildings. When the lost features are reinstated, occupants are commonly struck by how much warmer, as well as drier, the building now feels to them.

Figure 5. Vernacular buildings were made from local materials using local expertise, and designed to cope with local conditions. Villages were located in carefully chosen locations, and expanded organi-cally following the terrain and responding to the needs of the villagers. (Photo: Clive Murgatroyd).

The same loss of original features is equally important when it comes to indoor comfort. With the walls bare of the draperies and panelling that were once a standard part of interior furnishings, occupants will be radiating their body heat freely into the stone or brick or earth, and this will make any building feel very cold: thermal physiologists estimate this is the cause of at least 60% of the loss of heat from the body.[24]

Poor understanding of how building systems and materials behave in situ

Fossil fuels provided a way of overcoming deep problems in the building fabric or operation. Buildings could be shorter-lived, and discomfort could be addressed with building services instead of being addressed in the design. This allowed poor design and fabrication to be perpetuated in a way that would have been impossible in the past. The problems have been exacerbated by the increasing siloing of expertise. Today few building professionals have an understanding of all aspects of the building process, from material manufacture to construction and use (as would have been expected for a master mason or other medieval building master).

Standardisation of envelope design

Construction is increasingly a process of assembling manufactured products. These are often designed and made far from the construction site, using standardised approaches; and indeed, we now build in much the same way, using much the same materials, from Singapore to Helsinki. Instead of designing building envelopes to suit the local environment, architects rely on energy-consuming mechanical services such as air-conditioning to produce acceptable indoor conditions.

Poor integration of modern mechanical systems into buildings

The introduction of the building services (particularly plumbing) means that pre-carbon buildings must operate somewhat differently now to the way they did in the past. Well-meaning attempts to disguise water pipes and other modern additions may well lead to serious moisture problems, as hidden pipes begin to fail, or hidden pipes and cables act as conduits for water leaks. To run the services into the building, they need to puncture the building envelope: this can lead to floodwater ingress, and fire spread.[25] Problems may well only be noticed when they have become very serious.

Poor understanding of retrofit materials

Information about modes of failure for materials and systems is considered a basic requirement for use in building conservation. We know we need to understand how, why and when a material or system we are thinking of using will fail; otherwise we will not be able to judge where and how it can be safely used, how (and how often) it will need to be maintained and repaired, or its likely lifespan. We know a great deal about the failure modes of materials such as timber, lime and cement, but next to nothing about many proprietary materials, not least those being used for retrofitting.

Systems for testing proprietary materials such as the European or the British Standards investigate achievable practice, rather than seeking to determine best practice.[26] The tests used in the Standards usually expose the material or system to certain agreed conditions, to see whether they 'pass' (survive), rather than deliberately ramping up conditions until they fail. Undoubtedly, though, it is the latter approach to testing that is required to determine when and how a material or system can be used.

Clearly, we also need this information if we are to assess the whole-life carbon and energy costs of the retrofit.

Reliance on market-led retrofit solutions

This is related to the well-known issue of warranties. Developers and architects, and even some owners, prefer proprietary products which arrive complete with certificates and guarantees and user manuals to naturally variable traditional materials such as earth, lime and timber (which take expertise to use). Although most people do recognise that the warranties have little practical value, they serve to transfer risk in our litigious world.[27]

In fact, it could be argued that a fundamental roadblock to tackling the climate emergency in the built environment is the market-driven economy that arguably caused the problem in the first place. If retrofit continues to be seen as primarily about the installation of proprietary 'green' products, we will continue to court maladaptation.[28] This is one reason why, for existing buildings at least, 'fabric first' tends to work against genuine improvement.

Overcoming problems

Given all these very fundamental issues, it is no surprise that we are finding serious alignment problems between many of the actions undertaken with the laudable intent of reducing energy and carbon use or increasing occupant comfort, and the real outcomes (which include rebound effects and poor indoor air quality).

Reconsidering what it is we are trying to achieve

While is certainly possible to join the chorus criticising (to pick an example) the patchy understanding of the physics of heat and moisture transfer that underlies the modelling and measurement of u-values, there is a much more fundamental question that should really be the focus of our research: what does a low-energy, comfortable building actually look like? How would it work? How would we know it was working, and keep it working?

It is in considering such fundamental questions that building history comes into its own. We have much to learn from the pre-carbon built environment, where energy was expensive and difficult to obtain but building construction and occupation were much more closely intertwined. Put simply: in the past, people were forced to understand and deal with mistakes, and to learn from that process better ways of constructing, main-taining and operating their buildings.

With existing buildings at least, a better mantra than 'fabric first' is surely 'people-first': to begin planning a retrofit programme by first finding out how the occupants are actually using energy and why. What do they wish to be able to do in the building now and in the future, and what is stopping that being done in a low-energy low-carbon way?

Appraising retrofit options

Even after we have arrived at a better idea of the outcome we are hoping for, how do we sensibly compare retrofit options when outcomes can be so interconnected, and the old and new approaches to construction and operation of buildings are so different? Is there a way of unpicking the best approaches to reducing energy and carbon (whatever the period in which they were invented), and knitting them together to form a robust, sustainable and usable built environment?

There are a number of key issues that, if not considered during the design process, could easily lead to maladaptation:

- whole life costs, from cradle to cradle: we need to take proper account of all stages when energy or carbon will be introduced;
- lifespans, not just of the building but of any retrofit interventions;
- the maintenance and repair implication of retrofits, especially interventions on the building fabric, and any impacts on these may have on the building's lifespan;
- interdependencies:
  - whether the retrofit option requires a suite of interventions (for example insulation usually requires the inclusion of a 'vapour barrier'); if so these must be considered as a whole;
  - whether a system that uses energy or carbon is required for the normal operation of the building;
- although there is an overlap between energy use and carbon, they are not the same thing, and are both distinct from monetary cost.

It is clear that we need a simple approach that can deal much more transparently with these complex issues than any of the models can currently manage. Building owners and managers need simple tools they can apply with real confidence to make decisions that they can be sure will produce the right results, and not unleash undesirable consequences. It is clear too, that to assess the sustainability of buildings and retrofits we need to look across the whole lifespan of the building.

The critical features of any successful methodology must be simplicity, transparency, feedback, and iterative development. It must be straightforward to improve the tool based on actual outcomes.

Arguably, transparency is the key. As Brian Christian noted in a recent interview:

> *… for me transparency is the starting point. Just what is it you are trying to do in the first place? What is driving the recommendations that are being sent? … . if you think about a model, it has three parts. What are the inputs? What goes on in the middle? And what are the outputs? One way to make a model simple is to have fewer inputs; to have less stuff going on in the middle …* [29]

He speaks about the value of using transparent models to test what happens when the system is perturbed to test whether the model is successfully predicting outcomes.

Once a model has come through this perturbation process successfully, the same method (sensitivity testing) can be used to investigate which factors are critical to outcomes: indeed, this is arguably the best and most practical use of models. If the value of one factor is changed significantly, but that results in little if any change in the predicted outcomes, then that factor is not likely to be critical. On the other hand, if changing the value of a factor causes serious changes in the predicted end state, and those predictions appear feasible, that factor (and the way it links into the system) is a clear candidate for more careful consideration.

This may not be as difficult as it sounds, if we can bring ourselves to take a more broad-brush approach, rather than focussing on obtaining precise data. The following is a proposal of one simple way in which modelling might be approached.

The example is focussed on energy, but the same idea could be used for carbon, or any other aspects of sustainability: the key is to make it clear which individual factor is being assessed, and to not mix different parameters together.

Example: simplifying whole-life costing of energy

To begin with, we need to establish all the stages in a building's life during which energy is used.

This must be very much more fine-grained than the usual division into 'embodied' and 'operational', which is too simplistic for a real building, especially one that might be decades or even centuries old (and with many periods of alteration and refurbishment). By breaking this down more carefully we can begin to meaningfully differentiate between (for example) a material found locally and a similar material sourced farther afield, or investigate exactly how much a factor such as off-site processing might be affecting sustainability.

List of energy inputs

1. Beginning-of-life energy costs for:
   (a) Producing the raw building materials
   (b) Transporting the raw materials to the location where they will be processed
   (c) Processing the raw materials into building materials
   (d) Transporting the building materials to the building site
   (e) Construction
   (f) Disposal of waste.

2. Running costs: that is, the energy that must be fed in for the building element under consideration to operate (for example, the electrical energy needed to run artificial lighting).

3. Maintenance: that is, the energy that must be fed in regularly to keep the building material or system operational (for example, cleaning of gutters), including:
   (a) Producing the necessary raw materials
   (b) Transporting the raw materials to the location where they will be processed
   (c) Processing the raw materials into maintenance materials
   (d) Transporting the maintenance materials to the building
   (e) Undertaking maintenance
   (f) Disposal of waste.

4. Repair: that is, the energy that must be fed in at intervals to repair deterioration (loss to attrition) or damage, or otherwise keep the building usable, including:
   (a) Producing any raw materials
   (b) Transporting the raw materials to the location where they will be processed
   (c) Processing the raw materials into repair materials
   (d) Transporting the repair materials to the building
   (e) Undertaking the repair
   (f) Disposal of waste.

5. End-of-life costs
   (a) Demolition of the component or building
   (b) Disposal of waste
   (c) Preparation for replacement (unless this is included in the costing for the replacement).

Running through this list, major differences between 'traditional' and 'modern' construction are clear.

For a building constructed before the industrial exploitation of fossil fuels, the beginning-of-life inputs are simple: transport (the major cost) was kept to a minimum, and materials were found and processed on site. This was true also for maintenance and repair materials. Because the lifespan of many of these materials is essentially infinite, end-of-life costs are incurred only in certain circumstances, and only then after a very long period. This can be captured in a simple cyclical diagram, where the size of the circle represents the lifespan of the building. Clearly the bigger the circle the greater the ratio of benefit to energy expenditure, and hence the greater the sustainability (***Figure 6***).

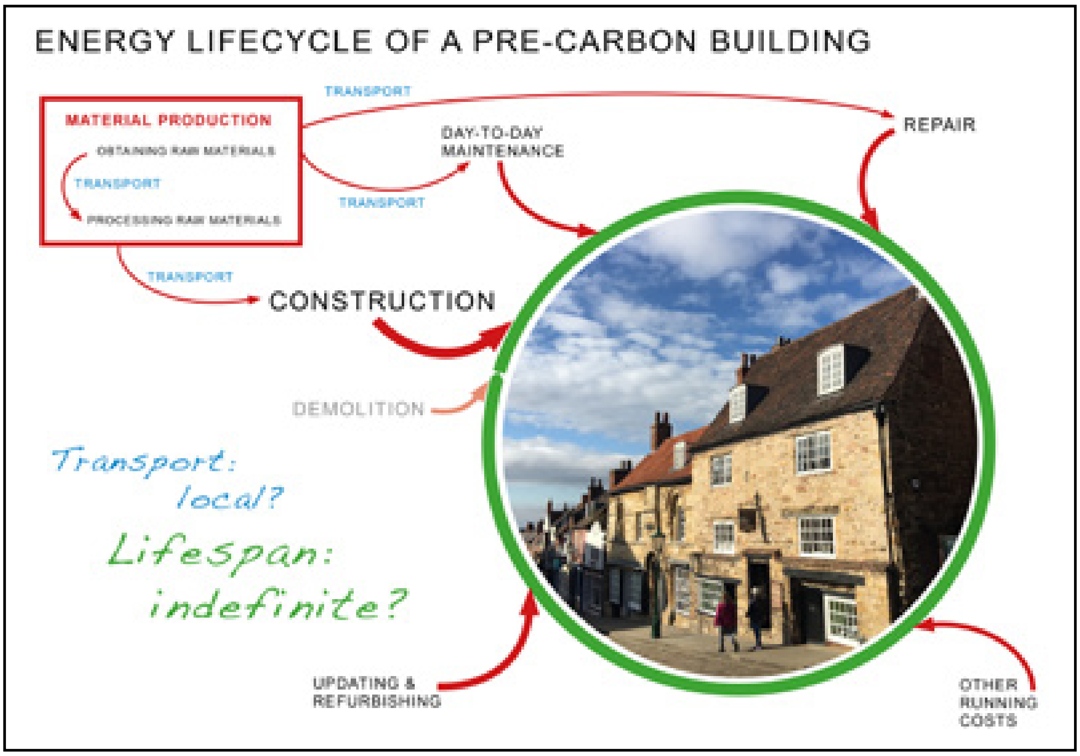


Figure 6. Prior to the exploitation of fossil fuels, the transport was difficult and very expensive, so building materials were sourced on site. This also gave benefits when it came to construction and care: not only were the materials readily available, but there was extensive local knowledge around the best way of designing and maintaining the building. Complete demolition was rare, but all materials were reused (often as part of the replacement building). (Diagram and photo: Robyn Pender).

For post-carbon buildings, the various inputs immediately become more complicated, since most materials and proprietary systems will incur several stages of processing and transport (*Figure 7*). To give a modern example, for a double-glazed unit the inputs include the costs for making aluminium, glass, plastic, and silicone, plus the costs of bringing these materials together to make the window. The raw materials are often mined in one country, refined in another, and processed elsewhere again. It is not necessary to have accurate figures for every energy input to be able to see that double-glazing is a very high-energy component.

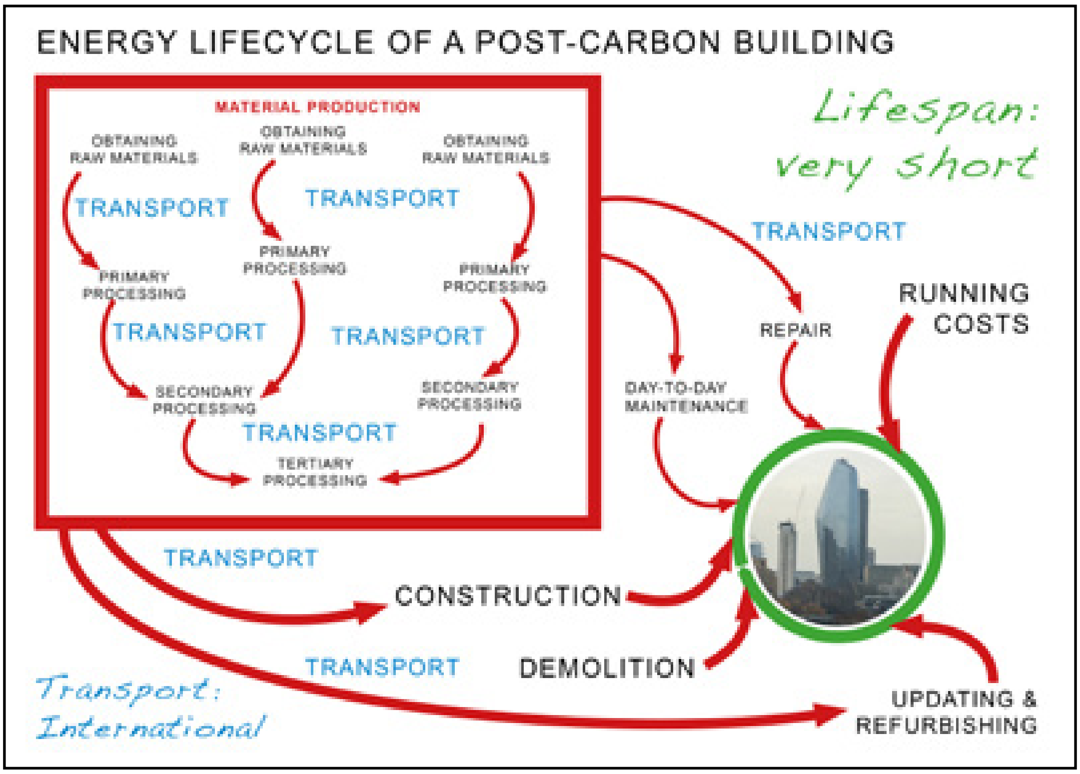


Figure 7. The Industrial Revolution made it possible to shift heavy goods long distances. This coincided with the growth in cities and a consequent building boom, fed by centralised production of materials. This in turn led to increasing standardisation of design, and an emphasis on construction rather than care: indeed, the resulting buildings are often very hard to maintain, which is one of the factors encouraging short lifespans. Demolition is however very energy-hungry, and most materials cannot be reused. (Diagram and photo: Robyn Pender).

This list of energy inputs can be conveniently expressed in a table, with the five stages becoming the columns, and the building or building component in question becoming the rows (*Figure 8*). Rows can be just one building element, or combine several building elements into one, according to the needs of the investigator. For example, it might be convenient to combine all aspects of a complex window system, from glazing to shutters, if you are considering the system as a whole; but if you are wishing to appraise different options for the window (shutters or curtains? double glazing or triple glazing?) it will be more useful to subdivide accordingly. The key is to make the description clear.

TABLE OF ENERGY USE

COMPONENT	Construction	Operation	Maintenance	Repair	End-of-Life	TOTAL
Wall Total area 250 m^2: see elevations	Solid construction using local stones, earth mortar made with local clay, haired lime render made with local materials *Materials*: 50 units *Lifespan*: *Indefinite (800 years)*	N/A	Gutter and drain clearance twice yearly *Materials*: 0.1 units *Frequency*: 6 months Limewash every 10 years or so *Materials*: 10 units *Frequency*: 10 years	(assuming good maintenance): Replace lime render once every 70 years *Materials*: 30 units *Frequency*: 70 years Repair water-shedding stone detailing every 200 years or so 20 units *Frequency*: 200 years	Can be dismantled by hand, and all materials can be reused on site *Materials*: 30 units *Frequency*: 800 years	2500 + 0.2 every 1 year + 2 every 5 years + 2 every 50 years + 20 every 200 years + 30 at end of 800 years Energy by end of building life (800 years): ~3100 units
Early sash window	Old-growth Baltic pine, original crown glass and replacement cylinder glass *Materials*: 250 units *Lifespan*: *Indefinite (300 years)*	N/A	Regular cleaning *Materials*: 0.01 units *Frequency*: 3 months Repaint every 7 years *Materials*: 0.5 units *Frequency*: 7 years	(assuming good maintenance): Replace sash cord every 20 years *Materials*: 0.1 unit *Frequency*: 20 years Replacement of broken glass panes *Materials*: 50 units *Frequency*: 50 years	Some possibility of reusing some components, including remelting glass *Materials*: 2 units *Frequency*: 300 years	250 + 0.04 every year + 0.5 every 7 years + 0.1 every 20 years + 50 every 50 years + 2 at end of 300 years Energy by end of component life (300 years): ~980 units
Replacement sash window (modern timber single-glazed)	Plantation pine, float glass *Materials*: 200 units *Lifespan*: 70 years	N/A	Regular cleaning *Materials*: 0.01 units *Frequency*: 3 months Repaint every 7 years *Materials*: 1 unit *Frequency*: 7 years	(assuming good maintenance): Replace sash cord every 20 years *Materials*: 0.1 unit *Frequency*: 20 years Replacement of broken glass *Materials*: 210 units *Frequency*: 50 years	Possibility of reusing glass if not coated *Materials*: 2 units *Frequency*: 70 years	200 + 0.04 every year + 1 every 7 years + 0.1 every 20 years + 210 every 50 years + 2 at end of 70 years Energy by end of component life (70 years): ~425 units (comparison with early window) at end of 300 years: ~1700 units
PVC Double-glazed unit	Aluminium, float glass, PVC, xenon gas *Materials*: 190 units *Lifespan*: 20 years	N/A	Regular cleaning *Materials*: 0.01 units *Frequency*: 3 months	N/A: if glass breaks, window must be completely replaced Replacement *Materials*: 190 units *Disposal*: 100 units *Frequency*: 50 years	Materials cannot be reused: waste costs *Materials*: 100 units *Frequency*: 20 years	190 + 0.04 every year + 290 every 50 years + 290 every 20 years Energy by end of component life (20 years): 2701 units (comparison with early window) at end of 300 years: ~5710 units
Micro CHP unit	Metal,plastic, microprocessor control unit (rare earths) *Materials*: 100 units *Lifespan*: 15 years	Energy supply (per year): *Materials*: 1060 units *Frequency*: yearly	Service yearly: *Materials*: 4.6 units *Frequency*: yearly	(assuming good maintenance): Replace seals and electrical components, and repair leaks: *Materials*: 1 unit *Frequency*: 5 years	If all recycleable components are recycled *Materials*: 31.5 units *Frequency*: 15 years	100 + 1060 every year + 4.6 every year + 1 every 5 years + 31.5 at end of 15 years Energy by end of component life (15 years): 16103.5 units (comparison with early window)

Figure 8. A simplistic example developed by the author to show how an energy table might work. Since all the numbers and assumptions are evident, they can easily be challenged and changed. Similarly, numbers can be altered to reflect changes in the energy costs for manufacturing, operation, repair or waste processing.

Any convenient unit could be used for measurement, as long as it is used consistently. One important thing is to make sure inputs that must be used together are not separated: for example, if a passive house retrofit requires mechanical ventilation and a building wrap system to protect the insulation, then all of these must appear on the table. On the other hand, operating sash windows may remove the need for further ventilation.

It is particularly important to keep in mind whether the building has a fundamental requirement for any energy-using elements. An assessment table for a multistorey building with deep floorplates for example, will need to include rows for essential energy-using features such as lifts, pumps, artificial lighting, and mechanical ventilation (*Figure 9*). By contrast, although you might choose to install air conditioning in a Georgian terrace house, the house does not require it to be usable: even if there is an overheating problem, that could be dealt with in other ways, such as installing awnings.

We should be seeking to compare buildings more fairly and transparently, and like-for-like. If that is proving difficult in any particular case, that would suggest that the row divisions are too coarse-grained, and need to be further subdivided. On the other hand, it is important to resist over-accuracy: splitting hairs paralyses decision-making.

Triaging should be enough. Given all the other factors potentially impinging on the performance of any real building in use (for example weather exposure, or changing local topography) we should be looking for significant effects that stand out clearly from the ‘noise’ (*Figure 10*).

Figure 9. Traditional buildings were designed to function without operation energy input: staircases, for example, were provided with windows. (Photo: Robyn Pender).

TABLE OF ENERGY USE

COMPONENT	Construction	Operation	Maintenance	Repair	End-of-Life	TOTAL
Cob wall	Foundation of local stones laid in local clay; local clay and straw mixed and laid by hand; limewash made from local limestone *Materials: 30 units* *Lifespan: Indefinite (300 years)*	N/A	Limewash every 10 years or so *Materials: 10 units* *Frequency: 10 years*	(assuming good maintenance): Little or none, but if necessary repairs can be made using local materials, once again processed by hand	All materials can be reused with minimal processing *Materials: 2 units* *Frequency: 300 years*	30 + 10 every 10 years + 2 at end of life **Energy at 300 years: 322 units**
Early sash window	Old-growth Baltic pine, original crown glass and replacement cylinder glass *Materials: 250 units* *Lifespan: Indefinite (300 years)*	N/A	Regular cleaning *Materials: 0.01 units* *Frequency: 3 months* Repaint every 7 years *Materials: 0.5 units* *Frequency: 7 years*	(assuming good maintenance): Replace sash cord every 20 years *Materials: 0.1 unit* *Frequency: 20 years* Replacement of broken glass panes *Materials: 50 units* *Frequency: 50 years*	Some possibility of reusing some components, including remelting glass *Materials: 2 units* *Frequency: 300 years*	250 + 0.04 every year + 0.5 every 7 years + 0.1 every 20 years + 50 every 50 years + 2 at end of life **Energy at 300 years: 980 units**
PVC Double-glazed unit	Aluminium, float glass, PVC, xenon gas *Materials: 190 units* *Lifespan: 20 years*	N/A	Regular cleaning *Materials: 0.01 units* *Frequency: 3 months*	N/A: if glass breaks, window must be completely replaced Replacement *Materials: 190 units* *Disposal: 100 units* *Frequency: 50 years*	Materials cannot be reused: waste costs *Materials: 100 units* *Frequency: 20 years*	190 + 0.04 every year + 290 every 50 years + 290 every 20 years **Energy at 300 years: 5710 units**

Figure 10. Triaging can be used to, for example, reflect confidence in the numbers: here, in a sample table developed by the author, green equals low error, red equals high error, and amber equals 'error could be reduced with further research'.

The other factor that must be included in the table is time: that is, how frequently any energy inputs are required. How often is maintenance needed? If, in addition to regular yearly maintenance, there is a five-year cycle of deep maintenance, that too must be included. Maintenance, repair and replacement cycles are usually overlooked, but they can make a dramatic difference to sustainability, as can quickly be seen from a step graph (*Figure 11*).[30]

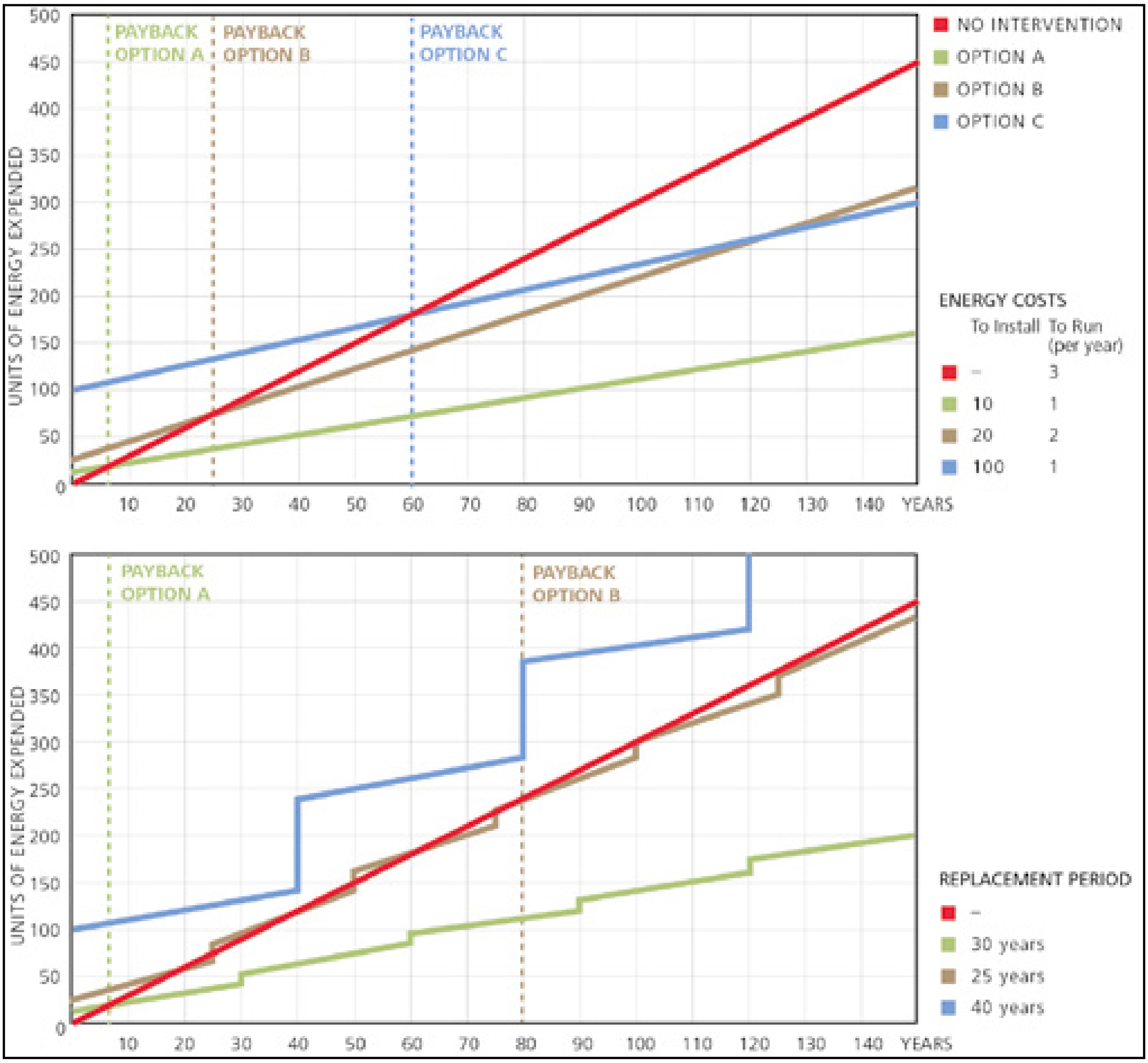


Figure 11. Factoring in component life can present a very different picture of long-term energy (and carbon) outcomes. The table at the top shows payback periods for three different retrofit options, when lifespan and embodied costs are ignored. In this case all the options appear to be an improvement on 'do nothing'; but if the lifespan and embodied costs are included, Option C will always cost more, and Option B will give little benefit. (©Robyn Pender/Historic England).

Indeed, if live step graphs could be incorporated in the table, it would produce a really helpful tool for assessment 'at a glance'. By adding graphs at the end of each row, it would be possible to quickly and easily compare the long-term energy implications of different options.

In the bottom corner, a 'total' graph could be included to summarise the whole-life energy of all the rows in the chart. If every significant energy-using element of a building was included in the table, then this graph would give a picture of the whole-life energy of that building (*Figure 12*).[31]

Live graphs would also allow us to test the impact of changing certain parameters. What happens to the graph if, for example, the lifespan of a retrofit element is doubled? Or if the running costs on another element is halved? Does it have a significant effect, or does it make little difference to outcomes over the long term? By playing with the model in this way, it is possible to determine where a little extra effort would pay the most dividends (whether what is sought is physical improvements in materials, or simply a more accurate idea of the true energy costs). We can also examine the impact the errors in the available data might have on our conclusions.

A more sophisticated system designed specifically for existing buildings, and to depict the entire energy history of the building, could incorporate such refinements as the ability to show when components were introduced, or show linkages between components that may affect each other (for example, awnings protecting windows and thus reducing the maintenance costs for the window, or – in the other direction – sealed windows increasing the risk of condensation increasing the window maintenance demand).

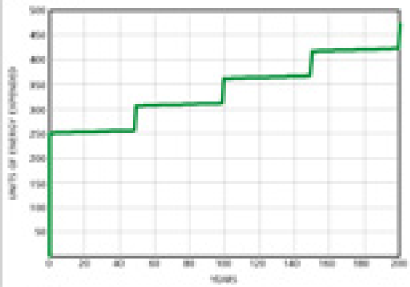
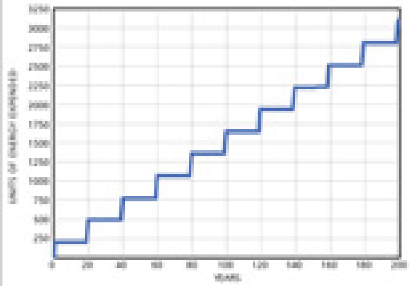
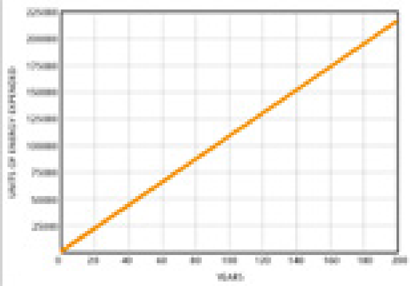
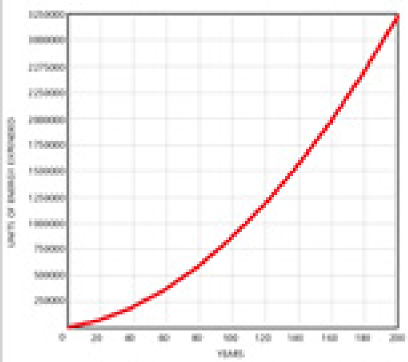
TABLE OF ENERGY USE						
COMPONENT	Construction	Operation	Maintenance	Repair	End-of	TOTAL
Early sash window	Old-growth Baltic pine, original crown glass and replacement cylinder glass *Materials: 250 units* *Lifespan: Indefinite (300 years)*	N/A	Regular cleaning *Materials: 0.01 units* *Frequency: 3 months* Repaint every 7 years *Materials: 0.5 units* *Frequency: 7 years*	(assuming good maintenance): Replace sash cord every 20 years *Materials: 0.1 unit* *Frequency: 20 years* Replacement of broken glass panes *Materials: 50 units* *Frequency: 50 years*	Some possibility of reusing some components, including remelting glass *Materials: 2 units* *Frequency: 300 years*	
PVC Thin double-glazed unit	Aluminium, float glass, PVC, xenon gas *Materials: 190 units* *Lifespan: 20 years*	N/A	Regular cleaning *Materials: 0.01 units* *Frequency: 3 months*	N/A	Materials cannot be reused: waste costs *Materials: 100 units* *Frequency: 20 years*	
Micro CHP unit	Metal,plastic, microprocessor control unit (rare earths) *Materials: 100 units* *Lifespan: 15 years*	Energy supply (per year): *Materials: 1060 units* *Frequency: yearly*	Service yearly: *Materials: 4.6 units* *Frequency: yearly*	(assuming good maintenance): Replace seals and electrical components, and repair leaks: *Materials: 1 unit* *Frequency: 5 years*	If all recycleable components are recycled *Materials: 31.5 units* *Frequency: 15 years*	
TOTALS	Total construction (baseline) energy over 200 years 250 + 9 x 190 + 13 x 100 **= 23780 units**	Total operational energy over 200 years 200 x 1060 **= 212000 units**	Total maintenance energy over 200 years 200 x 0.04 + 28 x 0.5 + 200 x 0.04 + 200 x 4.6 **= 950 units**	Total repair energy over 200 years 9 x 0.1 + 4 x 50 + 40 x 1 **= 241 units**	Total demolition energy over 200 years 9 x 100 + 13 x 31.5 **= 1310 units**	

Figure 12. A demonstration illustration by the author, showing how live step graphs that respond immediately to changes in the input figures might make it easy to see the long-term impact of changing parameters or values. In this highly simplified example, it is immediately clear that the most important contributor to long-term energy consumption is not necessarily the operational energy, but elements that have short lifespans but take a lot of energy to produce. This suggests that installing, say, highly efficient but short-lived boilers would be unlikely to truly reduce energy consumption.

Similarly, it would be helpful if the method could be used to test the impact of the occupation. If maintenance is neglected, requiring major repairs more widely spaced, what is the result for energy consumption? What are the knock-on impacts on other rows in the table?

Because the table records all the input energy values and lifespans in plain view, the requirement for transparency is honoured, and it is possible to see, understand and (if necessary) challenge all the assumptions and approximations being made. A system of this type allows for easy feedback. Errors can be corrected, new information added, and over time it may even be possible to develop a corpus of agreed 'rows' for the energy inputs of particular building types or building elements.

A tool for the future?

A simple model of the sort described above, using the example of energy assessment, would be easily adaptable to any parameter of importance: obviously carbon, but perhaps also more specialist impacts of the built environment, such as the use of plastic or non-recyclable materials. Equally it could be used to look more closely at the energy across the whole building environment, moving beyond the building in iso-lation to take account of drainage, transport, and other factors critical to sustainability.[32]

No doubt in each case the input values will be a subject for fierce debate; but that debate is exactly what is needed if we are to develop a sustainable future.

But the ultimate goal of any whole-life decision-making tool must be to incorporate the likely impacts of changing futures: for example, the decrease in heating demand and the increase in cooling demand as the climate warms, the increased maintenance and repair needed as weather events become more extreme, or the reduction in demand for sound-proofing as cars are phased out.

Conclusions

We know that the approaches we have been taking to retrofit, and to construction more broadly, have not been delivering the energy or carbon reductions we require: but we also know they have not been delivering the usability they promised, either. Despite all the massive expenditure of energy and carbon in construction and operation, we currently have built environments that are difficult to use without feeding in still more resources, for transport or servicing or liveability.

Even before the Covid-19 pandemic, the actions needed to create a sustainable built environment over the coming decades looked alarmingly complex; and as we have seen anxiety is apt to lead to panic, and hence to either paralysis or unhelpful knee-jerk reactions. But experts in planning, such as the National Audit Office, point out that planning should be 'output-led'; that we get much further if we can stop thinking of where we are, and how we might keep doing more of the same but achieve a different result.[33] Instead we must envisage a world in, say, 2050 where our problems have been solved, and we have a sustainable built environment. What does that world look like?

It probably looks, in many ways, quite a lot like the world before the Industrial Revolution, with buildings intrinsically part of their local environment, and operated by knowledgeable occupants. It would however incorporate piped water and some form of electricity supply, albeit much more effectively than at present, and it would put no emphasis on cars, electric or otherwise. It would not have air conditioning, and perhaps not space heating either, but the buildings would be more healthy and comfortable than at present – noting that ideas of comfort evolve, and in the fallout from the pandemic are likely to once again include significant ventilation, as was always sought after in the past.

Those of us working with the historic built environment are deeply aware of how many lessons it has for the future, and we must seize every opportunity to embed this understanding into wider planning for the climate emergency. Knowledge from the past often sits comfortably with the best of modern practice: for example, sustainable drainage systems closely resemble historic approaches to water management, but with the addition of some excellent modern tools.

It is promising to hear that the overtures being made by the Climate Heritage Network to the UN Climate Change bodies are meeting with a keen welcome. One of the many things we have to contribute is the breadth of our viewpoint. In building conservation, silos of expertise are not unknown, but they are very much less common. And our deep perspective on time delivers many benefits. We have the evidence to show decision-makers that decades pass very quickly, and that we can flourish under many different economic and societal models. Most importantly, we can show how changes, even sweep-ing changes, do not have to be about 'loss'.

To leave the final word to Brian Christian:

> *… the promise that technology offers society in the broadest terms is to make people happier. But when I think about am I happier as a function of having been born in the 1980s then if I had been born in the 1880s, I don't think so. I have better dental care. I'm not worried about an abscessed tooth or something like that. But broadly speaking, I care about my family, my marriage, my friendships. I want to do interesting work and write books, which I could have done 100 years ago. Viewed from that perspective, technology has surprisingly little to offer. I don't think it's bringing a lot to the table in terms of addressing the fundamental things that make people happy. Relieving the creature comforts and the physical drudgery associated with them, I think is huge. But we've been past that threshold for several generations at this point. And I think people are getting less happy, rather than more.*

Notes

1. The Ezra Klein Show, 'If "All Models Are Wrong", Why Do We Give Them So Much Power?Ezra Klein Interviews Brian Christian' (*New York Times podcast* June 4, 2021), https://www.nytimes.com/2021/06/04/podcasts/transcript-ezra-klein-interviews-brian-christian.html.

2. See, for example, the many papers cited in Frank J. de Feijter and Bas J. M. van Vleit, 'Housing Retrofit as an Intervention in Thermal Comfort Practices: Chinese and Dutch Householder Perspectives', *Energy Efficiency* 14, no. 2 (2020), https://doi.org/10.1007/s12053-020-09919-8. The fabric-first approaches to retrofit that have cause failures of hitherto successful buildings; but have also failed to deliver the promised carbon and energy gains or comfort benefits in return. Indeed, maladaptation – using more energy and carbon than you save – is a constant risk. The UK Economic and Social Research Council gives a pithy summary of this on their website: *The Rebound Effect*, ESRC website, https://esrc.ukri.org/about-us/50-years-of-esrc/50-achievements/the-rebound-effect/ (accessed July 14, 2021).

3. One of the most egrarious failures of deep retrofit programmes applied to older buildings is Preston, in Lancashire; this sparked the Each Home Counts review of the UK government's 'Green Deal' scheme. Kate de Selincourt discusses this example extensively on her blog: *Kate de Selincourt: Environment, energy, sustainable building*, Preston Retrofit Disaster, May 15, 2018, https://www.katedeselincourt.co.uk/preston-retrofit-disaster/ (accessed July 14, 2021). A widely discussed problem of deep retrofit is its adverse impact on indoor air quality; see for example the Environmental Protection Agency's website, https://www.epa.gov/indoor-air-quality-iaq/energy-weatherization-and-indoor-air-quality (accessed July 14, 2021).

4. English Heritage, *Practical Building Conservation: Building Environment* (London: Routledge, 2014). Historic England defines 'traditional' construction as the solid-wall approach to building that was all but ubiquitous before the Industrial Revolution, and remained common until well into the twentieth century. Since the middle of the nineteenth century, this solid-wall construction has been gradually displaced by 'hollow-wall' systems such as terracotta, cavity wall, brick veneer, and lightweight facades.

5. Barnabas Calder, *Architecture From Prehistory to Climate Emergency* (London: Pelican, 2021).

6. Robyn Pender and Daniel J. Lemieux, 'The Road Not Taken: Building Physics, and Returning to First Principles in Sustainable Design', *Atmosphere* 11, no. 6 (2020): 620, https://doi. org/10.3390/atmos11060620.

7. In the RIBA guide to whole life carbon assessment, it is noted that the lifespan for a new building is commonly taken to be just 60 years (Simon Sturgis, *Embodied and Whole Life Carbon Assessment for Architects* (London: RIBA, 2019)). In cities such as London, the projected lifespan for new development is still shorter: Edwin Heathcote of the Financial Times quotes 25 years (Edwin Heathcote, 'Construction is Turning London into a City of Holes', *FT Magazine*, April 21, 2016. www.ft.com/content/282e51f0-0683-11e6-9b51-0fb5e65703ce)

8. See note 6 above.

9. See note 6 above.

10. See note 5 above.

11. See note 6 above.

12. See note 6 above.

13. Brian Christian, *The Alignment Problem: Machine Learning and Human Values* (New York: W. W. Norton Company, 2020).

14. Freya Wise, Alice Moncaster, and Derek Jones, 'Rethinking Retofit of Residential Heritage Buildings', *Buildings and Cities* 2, no. 1 (2021): 495, https://doi.org/10.5334/bc.94.

15. See, for example: Rahman Azari, 'Chapter 5 – Life Cycle Energy Consumption of Buildings; Embodied + Operational', in *Sustainable Construction Technologies*, ed. Vivian W.Y. Tam and Khoa N. Le (Burlington, MA: Butterworth-Heinemann, 2019), 123–44, https://doi. org/10.1016/B978-0-12-811749-1.00004-3. In 2010, Ramash and colleagues drew on evidence from both residential and office buildings in 13 countries to conclude that operation energy represents 80–90% of energy use (T. Ramesh, Ravi Prakash, and K.K. Shukla, 'Life Cycle Energy Analysis of Buildings: An Overview', *Energy and Buildings* 42 (2010): 1592–600, https://www.researchgate.net/publication/229400115_Life_cycle_energy_analysis_of_ buildings_An_overview).

16. See, for example: Chris van Dronkelaar, Mark Dowson, E. Burman, Catalina Spataru, and Dejan Mumovic, 'A Review of the Energy Performance Gap and Its Underlying Causes in Non-Domestic Buildings', *Frontiers of Mechanical Engineering* 1, no.17 (2016): 1–14, https://www.frontiersin.org/articles/10.3389/fmech.2015.00017/full (accessed July 14, 2021)

17. Nick Hogg and Chris Botten, *A Tale of Two Buildings: Are EPCs a True Indicator of Energy Efficiency?* (Better Buildings Partnership and Jones Lang LaSalle, 2012); Keith Baker and Ron Mould, *Energy Performance Certificates: an Alternative Approach* (Common Weal policy docu-ment, 2018); Freya Wise, 'How We Measure Energy Efficiency in Homes isn'tWorking', *The Conversation* (theconversation.com), July 1, 2021, https://theconversation.com/how-we-measure-energy-efficiency-in-homes-isnt-working-162565 (accessed July 14, 2021).

18. Leatherby and Martin noted in 2019 that the world had almost doubled its energy consump-tion since 1980 (Lauren Leatherby and Chris Martin, 'How Each Country Contributed to the Explosion in Energy Consumption', July 9, 2019. *Bloomberg.com*; https://www.bloomberg. com/graphics/2019-international-energy-use-renewables-coal-oil/ (accessed July 14, 2021). Azzouz et al. note that carbon used in operating buildings is 10 times greater than their embodied carbon (Afaf Azzouz, Meike Borchers, Juliana Moreira, and Anna Mavrogianni, 'Life Cycle Assessment of Energy Conservation Measures during Early Stage Office Building Design: A Case Study in London, UK', *Energy and Buildings* 139 (2017 March): 547–68).

19. At the time of writing, the dedicated website for the Grenfell Tower Inquiry is being updated daily with transcripts of the evidence being presented: https://www.grenfelltowerinquiry. org.uk/evidence (accessed July 14, 2021)

20. See, for example, Carnegie Mellon University, 'Large Uncertainty in Carbon Footprint Calculating', *ScienceDaily*, December 13, 2010, https://www.sciencedaily.com/releases/2010/12/ 101213121741.htm (accessed July 14, 2021), or UN Industrial Energy Efficiency Project, 'The Importance of Setting an Accurate Energy Baseline', *IEEEgypt.org*, May22,2016, http://ieeegypt.org/the-importance-of-setting-an-accurate-energy-baseline/ (accessed July 14, 2021).

21. See, for example, William Bordass, Adrian Leaman, and Paul Ruyssevelt, 'Assessing Building Performance in Use 5: Conclusions and Implications', *Building Research and Information* 29, no. 2, (2001): 144–57, and J.F. Nicol and M.A. Humphreys, 'Adaptive Thermal Comfort and Sustainable Thermal Standards for Buildings', *Energy and Buildings* 34, no. 6 (2002): 563–72.

22. See note 23 below; also Sarah Khan, *Learning from History*, Historic England Research Report (London: Historic England 2021) (forthcoming)

23. In their introduction to a 1916 paper, Leonard Hill and his colleagues from the Medical Research Committee noted: *"For purposes of controlling the heating and ventilation of rooms the thermometer has been used and has acquired an authority which it does not deserve … It affords no measure of the rate of cooling of the human body, and is, therefore, a very indifferent instrument for indicating atmospheric conditions which are comfortable and healthy to man."* (Leonard Erskine Hill, O.W. Griffith and Martin Flack, 'V. The measurement of the rate of heat-loss at body temperature by convection, radiation, and evaporation', *Philosophical Transactions of the Royal Society B Biological Sciences* 207 (1916): 183–220, https://royalsocietypublishing.org/doi/pdf/10.1098/rstb.1916.0005). Together with other pioneers in thermal physiology, James D. Hardy invented tools to try to separate out – as much as possible – the different sources of thermal discomfort, noting that because the body processes act to control heat loss in complex ways: '…the physical laws of heat loss could not be applied directly to the human body'. Hardy's experiments suggested that at around 25°C 13–15% of heat loss from the body was by convection, about 21% by evaporation, and 66–68% by radiation (James D. Hardy, 'The Physical Laws of Heat Loss from the Human Body', *Proceedings of the National Academy of Sciences* 23 (1937): 631–7, https://www.pnas.org/content/23/12/ 631). Subsequent research places heat loss by radiation to around 60-65%: see for example, Igor Luginbuehl and Bruno Bissonnette, 'Thermal Regulation', in *A Practice of Anesthesia for Infants and Children, 4th ed.* (Philadelphia: Saunders/Elsevier, 2009), 557–67.

24. See note 23 above.

25. The fire which destroyed the Grade II Royal Clarence Hotel in Exeter is believed to have spread into the building through the holes cut through the walls for service runs (National Fire Chiefs Council, Cathedral Yard Fire, Exeter 28 October 2016, *NFCC Review* 25 July 2019 (Birmingham: NFCC, 2019), http://www.dsfire.gov.uk/News/Newsdesk/documents/NFCCReview.pdf)

26. Although 'best practice' and 'standards' are often assumed to be one and the same thing, there are important differences between them. 'Best practice' is defined to be the methodology that is generally considered to be optimal for achieving a desired goal. 'Standards' are rules used to ensure a specific minimum outcome or obtain a specific minimum result, often for certification purposes; they are typically established either by general consent, or more commonly by an authority such as the British Standards Institution (BSI). On its website, the BSi is very clear about the purpose of its Standards: https://www.bsigroup.com/en-GB/standards/Information-about-standards/what-is-a-standard/

27. Mohammad Kassem and Donald Mitchell, 'Bridging the Gap Between Selection Decisions of Facade Systems at the Early Design Phase: Issues, Challenges and Solutions', *Journal of Facade Design and Engineering* 3, no. 2 (2015): 165–83, https://content.iospress.com/articles/journal-of-facade-design-and-engineering/fde0037.

28. Craig Jones, 'Double or Triple Glazing? All Pane and No Gain?', *Circularecology.com*, January 21, 2014, https://circularecology.com/news/double-glazing-or-triple-glazing-all-pane-and-no-gain

29. See note 1 above.
"You may think you're building a risk assessment system to tell you whether someone will re-offend or recidivate, right? But you can't actually measure crime. You can only measure whether people were arrested and convicted. And so, you haven't built a crime predictor. You've built an arrest predictor … which is a very different thing."

30. These sample graphs were developed by the author for the special topic on reducing energy and carbon in Historic England's *Practical Building Conservation: Building Environment* volume (see note 4 above).

31. The data underlying these demonstrative illustrations was derived broadly as follows:

    Early sash windows

    - The figures for timber window frames are taken from Muhammad Asif, T. Muneer et al., 'Sustainability Analysis of Window Frames', *Building Services Engineering Research and Technology* 26, no. 1 (2005). The authors note that the production of timber frames in general has a comparatively low environmental impact, which will be minimal if the timber is sourced from a sustainably managed forest (true for all wood harvested prior to industrial forestry). Harvesting and processing were done by hand.
    - Early glass is more complicated, but is undoubtedly the greatest contributor to the energy (and carbon) cost of any early window. Quoted in an article for the Crosscut blog, Brandi P. Clark (executive director of Seattle's Glass Art Society), notes: *'We have always been harmful to the environment in that in early years we used wood-fired furnaces, so we were responsible for the deforestation of large areas to make glass.'* Later, the industry shifted to burning coal, and then natural gas. (Margo Vansynghel, 'Glass Art is a Gas Guzzler. Can Seattle Stoke the Flames of Environmental Change?' *Crosscut.com*, October 17, 2019,

https://crosscut.com/2019/10/glass-art-gas-guzzler-can-seattle-stoke-flames-environmental-change). Speaking with the author of this paper, Leonie Seliger (Director of Stained Glass Conservation at Canterbury Cathedral) noted that make a sugar-bag's worth of glass required the energy provided by a full-grown beech tree. Using this information and turning to sources such as Nickolas K. Meyer and Marco Mina, 'Wood Energy Fuel Cycle Optimization in Beech and Spruce Forests', *Environmental Research Letters*, 7 014001 (2012): 1–9, and Nike Kranjnc, *Wood Fuels Handbook*, (Pristina: Food and Agriculture Organisation of the United Nations, 2015), this equates to around 3600 MJ for kilogram of glass. In a 1 m × 1.5 m sash window with 2 mm cylinder glass, the weight of glass would be around 7 kg, so the energy used to make the window will have been upwards of 25,200 MJ (most of which will have been lost as waste).

- There are no operating costs, but all windows require cleaning, and timber frames require repainting or revarnishing every 5–10 years, plus perhaps the occasional replacement of a sash cord. Originally both paint and cord were produced by hand (largely from flax, *Linum usitatissimum*), and therefore had a very small energy footprint. Industrial processing and transport will now make all these materials rather more energy-expensive. Modern paints use fossil fuels as materials as well as for production: sources of information are scattered, but a reasonable estimate might be 100 MJ for a litre of acrylic paint. Replacement of occasionally broken panes would be much more energy-expensive again; although the broken glass could in theory be remelted and reused (a process requiring much less energy than conversion of the raw materials).

PVC double-glazed unit

- The figures for a double-glazed PVCu window are also determined using a range of sources. Figures for modern glassmaking depend on the efficiency of the process, and detailed information for float glass is surprisingly difficult to find (for an overview, see US Energy Information Administration, *Glass Manufacturing is an Energy-Intensive Industry Mainly Fueled by Natural Gas*, blog August 21, 2013, https://www.eia.gov/todayinenergy/detail.php?id= 12631) I am deeply grateful to Alice Moncaster for access to a recent report analysing publicly available data, which suggests an energy cost for tempered float glass of around 16 $MJkg^{-1}$ (Alice Moncaster, Jane Anderson, and Helen Mulligan, *Supporting the development of quality data: Availability, Quality and Use of Construction Product LCA Data for Ireland, Italy and Croatia* [Unpublished report for the Irish, Italian and Croatian Green Building Councils, 2021]). For two layers of glass, each 4 mm thick, this equates to 720 MJ.
- In an analysis of modern double-glazed windows, Raya Teenou does not include the energy cost of the glass, but notes that the major component of the energy cost is in the gases used to fill the double-glazed unit. Teenou gives figures a PVC frame that range from 4444 MJ for argon gas, to 18,599 MJ for the xenon gas used in thin units (Raya Yousef Teenou, *Energy and CO2 Emissions Associated with the Production of Multi-Glazed Windows* (MSc Thesis, Dept of Engineering and Environmental Science, Mid-Sweden University Ostersund, 2012), http://www.diva-portal.org/smash/get/diva2:532125/FULLTEXT01.pdf).
- Maintenance and repair are not currently possible for PVC windows, and there are no serious operational costs, but the lifespan of the units will be short: somewhere around 10–25 years, depending on quality. Because the glass is treated, it cannot be currently be remelted and used again to make window glass.

Micro CHP

- Micro CHP was chosen to represent a component requiring operational energy, because the energy figures are readily available (Evangelos Gazis and Gareth P. Harrison, 'Life Cycle Energy and Carbon Analysis of Domestic Combined Heat and Power Generators' (paper presented at Powertech 2011 IEEE, Trondheim, Norway, June 19–23, 2011), https://core.ac.uk/download/pdf/77021201.pdf). To make a unit costs around 10,000 MJ, for a lifespan of 15 years, with yearly maintenance costing an average 460 MJ. End-of-life costs are 3150 MJ (if all recyclable components are indeed recycled). Oper-ational energy costs are around 106,000 MJ per year.

  It should be noted that none of these figures include transport costs for either the raw materials or the processed products, although for modern components (with centralised production) these are likely to be significant.

32. Travel to the site remains the dominant component whenever carbon assessments are made of offices and other buildings in use. This is little surprise; for example, because of transport, tourism is now a greater source of greenhouse gases than the construction industry (accounting for 8% of emissions from 2009 to 2013) (Manfred Lenzen, Ya-Yen Sun, Futu Faturay, Yuan-Peng Ting, Arne Geschke and Arunima Malik, 'The Carbon Footprint of Global Tourism', *Nature Climate Change* 8 (2018): 522–8).
33. See, for example: National Audit Office, *Initiating Successful Projects* (London: NAO Communications, 2011), https://web.archive.org/web/20210516003300/https://www.nao.org.uk/wp-content/uploads/2011/12/NAO_Guide_Initiating_successful_projects.pdf; or the *Guide to Capability-Based Planning written by the Joint Systems and Analysis Group Technical Panel 3 of the The Technical Cooperation Program (TTCP)* (in Ben Taylor, *Analysis Support to Strategic Planning*, TTCP Technical Report TR-JSA-2-2013, June 2013, https://cradpdf.drdc-rddc.gc.ca/PDFS/unc194/p801995_A1b.pdf).

Disclosure statement

No potential conflict of interest was reported by the author.

Notes on contributor

Dr Robyn Pender is a physicist specialising in moisture transfer in building fabric, and has long-standing interest in sustainability. At the Centre for Sustainable Heritage at UCL she completed a scoping study for English Heritage looking at the effects of climate change onthe historic environment (archaeology and landscapes, as well as buildings), and then worked on a research project into flooding, before carrying both those interests forward to English Heritage (later Historic England) itself. As part of the team that produced the ten-part Practical Building Conservation series, Robyn was the editor for the *Building Environment* volume, as well as for *Metals*, and for *Glass and Glazing*. She is currently a Commissioner for the Cathedrals Fabric Commission for England, and researches and advises on all aspects of climate change mitigation and adaptation in the historic built environment.