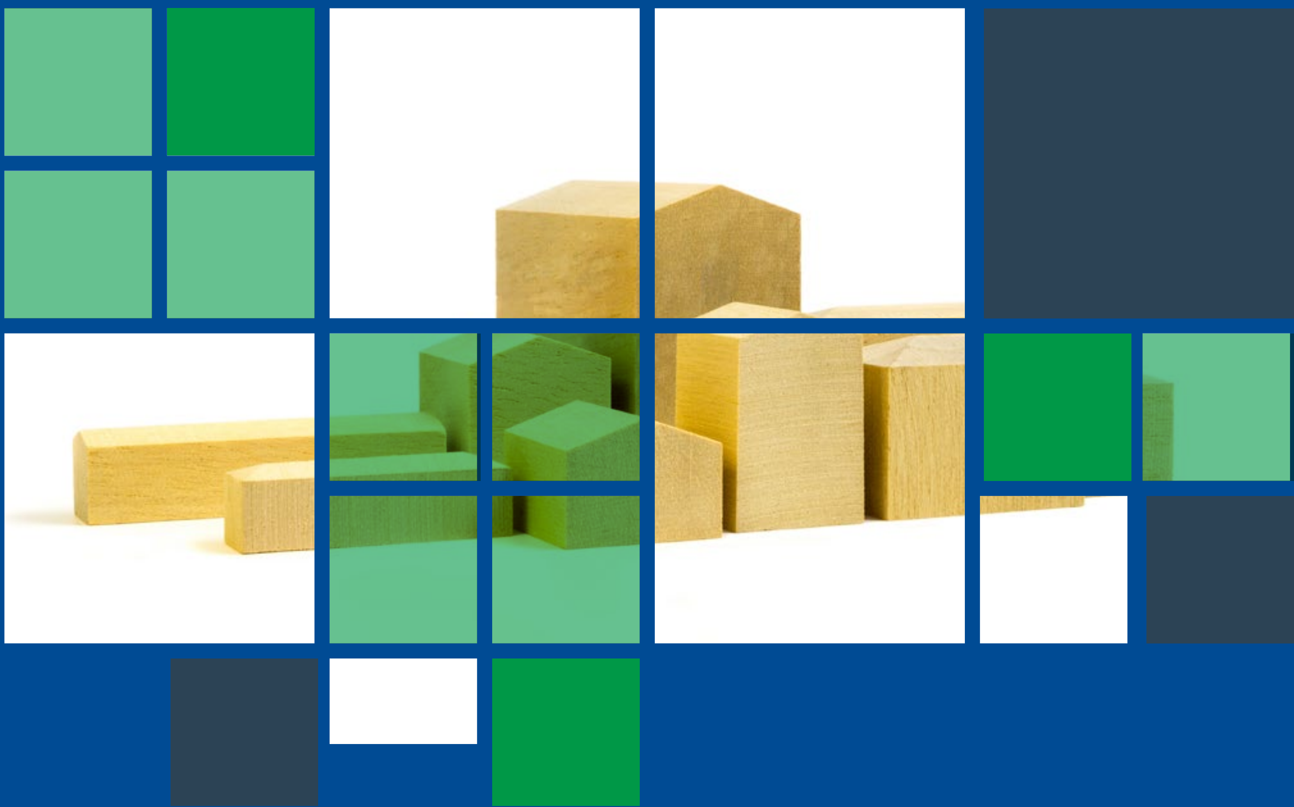
The challenge of shape and form

Understanding the benefits of efficient design



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Methodology

The space heating energy demand for the five house types used in this guide was calculated for the various scenarios using SAP software 'NHER Plan Assessor v. 6.1.2'. The house types all have a habitable floor area of 93m^2, and their fabric, ventilation and services are as specified in Appendix R of SAP v.9.92. Some of the conclusions were verified using the software 'Passivhaus Planning Package v.8.4'.

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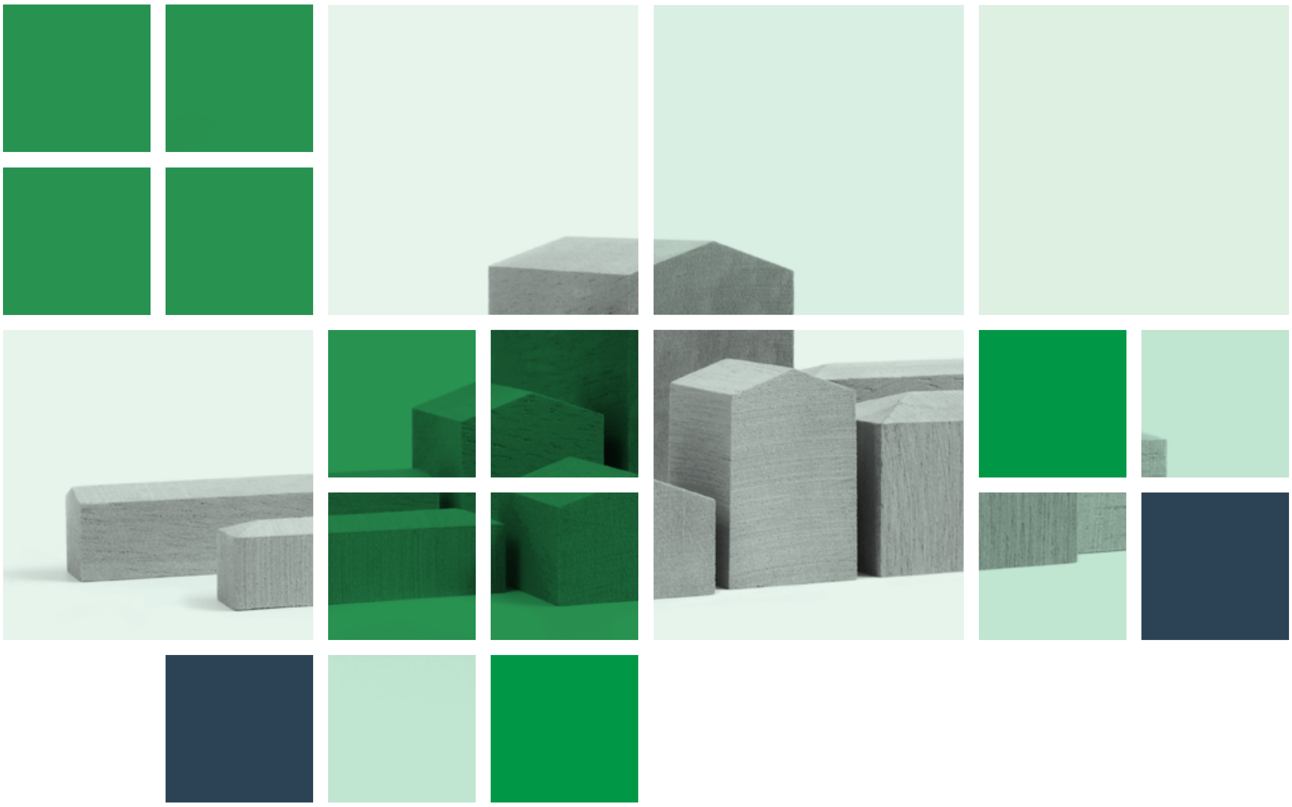

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October 2016

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The NHBC Foundation

The **NHBC Foundation**, established in 2006, provides high-quality research and practical guidance to support the house-building industry as it addresses the challenges of delivering 21st-century new homes. To date, it has published more than 70 reports on a wide variety of topics, including the sustainability agenda, homeowner issues and risk management.

The NHBC Foundation is also involved in a programme of positive engagement with the government, academics and other key stakeholders, focusing on the current and pressing issues relevant to house building.

To find out more about the NHBC Foundation, please visit **www.nhbcfoundation.org.** If you have feedback or suggestions for new areas of research, please contact **info@nhbcfoundation.org.**

NHBC is the standard-setting body and leading warranty and insurance provider for new homes in the UK, providing risk management services to the house-building and wider construction industry. All profits are reinvested in research and work to improve the construction standard of new homes for the benefit of homeowners. NHBC is independent of the government and house builders. To find out more about the NHBC, please visit **www.nhbc.co.uk.**

Contents

Foreword

The government's commitment, back in 2006, to a zero carbon target led to much debate about how new homes could be designed, specified and constructed to deliver a greatly-improved energy performance. A large part of the Foundation's work in the subsequent decade has focused on research and guidance which supports the low to zero carbon ambition. The industry has also been actively exploring the agenda, with a variety of approaches being trialled on individual homes and developments across the country.

Much of the focus has to date been on building fabric, insulation and new technology. Perhaps surprisingly, relatively little consideration has so far been given to how the shape and form of new homes impact upon energy efficiency. This report highlights the benefits of choosing efficient forms of housing and avoiding unduly complex shapes in order to minimise heat loss. Making the case for thinking about shape and form as early in the process as possible, the examples demonstrate that with careful design, homes with inherently energy-efficient shape and form need not lack visual appeal. It is perhaps even more important to note that they could actually be built at lower cost too.

Whilst further improvements to the energy efficiency standards of Building Regulations have been paused for the time being, the challenge of climate change will not go away. Coupled with the likelihood of continuing real terms increases in fuel costs, this suggests strongly that attention will return to improving the energy efficiency of new homes in due course. This report provides a useful insight into an approach which starts by considering the inherent efficiency of good shape and form before adding the fabric insulation and efficient services that are also needed. I hope it will prove thought-provoking and useful to all those involved in planning and developing homes for the future.

Rt. Hon. Nick Raynsford
Chairman, NHBC Foundation

1 Introduction

Introduction

The energy consumption of a building can be significantly affected by its type and shape. A mid-terrace house, for example, has a lower proportion of external wall and therefore a smaller heat loss area than a detached house of the same habitable floor area, and its energy consumption will be lower for that reason alone. Similarly, a home with a simple, compact plan shape (such as a rectangle) will have a lower energy consumption than one with a more complex outline such as an L-shaped or T-shaped plan. There are clear benefits to residents in terms of energy costs, and to the environment in terms of greenhouse gas emissions, if homes are of the optimal type and are designed with more efficient shapes. A home's type and shape can be collectively described as its 'Form Factor', a characteristic that can be defined numerically.

Figure 1 Different house types (left: detached; right: terrace)

Figure 2 Different shapes of houses (left: simple; right: more complex)

The mathematical models which are used to predict the energy consumption of homes (including the UK's national calculation methodology, the Standard Assessment Procedure, SAP) properly reflect the Form Factor and show a lower energy consumption for homes with better Form Factors, as expected.

However, when the basic results from SAP are fed into the Buildings Regulations compliance methodology which follows, the benefits of Form Factor do not register. The current Building Regulations in the UK are therefore unable to provide an incentive for industry to design and build homes that have a more efficient type and shape.

More importantly perhaps, designers who focus solely on Building Regulations compliance may not even realise that they can reduce the energy consumption of their homes by changing just the Form Factor. Improving the Form Factor can be a low-cost or no-cost measure, and even though Building Regulations give no credit for it, residents' heating bills can be reduced significantly – in some cases halved. It may be that government, when developing future policy, should consider ways of encouraging designers and developers to take advantage of this effect.

A drive for lower energy consumption through better Form Factors need not give rise to bland housing designs. Inefficient features can often be avoided or replaced by alternatives which are still architecturally interesting. So for example, a loss in building performance due to unfavourable solar orientation can often be recouped by adjusting the Form Factor.

A number of positive knock-on effects also arise from designing homes with better Form Factors. Certain designs can provide better comfort conditions for the residents, and can also reduce the amount of construction materials needed.

By paying more attention to this aspect of design, it is possible to provide visually appealing homes with lower energy consumption and a more pleasant internal environment. The challenge of shape and form is for anyone who wishes to procure, design, legislate for or build better homes at minimal extra cost.

2 Form Factor, and why it matters

The varied heat loss areas of different types of home can be appreciated more easily if their structures are 'unfolded', as in Figure 3. Note that both of the types illustrated have the same habitable floor area.

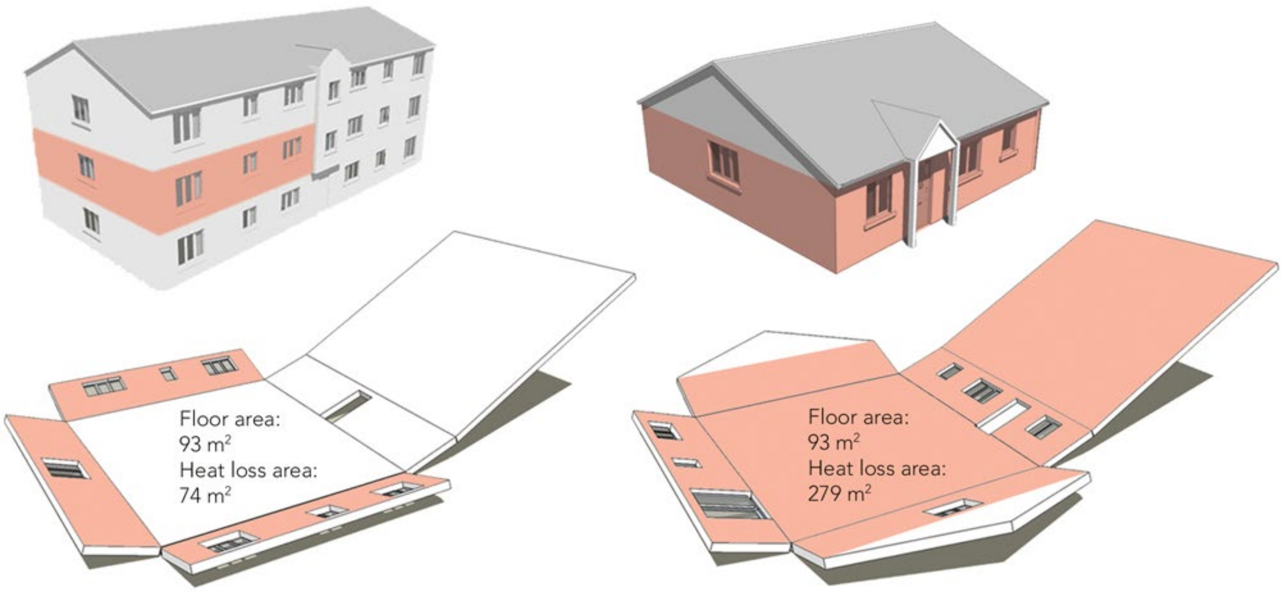


Figure 3 'Unfolded' structures with their heat loss areas shaded orange. End mid-floor apartment (left), bungalow (right)

In this report the efficiency of a building's type and shape is formally described by its 'Form Factor', which is defined as the ratio of the total heat loss area to the habitable floor area:

$$\text{Form Factor} = \frac{\text{Total heat loss area of walls, roofs, floors and openings } (m^2)}{\text{Habitable floor area of all storeys } (m^2)}$$

The lower the Form Factor, the more inherently efficient the building, because the heat losses are lower for a given floor space. Typical Form Factors for different types of home, all with the same habitable floor area, are shown in Figure 4.

	Type	Form Factor	Efficiency
	End mid-floor apartment	0.8	Most efficient
	Mid-terrace house	1.7	
	Semi-detached house	2.1	
	Detached house	2.5	
	Bungalow	3.0	Least efficient

Figure 4 The types of home and their Form Factors

Figure 4 shows, at the extremes, that even though the end mid-floor apartment has the same habitable floor area as the detached bungalow, the apartment is more than three times as efficient as the bungalow. Therefore, in order to achieve lower energy consumption (hence lower carbon dioxide emissions), designers and housing developers should aim for the types of home that have the lowest Form Factors[1].

Space heating energy demand

In this study, the energy consumption of the five house types shown in Figure 4 has been calculated using SAP software. All of the modelled house types have the same habitable floor area[2], so that the results show just the effect of Form Factor rather than being clouded by any difference in size. In terms of their fabric, ventilation and services, the house types correspond to a Building Regulations-compliant newbuild home at the time of writing[3].

Figure 5 shows how the space heating energy demand, in kilowatt hours per year (kWh/yr), increases as the Form Factor increases. However, the energy demand does not decrease completely to zero when the Form Factor is zero. This is because a certain amount of a home's heat loss occurs through ventilation rather than as conduction through the fabric.

All of these homes are the same size, and all of them pass Building Regulations. Yet the space heating energy demand of the worst one is more than twice that of the best.

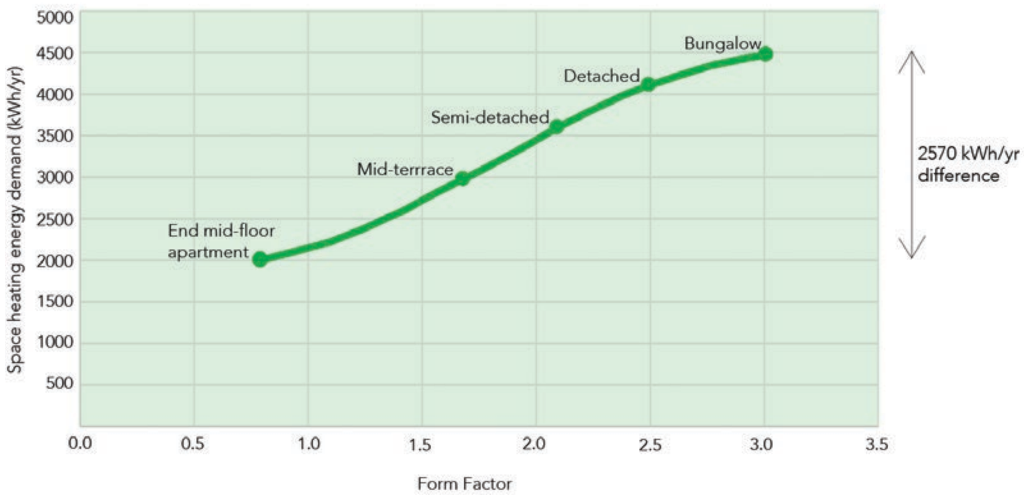


Figure 5 Space heating energy demand (kWh/yr) plotted against Form Factor for the different house types with the same habitable floor area

Figure 6 shows the same results but expressed as the additional space heating energy demand, in percentage terms, of each house type when compared to the one with the best Form Factor (the apartment). Remember that the habitable floor area is identical in all cases, and it is only the Form Factor that is changing.

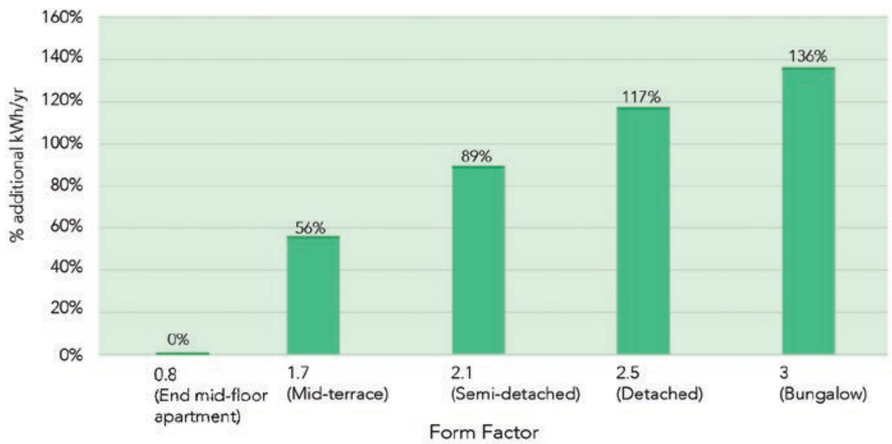


Figure 6 The additional space heating energy demand (%) for each type, compared to that of the end mid-floor apartment.

Similarly, the shape of a home affects its Form Factor and hence the space heating energy demand. Using the detached home as an example, the Form Factor varies from 2.5 to 2.7 when the building's shape is changed from a simple rectangle to a more complex L-shape with the same habitable floor area (see Figure 7).

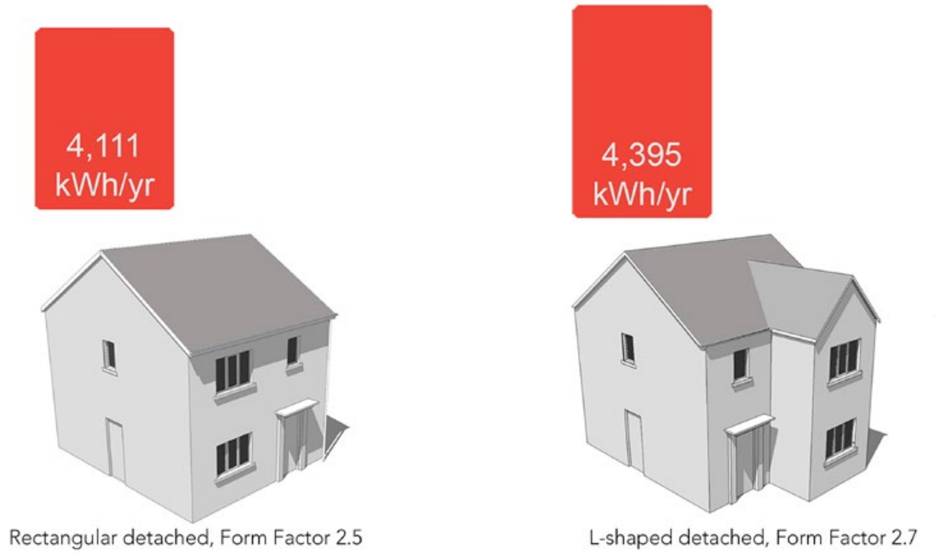


Figure 7 Different shapes of detached home

In addition to the basic type and shape of the home, a number of further features have a bearing on the Form Factor and hence the space heating energy demand:

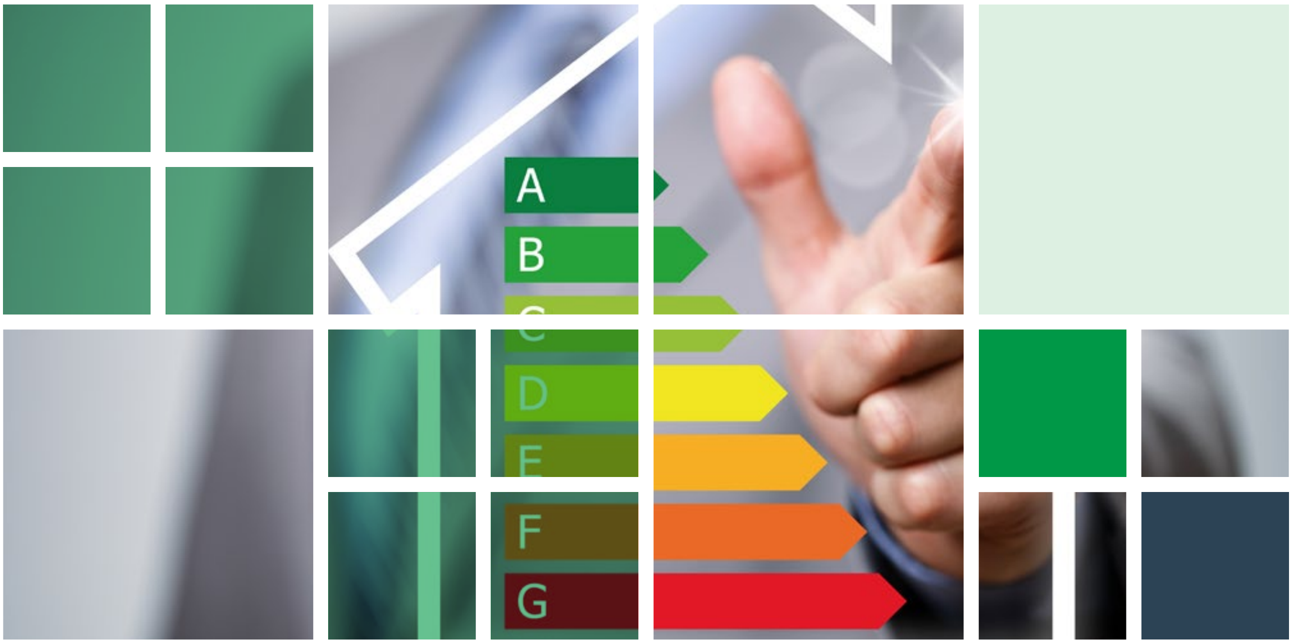
- the effect of the number of storeys
- whether there are rooms in the roof
- the amount of daylight penetrating the rooms
- various architectural design features

These are all discussed in the following sections.

Thermal bridging

A thermal bridge (or 'cold bridge') occurs at any point of weakness or discontinuity in the insulation of a thermal element. Commonly they occur at junctions between walls, floors and ceilings, where they are described as linear thermal bridges. When the Form Factor is changed, the length and type of linear thermal bridges at the construction junctions will usually change too. However, calculations show that the changes in the heat loss areas are far more significant. So while linear thermal bridges are important in absolute terms, and should always be minimised as recommended by various sources[4,5,6], in the context of encouraging better Form Factors they can be disregarded.

3 Building Regulations compliance



Figures 5-7 clearly demonstrate how the energy consumption of a home is affected by its Form Factor, so there is a direct benefit to the residents (in terms of running costs) and to the environment (in terms of carbon dioxide emissions) in designing and building homes with better Form Factors. This effect is accurately modelled by software tools such as the SAP.

However, the method by which UK homes are required to demonstrate compliance with the energy/carbon requirements of Building Regulations does not currently give credit for a better Form Factor.

The current method compares the proposed dwelling design with a 'notional' dwelling. The notional dwelling uses a standard set of values for its fabric, ventilation and services specifications, and these remain constant throughout the design process. However, **the type, size and shape of the notional dwelling always stay identical to those of the proposed dwelling, changing automatically whenever the proposed dwelling is altered by the designer.**

The calculated carbon dioxide emissions of the proposed design, known as the dwelling emissions rate or 'DER', must be less than or equal to the carbon dioxide emissions of the notional dwelling (the target emissions rate or 'TER').

Because of the way the method works, improvements to the proposed design's fabric and/or services will result in the DER decreasing both in absolute terms and relative to the TER, because the TER remains constant (see Figure 8).

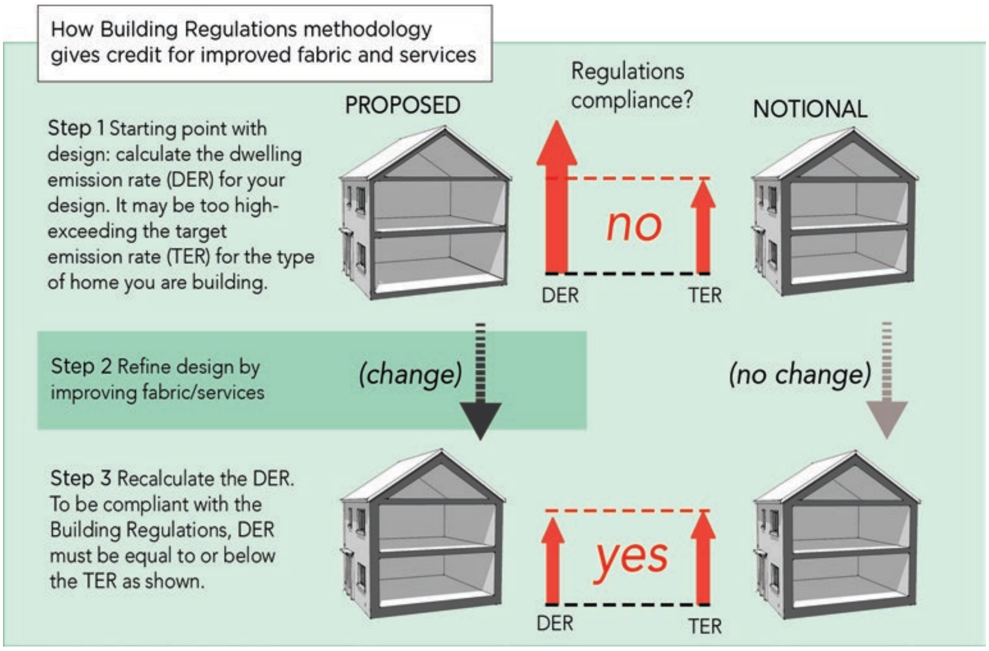


Figure 8 Improvements in fabric and/or services can achieve compliance

However, if improvements are made to the proposed dwelling's Form Factor instead, the DER and the TER will both decrease (see Figure 9). This is because the Building Regulations method requires that the proposed design and the notional dwelling must have identical Form Factors - so any improvements to the Form Factor will improve both the DER and the TER. In other words, the proposed design and the target move together, in the same direction, and as a result the proposed design will never be able to beat the notional dwelling by making improvements in Form Factor alone.

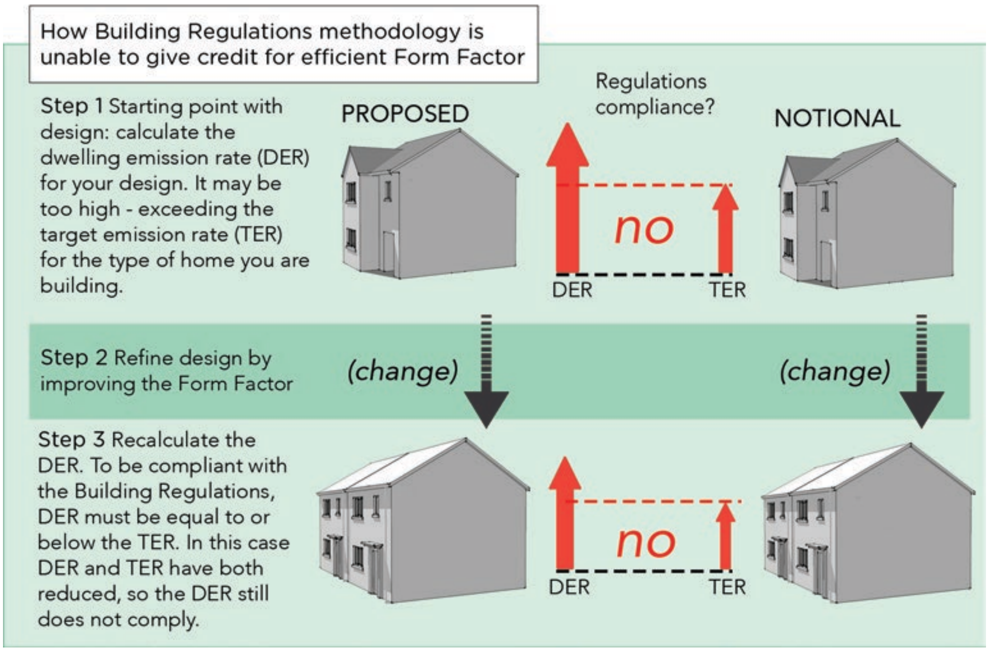


Figure 9 Improvements to Form Factor do not achieve compliance

It is worth noting that the additional fabric energy efficiency method of Building Regulations in England also works by comparing the proposed dwelling with a notional dwelling, and once again the notional dwelling target ('TFEE') moves in the same direction as the proposed dwelling ('DFEE') whenever improvements are made to the Form Factor[7].

Figures 8 and 9 demonstrate how the current Building Regulations methodology is unable to give credit for (let alone incentivise) the design of more efficient types and shapes. However, designers can often use the Form Factor to make their homes either better or worse in terms of energy consumption without affecting their compliance with Building Regulations – and improvements made via Form Factor can be low-cost, no-cost or even cost-negative in capital terms.

4 Design considerations

Form Factor is not only affected by the type of the home (whether it is an apartment, terrace, detached, etc.) but also by the detail of its shape. Features which add architectural interest such as recessed doors, bay windows or dormer windows, and site-dictated features such as staggered terraces are all likely to increase the total heat loss area of the home.

Figure 10 Bay windows, recessed doors, staggered terrace, dormer windows

Figure 11 below illustrates, for the mid-terrace house type, the change in space heating energy demand caused by making various design changes[8]. Once again the habitable floor area has been kept the same for all of the variations shown.

It is interesting to note that the change to a 'two-and-a-half storey' design, i.e. a room-in-the-roof, can actually improve the Form Factor slightly (i.e. reduce the energy demand) if roof lights rather than dormer windows are used. All of the other features make the Form Factor and energy demand worse.

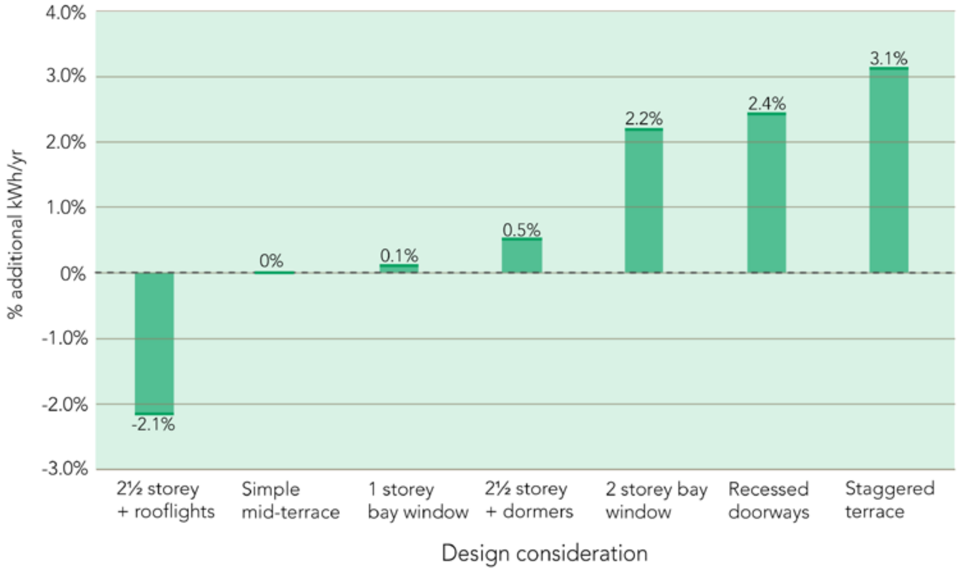


Figure 11 For the mid-terrace home, percentage changes in space heating demand caused by incorporating different design elements

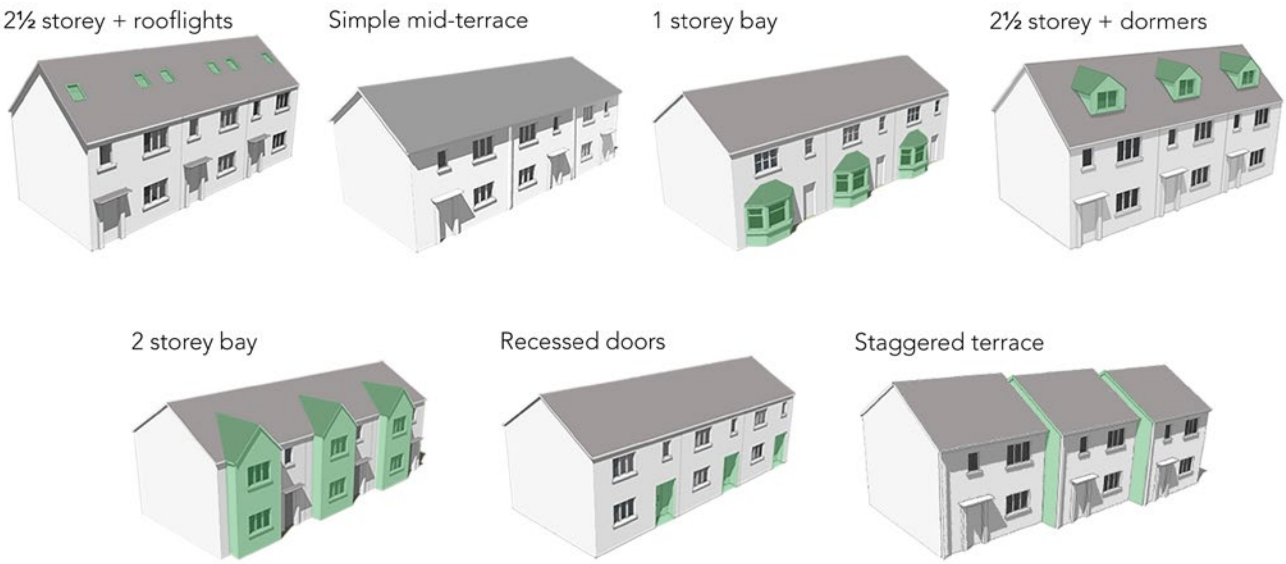


Figure 12 Design considerations, illustrated for mid-terrace homes

There is therefore a danger that, in striving for more efficient Form Factors, designers may find themselves led to produce bland designs with fewer aesthetic qualities. But this does not have to be the case. In purely architectural terms there are alternatives to all of these features. For example, recessed doors could be replaced by canopies over the entrance, and a similar 'feel' to bay windows could be achieved with window seats and alternative window reveal detailing. An example is shown in Figure 13.

Figure 13 Alternative design techniques replacing recessed doors and bay windows.

In many cases the imaginative use of materials can lend interest to a design without affecting the Form Factor. For example, the housing site in Figure 14 uses a change of material instead of a two storey bay to achieve the visual appeal of a more complex shape.

Figure 14 Imaginative use of materials to create visual appeal

Another example is the use of cladding and overhanging eaves to give a three-storey home the look of a two-storey home. In the example shown in Figure 15 the planning authority initially requested a two-storey design, but the client wanted three storeys because of its better Form Factor and lower energy consumption. Both parties were happy with the resulting design.

Figure 15 Two storeys or three?

Integral garages

Incorporating an integral garage fundamentally changes the type and shape of a home. For example, in terms of heat loss area, incorporating an integral garage into the mid-terrace type effectively turns it into a semi-detached type; its Form Factor increases by nearly 25% from 1.7 to 2.1. In this example the space heating energy demand also increases by nearly 25% (677 kWh/yr). This effect is sufficiently large that integral garages should be given special consideration during design[9].

Figure 16 Integral garages

5 The effect of solar gain

The definition of Form Factor does not include the compass orientation of the building. Nevertheless, many designers habitually consider orientation alongside type and shape when determining optimal site layouts. Some researchers have said that the effect of Form Factor is comparable in magnitude with that of dwelling orientation; the view was that where a site is constrained so that efficient Form Factors are impossible (or are undesirable for, say, aesthetic reasons), the lost energy benefit can be clawed-back through more favourable solar orientation.

More recent thinking, however, has begun to question the pursuit of lower energy bills through 'extreme' passive solar techniques[10]. Firstly, the amount of beneficial solar gain under winter conditions that can be typically exploited in a modern well-insulated, lightweight home is, in fact, relatively small. Figure 17 shows the change in space heating energy demand of the detached house type as it is orientated progressively away from South. **It is important to note that this house is a 'typical' new home, not one that is deliberately designed to maximise solar gain.** In this case it can be seen that as the orientation is changed the variation in space heating energy demand is small. So for typical new homes (as opposed to ones that have been specifically designed to maximise solar gain), orientation plays little part in determining the energy consumption.

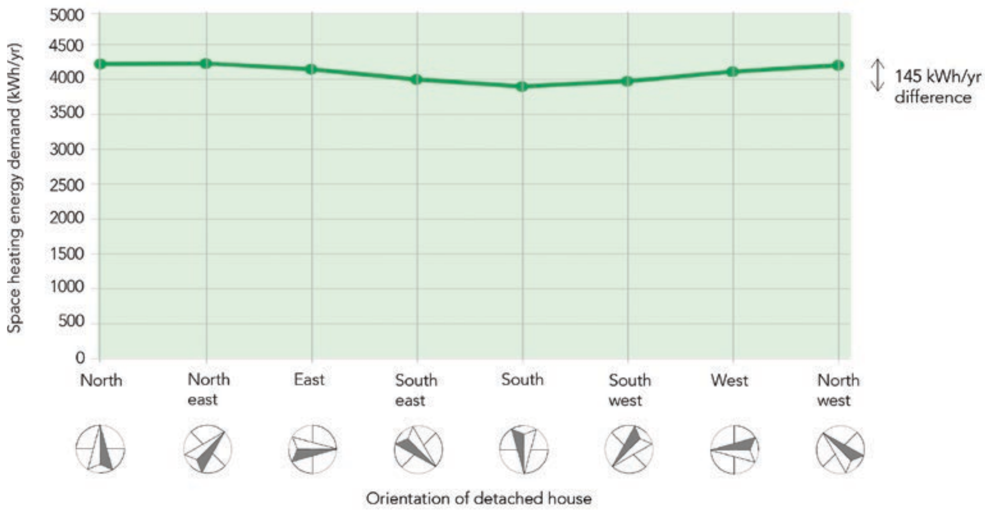


Figure 17 The effect of changing orientation

By way of comparison, Figures 5-7 in Section 2 show that the effect of Form Factor, for five different types of home all with the same floor area, is many times more significant than the effect of changing orientation. So the new thinking on passive solar techniques does not present a problem; any perceived lost benefit can easily be recouped through better Form Factors.

There is also a growing awareness of the potential for some new homes to overheat in summer. In 2015 a survey of housing providers[11] found that '53 out of a possible total of 75 organisations (70%) reported experiencing at least one instance of overheating in their housing stock in the last 5 years.' Another study in 2013[12] concluded that of nearly 200 unheated homes that were monitored during a single summer, '47% of bedrooms exceeded temperatures of 24°C for more than 5% of occupied hours – the temperature at which sleep is thought to become impaired.'

Homes designed deliberately to maximise solar gain can have extremely low energy consumption, but their design is a specialist matter which is outside the scope of this report. Designers and builders of typical new homes may therefore prefer to focus on Form Factor rather than solar orientation as a strategy for reducing energy consumption.

6 Additional considerations

Once designers start to place more emphasis on achieving an efficient Form Factor, it also becomes necessary to consider various side-effects. Some of these are beneficial, and others are potentially detrimental.

Daylighting

The pursuit of a better Form Factor can lead to deeper-plan homes, where the rooms extend further back from the external walls. This can cause the rooms to become gloomier, because the daylight from the windows does not penetrate as effectively to the far side of the room. This can have a negative impact on the residents' wellbeing, as well as requiring more electric lighting with its associated higher bills and carbon emissions.

Figure 18 A poorly-daylit deeper-plan room

The daylighting within a room can be improved by using brighter, more reflective, surface colours. It can also be improved by raising the ceiling height, essentially allowing the installation of taller windows which provide an increased view of the sky outside; Victorian and Georgian houses famously used this technique, although larger modern homes can also make use of it. The extent of daylighting within a room can be predicted by carrying out an Average Daylight Factor calculation[13].

Figure 19 A well-daylit Georgian house; note the high ceiling and tall window

It is important to avoid summertime overheating as discussed previously, and there is clearly an optimum window size where daylighting is maximised yet excess solar gain can be avoided. A common rule of thumb for designers is that window areas of around 20% of the external wall area of the room will achieve good daylighting[14,15]. Shading devices can help to avoid overheating as discussed in Section 5, although care must be taken that they do not reduce the extent of daylighting too much[16].

The trade-off between daylighting and overheating is a specialist area for which designers may wish to seek expert advice.

Passive ventilation

As discussed in Section 4, room-in-the-roof design can improve a home's Form Factor. A useful side-effect is that roof rooms are commonly 'cross-ventilated' because they often span the whole house and have openable windows on opposite sides of the room; this type of ventilation can make the room feel cooler in summer.

Room-in-the-roof design can also provide a very simple form of passive stack ventilation where, simply by opening the roof lights on a hot day, a cooling draft can be created through much of the home via the stairwell[17]. The system can be enhanced by the inclusion of an automatic window opener which responds to elevated temperatures (and closes automatically if it rains).

The Sigma home

A study conducted on the Sigma Home at BRE's Innovation Park in 2008[18] concluded that 'The passive solar stack and automatic window at the top of the house proved key to preventing peak day overheating. This automatically responded to the overheating spikes at peak summertime day temperatures, particularly when the occupants were returning to the home following work. Passive solar stack ventilation provides effective mitigation of overheating without compromising security and is likely to be commonplace in future "zero carbon" homes.'

Figure 20 The Sigma Home

Where more sophisticated ducted passive stack ventilation (PSV) systems are installed, they generally perform better in taller buildings. Taller buildings also achieve better Form Factors, so the pursuit of improved Form Factors can in this instance have the beneficial knock-on effect of improving the home's ventilation levels.

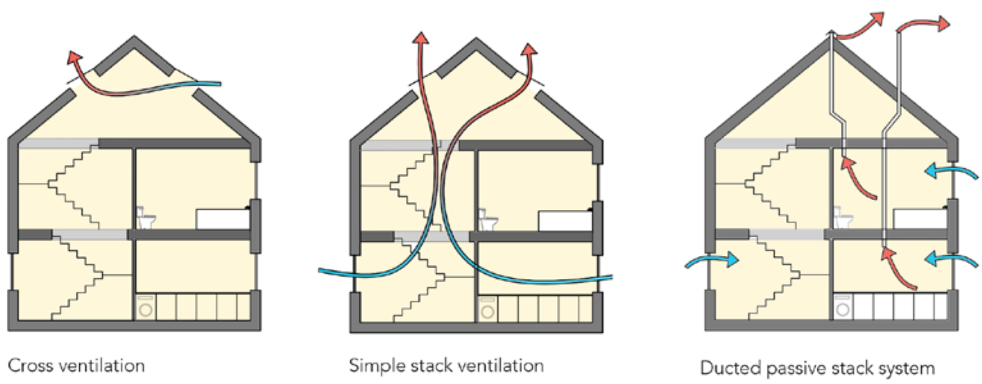


Figure 21 Cross ventilation; simple stack ventilation; ducted passive stack system.

Basements

In terms of Form Factor, incorporating a basement has the same beneficial effect as adding a storey (assuming that the habitable floor area remains the same). A useful side-effect of basements is that they also provide a cool space, improving the overall thermal comfort level of the home.

However, basements present specific design challenges, depending on ground conditions. NHBC Standards offer guidance on design, materials and construction[19].

Land and materials

In many cases, homes with better Form Factors will take up less land. For example, a 3-storey house of a given habitable floor area will have a lower ground-floor area than a 2-storey house with the same habitable floor area. This could enable more efficient site layouts and improved economic viability.

In other cases, the amount, and hence cost, of materials required for construction can be reduced by building homes with better Form Factors. For example, a row of terraced houses will require fewer facing bricks than the same number of semi-detached houses, simply because there is a smaller area of external wall.

7 Conclusion

This study demonstrates that by achieving better Form Factors, designers and developers can significantly reduce the energy consumption of new homes, sometimes at little or no extra cost. Whilst it is not possible to quote a single 'best practice' value of Form Factor at which designers might aim, a greater understanding of Form Factor can bring benefits to both house builders and residents.

Ideally, Form Factor will gain a 'currency' of its own, and will be included among the key parameters that are tracked and discussed as a housing development design evolves. This is already the case in countries where alternative design approaches are popular; the Passivhaus standard, for example, lists efficient building shape as one of the five key design considerations when planning a new energy efficient building[20].

A greater awareness of Form Factor can also help designers to avoid style features which negatively affect a home's energy consumption. Done properly, this does not have to lead to architecturally bland homes. There are, or course, factors other than energy and carbon dioxide emissions to consider (for example consumer attitudes to the different types and shapes of homes, noise transmission, tenure, etc.). The pursuit of a better Form Factor need not conflict with these areas either, and the benefit to the residents can be compelling.

An understanding of Form Factor will also help to inform those who are considering how Building Regulations might be evolved in the future.

Notes and references

1 The ratio of surface area to volume is sometimes used as a similar indicator to Form Factor, and leads to the conclusion that the most efficient three-dimensional structure is a sphere. Form Factor, as defined in this report, is a more useful indicator for homes because it encapsulates not only the surface area to volume ratio but also the type of home and its size.

2 Floor area = 93m^2, taken from Table 1 of Technical housing standards – nationally described space standard. Department for Communities and Local Government. 2015.

3 See reference values in Appendix 'R'. The government's standard assessment procedure for energy rating of dwellings 2012 edition version 9.92, dated October 2013 revision June 2014. Department of Energy and Climate Change. 2014.

4 Designing homes for the 21st Century - lessons for low energy design. NHBC Foundation. NF50. 2013.

5 Part L 2013 - where to start: An introduction for house builders and designers - masonry construction (NF58) and timber frame construction (NF59). NHBC Foundation. 2014.

6 Thermal bridging guide. Zero Carbon Hub. 2016.

7 Note that the fabric energy efficiency method does not apply in Wales or Scotland.

8 A similar effect occurs for all of the house types, with the changes in space heating energy demand broadly similar in absolute terms.

9 See Section 2.4. Designing homes for the 21st century – lessons for low energy design. NHBC Foundation. NF50. 2013.

10 See, for example, http://www.greenbuildingadvisor.com/blogs/dept/musings/gba-prime-sneak-peek-reassessing-passive-solar-design-principles.

11 Overheating in homes – the big picture. Zero Carbon Hub. 2015.

12 National survey of summertime temperatures and overheating risk in English homes. Beizaee A, Lomas K J and Firth S K. Building and Environment, Volume 65. July 2013.

13 Site layout planning for daylight and sunlight: a guide to good practice. Littlefair PJ. IHS BRE Press, 2nd edition. 2011.

14 For rooms with windows on one side, up to 7m room depth. Huw Heywood. 101 Rules of Thumb for Low Energy Architecture. RIBA Publishing. 2012.

15 Alternatively an Average Daylight Factor can be calculated, with a value of 1.5% normally being considered adequate for living rooms, dining rooms and studies.

16 Understanding overheating – where to start: An introduction for house builders and designers. NHBC Foundation. NF44. 2012.

17 See Section 2.5. Designing homes for the 21st Century - lessons for low energy design. NHBC Foundation. NF50. 2013.

18 Thermal comfort in UK housing to avoid overheating: lessons from a 'Zero Carbon' case study. Rijal H B and Stevenson F. Proceedings of Conference: Adapting to change: new thinking on comfort. Windsor UK. April 2010.

19 Waterproofing of basements and other below ground structures. NHBC Standards, Chapter 5.4. 2016.

20 Passivhaus primer: Designers' Guide – a guide for the design team and local authorities. BRE. See page 2.

The challenge of shape and form

Understanding the benefits of efficient design

The energy and carbon requirements of Building Regulations do not explicitly give credit for housing designs with lower heat loss areas or more efficient shapes. Yet through a better understanding of these issues, designers and developers can significantly reduce the energy consumption of new homes, sometimes at little or no extra cost. This report explains the issues and discusses ways that designs can be improved.

The pursuit of lower energy consumption through more efficient shape and form does not have to lead to bland or monotonous housing designs. The report describes how the most inefficient design features can often be avoided or replaced by alternatives which are still architecturally interesting. Many designs can provide better comfort conditions for the residents as well.

The NHBC Foundation, established in 2006, provides high quality research and practical guidance to support the house-building industry as it addresses the challenges of delivering 21st century new homes. Visit www.nhbcfoundation.org to find out more about the NHBC Foundation research programme.

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