Alternative, more sustainable, wall construction techniques than brick and block, for new housing in England and Wales

Alternative, more sustainable, wall construction techniques than brick and block, for new housing in England and Wales

by

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Abstract

There is a need to reduce the emissions of the country as a whole, to limit the risk of climate change due to Global warming and to meet targets set by the Kyoto agreement and the Climate Change Act. The large number of houses constructed annually in England and Wales have an important role to play in this. By reducing emissions, resulting from both the manufacture of construction materials and the energy used by house occupants, housing can help achieve the necessary emissions reductions. Alternative construction methods can contribute to this, either by having a lower embodied energy or by demonstrating good thermal properties to limit heat loss and hence operational energy. However, it is essential that both the construction industry and the public accept the alternative construction methods for them to be economically viable. In addition, there should be no loss of performance as a result of using alternative construction methods.

Six methods of construction were studied in depth, including generating embodied and operational energy requirements and identifying their performance in terms of airtightness, wall thickness, and fire resistance. Public and industry acceptability were examined by use of questionnaires. A comparison of the data collected showed that identifying the best, or optimal, option visually is a challenging task as no single method of construction is best in all areas. A methodology was created to aid the selection of a wall construction method. The methodology is capable of examining multiple variables, in this work it is demonstrated with construction method and front building dimension. To identify the optimal method, optimisation by genetic algorithms is used. Use of the methodology was demonstrated with a case study based on the most frequently constructed housing type for England and Wales. The importance of weighting was demonstrated with the use of weightings based on concerns held by different parties. It was found that minimising the external wall area gives the optimal solution as less material is needed and there is less opportunity for heat loss. For the situation examined in the case study, Structural Insulated Panels (SIPs) were identified as having the potential to reduce the environmental impact of housing construction in England and Wales without impacting saleability or performance.

Contents

List of tables

List of figures

1. Introduction

1.1. Background and motivation

The need to reduce energy use and the associated carbon emissions on a global scale is widely known. In England and Wales, over 100,000 houses are built every year (DCLG 2012a).This large number of houses contributes significantly to the energy emissions of the countries. Energy used to manufacture materials for construction has an immediate effect on emissions; the performance of the buildings has an impact on the emissions far into the future across the lifespan of the building. Reducing these energy requirements has the potential to play a significant role in reducing the carbon emissions associated with energy generation for England and Wales.

The use of alternative methods of construction, moving away from the traditional method of brick and block, may offer a solution to this. This may be as a result of choosing methods which require less energy to manufacture, or ones which demonstrate better thermal efficiency, resulting in reduced heat loss and hence reducing the energy required for heating and its associated emissions. However, it is necessary to maintain other aspects of performance as required by the Building Regulations (DCLG 2013a). In addition, houses that are constructed must be acceptable to purchasers and the construction industry. If there is no market for houses built using alternative methods they may result in a financial loss and hence would not have the support of the construction industry. The construction industry must be prepared to use and invest in an alternative method of construction for it to achieve wide spread use in housing.

Considering all these aspects presents a challenge. A large number of factors must be evaluated and there is rarely a single solution that presents a clear best option (Tam et al. 2007). Some level of compromise will always be necessary. In this work optimisation is used as the basis for a selection method, identifying the best possible compromise for a given situation.

1.1.1. Climate change

Greenhouse gas emissions are widely acknowledged to have a negative impact on the environment, in particular, resulting in changes to climates across the World as a result of "global warming". The mechanism believed to be responsible for this is the increased quantities of greenhouse gases in the upper atmosphere reflecting heat back onto the Earth's surface, rather than allowing its emission out in to space. The Intergovernmental Panel on Climate Change (IPCC) report on global warming and climate change found as high as a "90% confidence that human activity was responsible for global warming" (IPCC 2007). The result of this is a net increase in the global temperature. Increasing temperatures are predicted to result in widespread changes to the environment, including changes to regional climates, melting of the polar ice caps and increasing sea levels. All of these have the potential to negatively affect populations and ecology on a global scale.

In order to limit the potential for global warming, and the resulting climate change, emissions of the greenhouse gases responsible need to be reduced. Internationally this was agreed by many countries at the Kyoto summit in 1998, which resulted in the Kyoto Protocol (United Nations 1998). The Kyoto Protocol committed the participating countries to achieve set reductions or stay below a maximum increase in greenhouse gas emissions by the end of 2012. In the case of the EU the target to be achieved was an 8% reduction below 1990 levels (United Nations 1998). The emissions reduction requirements were shared among the member states by the EU. As a result of this the UK was been set a target of a 12.5% decrease in emissions below 1990 levels (Department of Energy and Climate Change, 2012). This is an increase on the 8% required for the UK independently by the Kyoto Protocol. A number of summits have been held in an attempt to set ongoing targets for emissions reductions once the Kyoto Protocol deadline has passed. These have taken place in Bali (December 2007), Poznan (December 2008), Copenhagen (2009), Cancun (2010) and Durban (2011). However no further agreement has been reached.

To achieve the emission reduction targets set for the UK as a result of the Kyoto Protocol, the Climate Change Act came into force in 2008. This sets a legally binding requirement for the UK to reduce carbon emissions to 80% below 1990 levels by 2050 (Climate Change Act 2008). This is an ambitious target, to achieve it all areas of life will have role to play. In England and Wales, Part L of the Building Regulations incorporates emissions restrictions to help achieve the required emissions reductions (DCLG 2013b), see Chapter 1.1.2.

1.1.2. House building

House building in England and Wales is controlled by a number of Governing bodies, including Planning and Building Regulations. Although there has been a dip in the number of houses constructed annually as a result of the recession, 113,400 dwellings were completed in England and Wales during 2010-2011 (DCLG 2012a). It can be seen that even a small saving in the energy and associated emissions on each property could result in a significant saving each year. This saving would help with achieving the goals of the Climate Change Act (2008).

Currently the levels of emissions from operational energy, that is, energy used for heating, lighting, hot water and building services is controlled by the Building Regulations via the Code for Sustainable Homes. By 2016 all new houses built should achieve a Level 6 in the Code for Sustainable Homes which requires them to meet the zero carbon standard (Department for Communities and Local Government 2007a). To achieve this, the annual net value of heating, lighting, hot water and building services energy requirements must be zero. The Code for Sustainable Homes also gives consideration to other aspects of the construction, such as waste management and materials, however energy use accounts for much of the score achieved.

1.1.3. Use of alternative construction methods

The typical method of housing construction for England and Wales is a double skinned brick and block construction, with an air cavity between the leaves; it was used for 88% of housing In England from 1990 to March 2009 (DCLG 2010). There is evidence of other construction methods being used, in particular, timber frame, which accounted for 7% of houses constructed in England from 1990 to March 2009 (DCLG 2010). Examples of alternative construction include those presented by The Insulating Concrete Formwork Association who provide information on the use of Insulating Concrete Formwork (2009); Morley (2000) gives details of using Structural Insulating Panels (SIPs) and Jones (2007) who discusses straw bale construction. The use of a wide range of materials in construction, their benefits and disadvantages is discussed by Calkins (2009). The authors who discuss alternative methods of construction present their advantages, and drawbacks. However, despite the advantages presented, alternative methods of construction are rarely used, “other” methods making up only 5% of construction in England from 1990 to March 2009 (DCLG 2010).

Timber framed construction went through a period of greater use in the nineteen sixties and seventies. However, the popularity fell drastically when a 1983 television report stated that timber framed construction was prone to rotting and fire (Cavill 1999). Cavill (1999) stated that the use of timber framed construction was increasing in England and Wales, with prefabricated timber construction of particular interest.

The use of a wide range of construction methods has been demonstrated by the Building Research Establishment (BRE) at the BRE Innovation Park (BRE 2013). These methods are predominantly innovative, with methods used which have little history of use in the UK. This provides an opportunity to examine how these construction methods perform in the UK climate. Construction methods such as Structural Insulating Panels and Insulating Concrete formwork can be seen to be moving from the innovative, research based, area of construction, becoming more mainstream (The Insulating Concrete Formwork Association 2009).

International experience can also be considered when examining alternative construction methods. Timber framed construction is widely used in the USA. Although the variations in climate must be considered, the performance and lessons learned from overseas examples can be applied to the UK situation.

Typically, innovative methods of construction have been for research purposes and, in some cases, adopted by self-builders (Jones 2007). Identification of innovative methods of construction that have the potential for mainstream use is necessary to achieve the benefits they can offer in terms of enhanced performance.

1.1.4. User views

It was considered that the views of the public are often discounted when making construction decisions. As they represent the end user and are the ones who will make an investment in the finished property, their views are important when making decisions. If a particular option does not have public support, selling the finished house will be difficult. This makes the option undesirable to the construction industry as they risk making minimal profit, or a loss. The acceptability of construction methods within the construction industry must also be considered. Issues with saleability are not the only factor that can reduce industry interest. Lack of knowledge or perceived difficulties with the construction method would decrease its appeal. Resistance to change, both from the public and the construction industry, was expected to be identified in this work as one of the greatest challenges for alternative methods of construction.

1.1.5. Selection of construction methods

It is stated above that selecting the best option from a range of construction methods can be challenging as desirable characteristics are often in conflict with each other (Castro-Lacouture et al. 2009, Seo et al. 2004, Diakaki et al. 2010). Making a decision between the available options, when there is often no one "best" solution can be a challenge (Emmanuel 2004).

A number of methods exist for assessing a building design, ranging from scoring it based on the Code for Sustainable homes to a full Lifecycle analysis (LCA) in which all aspects of the construction throughout its life are considered. The Code for Sustainable Homes considers options on a limited number of aspects. Those affecting construction method choice are energy use and materials (DCLG 2007a). Methods such as LCA can be time consuming and costly (Björklund 2002). A more effective method that balances the wider range of aspects which need to be considered, with a reasonable time and cost input is required.

1.2. Work carried out

In this work, the construction method is taken to be the combined materials used to build the house wall, rather than the actual way in which it is constructed. "Construction material" was discarded as a term as each method uses multiple materials. Brick and block construction, with an insulated and air filled cavity is considered to be the typical method. Alternative methods of construction are any other method, five alternatives were examined in detail- Structural insulated panels, insulating concrete formwork, prefabricated straw bale panels, thin joint block work, timber frame with brick cladding.

This work focused on two areas of the issue of using alternative methods of wall construction as a way to reduce the environmental impacts of housing construction: the acceptability of a range of alternative construction methods, and the use of optimisation in a design methodology to assist with choosing the best method. Six methods of construction were chosen for detailed study. These included brick and block as a "control" and a range of alternative methods, including modern methods of construction and a method considered highly unusual. The alternative construction methods were Structural Insulated Panels (SIPs), Insulating Concrete Formwork (ICF), prefabricated straw bale panels, thin joint block work and timber frame with brick cladding. Methods were selected to maintain a brick outer appearance where possible in order to avoid acceptability being affected by visual appearance.

To examine the awareness acceptability of the construction methods two surveys were carried out. The acceptability was examined from the point of view of the public and the construction industry. It was considered that both these parties must support an alternative construction method for it to be considered a viable method for use. It was found that awareness of alternative methods of construction is fairly high, particularly within the construction industry. The acceptability of the construction methods examined varied greatly. Brick and block had the highest acceptability; this was expected as it the typical method used in the area of study. Good levels of acceptability were also seen with SIPs, ICF and thin joint block work, indicating these have the potential to be used in mainstream construction. Poor acceptability was seen for prefabricated straw bale and timber frame construction, although some respondents showed interest in their use. These methods are less likely to be suitable for speculative construction as there would be a limited market and they would present an economic risk for the builder. The acceptability scores for each construction method were used in the optimisation based design methodology created later in the work. Responses to the survey indicated a wide range of concerns about each construction method. It was noted that many of these concerns have already been disproven by existing research or anecdotal evidence. If these concerns could be addressed, the acceptability of all the examined methods may be increased. Education is the key to achieving this, and accessing the advantages alternative construction methods present.

Views were also collected on factors which are important when considering a house purchase or method to use in construction. Principal component analysis, which combines the factors into groupings which demonstrate key issues, was used to identify areas of public concern as environmental, financial, and risk. For the construction industry the most important factor was thermal efficiency. The importance of factors was used to create weightings for the case study which demonstrates the use of the optimisation based methodology.

The optimisation based methodology created in this work was intended to demonstrate the methodology of selecting the construction method and front building dimension based on the best compromise of energy use, acceptability and performance criteria. There is great potential for expanding the methodology using the methods demonstrated to create a fully functional design methodology.

Each of the construction methods being examined was studied in depth. Data was collected and generated regarding the embodied energy and performance of the walls created, including *U*-value, wall thickness, airtightness, and fire performance. These aspects were used as they demonstrate a range of criteria and can all be affected by changing the materials used in wall construction. Particular consideration was given to the embodied energy of the construction methods. It was noted that bricks had a major impact on the total embodied energy of all methods that used them. Consideration was given to how this impact could be reduced and the impact this may have on the optimisation. Survey results indicated a strong preference for a brick external finish. The need to balance the reduced embodied energy with the acceptability based on appearance was identified as an important consideration. Brick slips were identified as a possible solution.

An equation was generated which combines all the performance criteria with weightings and normalisation to create a single value, representing the score for the combination of variables being considered. Optimisation was then applied to this equation, running it multiple times with different input values in order to find the best solution. For this work the variables selected were front building dimension and the construction method used. Other factors, such as floor area, house type and region could also be used as variables.

To demonstrate the use of the optimisation based methodology a case study was created. The values used in this were based on the most frequently constructed house type and size in England and Wales. An initial run, with equal weightings for all factors identified brick and block construction as optimal. Values for this optimisation run were used to demonstrate how examining the fitness landscape by use of visual representations of the solution space, for example two and three dimensional graphs, can lead to the selection of optimal and sub-optimal solutions. Equal weightings were not considered to be representative of a realistic scenario. Two sets of weightings were generated based on survey responses, one focusing on the public interests and one on the interests of the construction industry. The results of the public focused weighting indicated that prefabricated straw bale construction was the best option, with SIP construction being sub-optimal but scoring well. The industry focused weighting found SIP construction to be the optimal solution. Based on these two sets of results and consideration of the two construction methods, SIPs were identified as the best method of construction for the given scenario and situation.

1.3. Aims and objectives

This thesis aims to explore the benefits that alternative methods of construction may present and the issues with their use. Ways in which the use of alternative methods of construction can be increased are considered. Increased use would allow the benefits to be accessed.

The objectives of the work were:

- To examine the potential for alternative methods of construction to reduce the operational and embodied energy associated with housing whilst maintaining performance.
- To determine the current acceptability of alternative methods of construction to house purchasers and the construction industry.
- To identify what might increase the acceptability of alternative methods of construction.
- To develop an assessment method using optimisation to identify the optimum construction method to use in a user defined scenario, this may be by designers, builders, planners.
- To demonstrate the use of this assessment method with a case study.
- To consider the impact the case study solution could have on housing construction in England and Wales.

1.4. Limitations

In order to complete the work a number of limitations were set.

- The area of study was restricted to England and Wales. At the time of this work they were covered by a single set of Building Regulations. Scotland and Northern Ireland were excluded as they are covered by different construction regulations. However, these countries have many similarities; the design methodology could be used with only minor alterations.
- The area of study was split into regions based on standard divisions. These were East Anglia, East Midlands, London, North East, North West, South East, South West, West Midlands, Yorkshire and Humberside and Wales.

- The number of methods of construction was set at six to allow time for the depth of study required.
- Methods of construction focused on the walls only, other elements such as roofing, windows and foundations were not included.
- A maximum height of three storeys was considered in this work. Some of the construction methods considered in this work cannot be used at heights greater than this, therefore it was set as a limitation.
- Only houses were considered in this work. Flats were not considered as they typically have different construction methods and tend to be built to a greater height than the three storeys considered here.

Although these limitations were placed on the work presented here, the optimisation based methodology was designed so that it could be expanded to allow a wide range of these aspects to be included. Greater numbers of construction methods, other countries and regions, other construction elements and different building types could all be accommodated using the methods presented here. It was intended to present a methodology, rather than create a fully functional design tool.

1.5. Thesis structure

Literature review- A review of current literature covering this topic was carried out. The results of this are discussed.

Construction methods- The selection and details of the six construction methods used in the work are discussed. Consideration is also given to construction methods not selected and the reasons why. Further details of the selected methods' performance and embodied energy are given.

Public acceptability- Details of the survey carried out to determine user acceptability are given. The results and analysis are discussed.

Construction industry acceptability- Details of the survey carried out to determine the views of the construction industry on alternative methods of construction. Consideration of the results of the survey and the implication for use of alternative construction methods.

Creation of the optimisation based methodology- Data identified from the Construction methods and Acceptability chapters was combined with optimisation techniques to create a method of selecting the best construction method for a given scenario.

Case study- To demonstrate the use of the optimisation programme a case study was developed. This was based on the most frequently constructed housing type for England and Wales. A range of weightings were used. Comparison of the embodied energy, operational energy and performance of the suggested method with the traditional method of construction is given.

Conclusions- Conclusions drawn from the work are discussed.

Further work- Potential areas for adjustment and expansion of the design methodology are given.

References- References used during the work

Appendices- Further details on aspects of the work not included in the main text.

2. Literature review

2.1. Introduction

Aspects of existing literature considered to be relevant to this work were housing construction in England and Wales, the use of alternative methods of construction, decision making in construction and the role of acceptability in construction decision making. Existing work on these elements was reviewed in relation to the themes of this thesis.

2.2. Housing construction in England and Wales

2.2.1. Construction figures

The number of houses constructed in England and Wales has been seen to fall recently, believed to be as a result of the recession. Table 2.1 shows the number of houses constructed for the years between 2000 and 2011.

Table 2.1- Number of houses completed in England and Wales from 2000 to 2011 (DCLG 2012a).

	Number of houses completed		
Year	**England**	**Wales**	**Total**
2000-01	129,870	8,270	138,140
2001-02	137,740	8,310	146,050
2002-03	143,960	8,300	152,260
2003-04	155,890	8,490	164,380
2004-05	163,400	8,260	171,660
2005-06	167,680	9,330	177,010
2006-07	170,610	8,660	179,270
2007-08	140,990	7,120	148,110
2008-09	119,910	6,170	126,080
2009-10	107,890	5,510	113,400
2010-11	118,190	5,580	123,770

It can be seen from Table 2.1 that there was a reduction in the number of houses constructed between 2007 and 2011. However, the number of completions increased from 2009-10 to 2010-11. Although the number of completions for 2010-11 was thirty percent lower than the peak seen in 2005-06, there are still a large number of houses being constructed. This means that even a small saving in energy requirements and the associated emissions per housing unit could have a significant impact on the overall emissions of England and Wales.

2.2.2. Construction type

New housing built in England and Wales is typically of the speculative type. Housing is often built in large numbers on a single site. The design and layout of the buildings is often replicated many times on a large site, with a small number of layouts being repeated. The scale of speculative construction is discussed by Barlow (2000) and Roy and Cochrane (1998). Much of the new housing construction in the UK is carried out by a relatively small number of building firms, ten firms were responsible for 82.5% of completions in 2008 (McMeeken 2009).

An important impact of the speculative nature of construction in England and Wales is the need for the buildings to have widespread public appeal. Houses are typically planned and built before the end user is identified (Barlow 2000, Roy and Cochrane 1998). In order to be economically viable the selection of housing construction method must not negatively impact the potential for sale. This work gives greater focus to the speculative method of construction by including acceptability in the decision methodology discussed in Chapter 6. The decision methodology could also be used in a one off design situation to identify the best compromise in terms of energy use and performance; however acceptability would be based on the client's preference.

Consideration was given to the typical aspect ratio of housing in England and Wales. This is affected by the values of front building dimension, which was used as a variable in the optimisation based methodology. Work which makes use of a typical house as a case study, such as that presented by Monahan and Powell (2011); show an aspect ratio in the region of 1:2. In this work the impact of altering the front building dimension, and therefore the aspect ratio is considered. A dimension of 5.0m is recommended by Chown (1999) as the minimum front dimension for easy internal layout design, although it is suggested that dimensions as low as 3.5m are possible. The impact of this on aspect ratio will vary with the floor area of the house.

2.2.3. Sustainability in construction

The impact of the construction industry on the environment is controlled to some degree by the need to meet the requirements of the Code for Sustainable Homes. The code is a set of mandatory and optional standards that are used to assess the environmental impact of housing. Once assessed, the house is given a level to indicate its performance. From 2013 all new build houses are required to meet Level 4 standards; by 2016 all new build homes must achieve Level 6 (DCLG 2008a).

The element of the Code for Sustainable Homes with the greatest impact is the requirement for new build housing to meet the zero carbon standard from 2016, i.e. to achieve Level 6 of the Code for Sustainable Homes. This requires the emissions associated with heat and lighting, hot water and building services to meet levels which drop progressively towards zero by 2016 (DCLG 2007a). In addition to representing the greatest number of points in the Code for Sustainable Homes scoring system, energy use also has a greater weighting than the other categories, giving it the greatest significance. Other environmental impacts, such as water use, materials, waste disposal and impact on ecology are also considered, with points available for these which can improve the level achieved.

Several elements of the Code for Sustainable Homes potentially have an impact on this work. Operational energy will be impacted by both the construction method used, and the value of front dimension for semi-detached and terraced houses. The construction method will affect the operational energy as a result of varying U-values across the methods considered; a method with a low U-value will result in a better score than one with a higher U-value. In the consideration of detached houses the front dimension does not affect the total external wall area so will have no impact on energy use. However, for semi-detached and terraced properties, increasing values of front dimension will result in a greater value of external wall, and hence greater heat loss if no changes to construction materials are made. This will increase the operational energy requirements. The score given in the Code for Sustainable Homes for materials also impacts the construction method selection process. Points are given for responsible sourcing and the green guide rating. However, all materials considered in this work achieve a rating of A or A+ so there is little differentiation between them under the Code for Sustainable Homes (BRE Global Ltd. 2008). Additionally, many of the aspects considered in this work, such as embodied energy, acceptability and wall thickness have no impact on the score achievable. As such the Code for Sustainable homes was discounted as the basis for optimisation work carried out in Chapter 7 of this work.

The need to minimise the operational energy was taken as an important factor from the Code for Sustainable Homes. In order to achieve the increasing level requirements as time progresses it will be necessary to construct ever more efficient buildings.

Identifying construction options which contribute towards this will help in the design of buildings able to meet the required level.

2.3. Using alternative methods of construction

2.3.1. Available methods

A wide range of construction methods and materials that can be used instead of brick and block exist. Many of these methods have already been used to build houses in England and Wales, for example, in England timber framed construction was used for 7% of the houses constructed from 1990 to March 2009 (DCLG 2010). "Other" methods, were used for 5% of houses over the same time period. Brick and block and Timber frame have a significant history of use in England and Wales for housing. In addition there is support for their use, such as Accredited Construction Details (DCLG 2011) and Enhanced Construction Details (Energy Saving Trust 2011) which provide guidance on meeting part L of the Building Regulations. They are currently only available for brick and block, timber frame and steel frame.

Examples of other methods of construction that have been used in England and Wales include straw bales, steel frame, prefabricated "pod" construction and rammed earth. It is worth noting that the Approved Documents, which provide guidance for the Building Regulations, do not prescribe any particular method, any method can be used, provided the requirements of the Building Regulations are met (Tricker 2004). Regulation 7 of the Building Regulations states that materials should be "adequate and proper", appropriate for the circumstances and installed properly (HM Government 2006). Any construction method that can satisfy all these requirements can potentially be used for housing in England and Wales. Details are also given in Regulation 7 of ways that a material can be shown to satisfy the requirements. These include meeting British, European or other national standards; having technical approval, for example, CE marking or approval by an independent certifier; testing and calculation to demonstrate performance; past performance to the required standard or higher and sampling and testing of the chosen materials by Building Regulations inspectors (HM Government 2006).

The environmental impacts, both positive and negative, of a wide range of materials are discussed by Calkins (2009). It can be seen from the work by Calkins (2009) that material selection will always require a degree of compromise, all materials require energy to produce and hence have an environmental cost from the outset. There will be both benefits and drawbacks to any construction methods considered.

A number of authors such as Jones (2007), Morley (2000) and the Insulating Concrete Formwork Association (2003) identify alternatives to brick and block construction and discuss their benefits. Choosing between the options available is not usually considered. Desirable characteristics are often in conflict with each other (Seo et al. 2004, Tam et al. 2007, Diakaki et al. 2010), so compromises must be made. Achieving the best compromise requires the various properties and their relative importance to be considered. This challenge of identifying the best compromise is explored in this work with the use of optimisation.

Timber framed construction shows the greatest level of research and past examples of the alternative methods of construction considered in this work. It is a method with a long history of use and is widespread globally. Historically, England and Wales showed an increase in timber framed housing construction during the nineteen sixties and seventies. However, a television programme shown in 1983 claimed timber frames were vulnerable to rotting and fire, this caused a significant loss of consumer confidence, and resulted in a drop in timber framed housing (Cavill 1999). An increase to the 7% of new build homes from 1990 to March 2009 (DCLG 2010) has been seen. Cavill (1999) suggested that timber frame would be popular with builders because of the time and cost advantages of preassembly, the potential for better thermal performance and the potential to sell timber as “environmentally friendly”. However, the demonstration of the impact customer acceptability can have is important to consider. Mahaptra et al. (2012) give the main advantage of timber frame is given as the ability to prefabricate.

Examples of alternative methods of construction in England can be seen at the BRE Watford Innovation park (BRE Ltd. 2013). Buildings at the Innovation park have been constructed to demonstrate ways in which high levels of sustainability can be achieved in construction. This includes buildings constructed to meet Level six of the Code for Sustainable Homes, and buildings constructed using a wide range of methods, including framing, traditional methods, natural materials, modular construction, off-site construction, structural insulated panels, (BRE Ltd. 2013). These examples provide data and examples which can be used to encourage the use of these alternatives on a wider scale within England and Wales.

Consideration should also be given to the international experience of housing construction. Framed construction is widely used for housing globally, in particular in the US and Japan (Roy et al. 2002) and Sweden (90% of single family houses Mahaptra et al. 2012). Work by Mahaptra et al. (2012) examined the acceptability of timber framed construction to the public and construction industry in the UK, Germany and Sweden. Negative views of the method were identified in all countries from construction professionals, and from the public in the UK and Germany. These negative views were considered to be a barrier to increased use of timber framing.

There is much greater use of timber frame in Scotland; 29% of houses built from 1997 to 2002 were constructed with timber framed walls (Communities Scotland 2002). Cavill (1999) reports that the fall in acceptability seen during the nineteen eighties in England and Wales was not experienced in Scotland and suggests this may be a result of better thermal performance from timber framed construction. This provides examples of timber frame in a similar climate to that seen in England and Wales and demonstrates the achievable performance.

Straw bale construction began in Nebraska in the US, as a process it has since been altered and refined and is now used globally (Jones 2007). An important consideration when comparing international examples is the impact of the climate experienced by the England and Wales. The temperate climate experienced, which tends to be warm and wet, has the potential to negatively impact on construction materials. Long term evidence of performance is required (Jones 2007). An example of straw bale construction in a mainstream use exists in the form of social housing constructed by North Kesteven District Council (North Kesteven District Council 2012), who state it was a cheaper construction method.

Modern methods of construction, such as Insulating Concrete Formwork (ICF), Thin joint blockwork and Structural Insulated Panels (SIPs) can be seen as emerging forms of construction. Much of the work that has been done on these construction methods comes from international experience, such as work by Morley (2000), Denzer and Hedges (2007) Johnston and Gibson (2008), Mosey et al. (2009). This existing body of work based on international experience can be combined with examples in the UK to provide information and evidence to encourage the use of these methods. Research has also been carried out on these methods within the UK, for example work by Barista (2008) and Bregulla and Enjily (2004). Additional UK support for these methods of construction exists in the form of specialist associations, for example The Insulating Concrete Formwork Association, who provide guidance on the use of ICF (ICFA 2009) and the UKSIPS Association who provide guidance on the use of SIPs (UKSIPS 2012).

Morel et al. (2001) discuss the potential for local materials to reduce the environmental impact of housing. This is demonstrated with the use of a French case study. A complexity which can be seen with the use of local materials is that the available materials will vary with location.

A key example of international housing construction with an environmental focus is the development of the Passivhaus standard in Germany. The standard aims to minimise the energy requirements of housing by the use of passive heating and cooling methods, for example good thermal properties, airtightness and natural ventilation (BRE Ltd. 2011). This method of construction is comparatively common in Germany, with 20,000 units built by July 2012, however it has yet to be widely adopted in the UK, with just 165 units by July 2012 (NHBC Foundation 2013). This is a set of design criteria which can be combined with any method of wall construction, provided the thermal performance and airtightness are sufficiently high.

2.3.2. Innovation

It has been shown that there is little use of alternative methods of housing construction currently in England and Wales, with the typical methods being brick and block (88%), timber frame (7%) and “other methods” used for 5% of new build houses (DCLG 2010).

The need for innovation to access alternative methods of construction is considered by Mahaptra et al. (2012) in relation to timber frames. Methods such as demonstration houses, education for both the construction industry and house purchasers, financing of research and legislation are suggested as ways to increase the attractiveness of alternative methods of construction. Of these methods, the main driver for innovation in England and Wales may be the Code for Sustainable Homes. When the reluctance of the construction industry to change is considered, as discussed by Ravetz (2008), innovation may only occur when it is forced. The role of legislation should therefore be considered. Support for innovation in relation to alternative methods of construction could take the form of education, financial incentives and research to prove performance. The creation of Accredited Construction Details (DCLG 2011) and Enhanced Construction Details (Energy Saving Trust 2011) for alternative methods of construction could also support their use. These provide guidance on meeting part L of the Building Regulations and are currently only available for brick and block, timber frame and steel frame; having this support for alternative methods of construction may increase their acceptability and drive innovation.

The adoption of innovative methods is discussed by Emmitt and Yeomans (2008), with the process being awareness of the innovation, gathering of information, making the decision to adopt or reject the option, if is chosen, then it is implemented and reviewed, with a decision made as to whether the option should be used again in the future. The gathering of information is a key step here, which ties with previous comments on the need for education and information to encourage innovation. Emmitt and Yeomans (2008) and Mackinder (1980) both note the importance of time in designers adopting innovative options. Time is required to research and fully understand innovation solutions, this can discourage their use. Information on products must also be easily accessible, Mackinder and Marvin (1982) note that designers are reluctant to find written information from manufacturers regarding products.

Examples of innovation in construction can be seen in work carried out by the Building Research Establishment (BRE). Research into materials and sustainable construction is demonstrated at the BRE Watford Innovation Park, where sample houses have been constructed to high sustainability standards using a range of alternative materials. BRE support for innovation can also be seen in the promotion of the Passivhaus standard, with guidance provided for achieving the Passivhaus standard (BRE Ltd. 2011). If similar guidance were provided for alternative methods of construction, this may support their adoption by the industry and public.

An example of innovation can be seen in North Kesteven District Council building social housing using straw bale construction, this has led to Epping Forest District Council planning a similar development (North Kesteven District Council 2012). This demonstrates the need for one company, council or group of people to take the first step, to make the innovation, and demonstrate the benefits which can be accessed.

2.3.3. Operational energy

The operational energy of a building is the energy required to run heating, lighting and all other power requirements. Legislation requires that from 2016 all new build homes are constructed to zero carbon standard (DCLG 2007a). In 2011 zero carbon was defined as meeting all energy requirements for heating, fixed lighting, ventilation, hot water and building services. Energy requirements associated with other activities, such as running appliances, is not covered.

In order to reduce the heat loss from the building high standards of airtightness and U-value should be aimed for. The selection of construction methods which perform well in these areas will reduce the heat loss, and hence the energy required to heat the building. This places a lower requirement on the energy generation and makes the required construction standard more achievable. From this it was taken that the U-values of alternative methods of construction should be considered and their impact on operational energy requirements considered.

2.3.4. Embodied energy

The embodied energy of a material or system is the energy required for its manufacture. The energy required for transportation, installation and end of life disposal can also be considered to form part of the embodied energy. The embodied energy associated with construction is not currently considered in the assessment of housing in England and Wales; however, in recommendations made by the Low Carbon Construction Innovation and Growth Team (2010) it is suggested that a method should be agreed upon and implemented to allow for the whole life accounting of carbon in projects. Ravetz (2008) estimates embodied energy is responsible for 27% of the energy associated with housing. As the value of operational energy falls in line with the Code for Sustainable Homes requirement, embodied energy will be responsible for an ever increasing proportion of the lifetime energy cost. An additional benefit of reducing the embodied energy of construction is that it does not rely on user behaviour. By making changes to elements which do not rely on a specific type of behaviour, such as the building fabric, the intended improvements can be maintained and the effects of unpredictable behaviours limited.

A number of authors have discussed how the use of alternative methods of construction can contribute to a reduced embodied energy. Buchannan and Honey (1993) present an example comparing concrete and steel construction with an equivalent timber building. They demonstrate, through the use of material quantities combined with embodied energy coefficients, that the use of timber results in a building with a lower embodied energy and hence reduced carbon emissions. Hammond and Jones (2008) discuss the generation of embodied energy coefficients and demonstrate their use in assessing the embodied energy of buildings using a similar method to that in the work by Buchannan and Honey (1993). Gonzalez and Navarro (2006) carry out an analysis of a real life building and its equivalent, fictional, counterpart constructed from low impact materials. They demonstrate that careful selection of materials has the potential to reduce the energy requirements and environmental impacts of construction. However, it is noted that selecting a material with a higher embodied energy may be preferable if the lower energy option has other negative environmental impacts (Gonzalez and Navarro 2006). Issues associated with comparing embodied energy values for houses and apartments are discussed by Hammond and Jones (2008), the variations in living space, stairways and external works affect the values for different housing types.

A higher value of embodied energy may still be a viable construction option if it results in better performance. The greater embodied energy can be balanced against the value of operational energy saved. This relates to comments by Gonzalez and Navarro (2006) about the selection of a material with a higher embodied energy if it has a lower environmental impact in some other way, such as pollution during manufacture.

2.3.5. Performance

The performance of construction methods can vary greatly, depending on their material components. The potential exists to greatly improve the performance of housing by selecting alternative construction methods which demonstrate the desirable characteristics. For example, the airtightness of brick and block construction is considered to be $4.5m^3/hr.m^2$ at 50Pa (Miles-Shenton et al. 2007); this can be compared with an airtightness of 0.5 to 1.0 $m^3/hr.m^2$ at 50Pa for Insulating Concrete Formwork (ICF) construction (Miller 2012). A lower value of airtightness is desirable as reduced movement of air results in lower heat loss and hence lower operational energy. The continuous nature of the concrete achieved by ICF contributes greatly to the low value of airtightness. In comparison, the multi element nature of brick and block construction makes such levels difficult to achieve.

Aspects to consider could include speed of construction, U-value, embodied energy, durability, cost, wall thickness, airtightness, fire performance, and any other aspect of performance that is considered important to those involved with constructing the building and the end user. Including these aspects in the decision making process adds to the complexity as it is rare for one construction method to perform best on all aspects under consideration. The optimisation method discussed later in this work provides a way to deal with this issue.

In this work consideration is given to U-value (assessed through operational energy), embodied energy, airtightness, fire performance and wall thickness. Although this is a limited range, it was selected for use in the optimisation process with the intention that the methods demonstrated could be used for future expansion of the construction method selection methodology created in Chapter 6.

2.4. Decision making in construction

The decision making process for adopting innovative solutions has been considered in Chapter 2.3.2. An important consideration from this is that time is required for designers to become familiar with new products in order to use them (Emmitt and Yeomans 2008, Mackinder 1980). If time is not available or other difficulties with decision making arise, such as lack of information or understanding, designers will typically opt for solutions they are familiar with (Emmitt and Yeomans 2008). In the case of this work, the familiar decision would be brick and block. This can be seen as a barrier to the adoption of alternative methods of construction. Emmitt and Yeomans (2008) also note that construction professionals often have preferred options, which they will choose over alternatives based on this personal preference.

However, despite the tendency of the industry to resist change, alternative methods of construction are used in some cases. Methods which can be used in the information gathering and decision making aspects of adopting innovation are considered here. Two aspects of assessment are considered- the way in which a particular method performs can be assessed using a wide range of tools and methodologies; ways in which a method can be selected from a range of options are also examined. Optimisation was chosen as the selection method for this work; it is discussed in greater detail in this chapter. Background information and examples of use are given.

2.4.1. Assessment methods

Performance assessment will typically form part of the method selection. It is usually necessary to assess the performance of an option in order to compare it with an alternative. As further options are identified they will need to be assessed to allow comparison and identification of the best option. As the assessment may need to be carried out multiple times when selecting from a range of options, it is necessary to balance time and cost requirements with the level of detail achieved.

Options can be assessed in relation to a National, or local, set of regulations or recommendations. Examples of these include the Code for Sustainable Homes (CfSH) in England and Wales, and the Leadership in Energy and Environmental Design (LEED) system in the U.S. An example of this is work carried out by Castro-Lacouture et al. (2009). Alternatively the options can be assessed against a set of criteria selected by the method designer, such as in work by Abeysundara et al. (2009), Emmanuel (2004), Seo et al. (2004), Li and Shen (2002) and Harris (1999). Lifecycle assessment (LCA) is used as a way of examining the performance and cost of a building throughout its lifespan. This method is demonstrated by a number of authors, including Monahan and Powell (2011) and Anastaselos et al. (2009). Issues with LCA are discussed by Björklund (2002).

Harris (1999) considers the assessment of the environmental impact of building materials in terms of a number of factors. Embodied energy is considered here, the calculation method used is the same as the one presented by Hammond and Jones (2008). Material quantities are combined with the embodied energy per unit to create a total. Those factors which cannot be assessed using quantitative means were scored from 0-3 in terms of perceived impact. In work by Harris (1999) the values found for each impact factor are not combined into a single figure. Harris (1999) considers that this would risk masking issues in one area with benefits in another, preferring the use of a profile. As well as assessing the performance of an option, Harris (1999) demonstrates the use of the profiles to compare two options. Although comparison of a small number of options can be carried out visually based on a profile, if a larger number of construction methods are to be compared this would become highly complex. Visual inspection of a profile may make it difficult to identify the best option as it is rare for a material to perform best on all factors. In order to compare many different options in this work a single figure must be generated to allow the use of optimisation. In addition, the application of weighting would limit issues associated with poor performance being in a highly important area.

Monahan and Powell (2011) demonstrate the use of a lifecycle analysis in comparing the construction of a timber framed building with a more traditional equivalent. The work by Monahan and Powell (2011) examines the embodied energy and associated carbon emissions of the buildings considered throughout its entire life, from material production to disposal at end of life. As with other methods presented in existing work, identification of the best option by Monahan and Powell (2011) is carried out visually. While this is effective for a small number of options it would be inefficient across the number of options considered in this work, as an example, the case study presented in

Chapter 7 would require the consideration of 5.8×10^4 options. LCA is widely considered to give the most accurate values as all inputs and outputs are required. However, to carry out a full lifecycle assessment on the larger number of options examined in this work would be highly computer intensive and time consuming, and hence costly and impractical for design work. In addition to cost and time taken, difficulties associated with LCA identified by Björklund (2002) include reliability of input data and changes over time. Therefore, a method of assessment was sought that would consider the costs and benefits of each option in a way that showed acceptable accuracy but required a smaller degree of calculation.

The method presented by Anastaselos et al. (2009) makes use of a materials database to generate a LCA for a range of insulation options. The method relies on the user inputting their option and examining the results. Identification of the best option is not carried out by the tool described by Anastaselos et al. (2009); it is an assessment method rather than a selection tool. Work by Anastaselos et al. (2009) gives consideration to the embodied energy associated with the materials used. This was considered to be an important aspect of the environmental cost of construction which is often ignored in building design. Although social aspects are mentioned in work by Anastaselos et al. (2009) the acceptability of the options considered is not. Acceptability, and its impact on economic viability, is considered to be an essential factor for inclusion in a construction method assessment.

2.4.2. Construction method selection

It has been noted that making a decision which of two or more construction methods to use can be challenging (Castro-Lacouture et al. 2009, Diakaki et al. 2010, Seo et al. 2004, Li and Shen 2002). Examples of just a few of the criteria which could affect the decision include environmental impact, cost, buildability, acceptability, safety, past experience, thermal performance, ability to meet the Building Regulations, and many more. The large number of factors which apply means that no method is likely to be easily identified as the best option. For example, a low operational energy may result from using a large amount of insulation; however this would give a high embodied energy. Selecting the best option will typically require compromise (Li and Shen 2002). The relative importance of each factor should also be considered. For example, if the intention is to meet the requirements of the Code for Sustainable Homes (CfSH), operational energy would be extremely important, embodied energy is not considered.

Therefore, the previous example with low operational, but high embodied energy would be acceptable. If the importance were reversed it would not be considered acceptable.

The selection of construction materials and methods has been addressed by a number of authors. For example, Tas et al. (2007) consider the selection of materials based on a database; Castro-Lacouture et al. (2009) use optimisation to identify the best material in relation to a modified Leadership in Energy and Environmental Design (LEED) rating and Seo et al (2004) use fuzzy decision making to select building materials. Material selection in other industries, for example manufacturing, can also provide useful insights into methods of making the best compromise when selecting a material or construction method. Rao (2006) presents the use of a “material suitability index” for material selection in an engineering environment. Although it is often the selection of individual materials which is considered in these works, they can be applied to the selection of a construction system, as examined here. Works which discuss the selection of materials typically start with the discussion of an assessment method; the selection is made based on the results of this. Work from international authors was considered as the methodologies can be incorporated in work with a focus on England and Wales, although details such as Building Regulations may vary.

A recurring theme in works relating to the issue of building material selection is the need to balance the many different aspects and impacts of construction. Some of the issues identified include environment, cost, performance and occupant convenience (Seo et al. 2004). The fact these requirements are often in direct conflict is demonstrated by Castro-Lacouture et al. (2009) and noted by Seo et al. (2004) and Diakaki et al. (2010). The key to resolving this is identified as finding the best compromise.

The use of an environmental suitability index is discussed by Emmanuel (2004). Aspects of wall material construction, in this case embodied energy, cost and reusability were assessed and scored. Normalisation, based on the average value achieved for each factor between all the options was carried out. The sum of the normalised values then provides the Environmental Suitability Index, which is used as the basis for decision making. The work has similarities with the equation used in this thesis as the basis for optimisation. Different factors are combined after normalisation to create a score. However, the work by Emmanuel (2004) does not give consideration to weighting of factors. In addition, the comparison between options is done visually, which would not be possible over the number of options considered in this work. As optimisation seeks to identify the lowest value, the equation designed for this work penalises undesirable characteristics by increasing the score, and rewards desirable ones by reducing it. This is in contrast to the work by Emmanuel (2004) which seeks to achieve the maximum score for the best option. An important point identified by Emmanuel (2004) is that the output of a tool cannot be used to identify a definitive “best” option, it can only identify the best of those considered for the situation examined. This also reflects the impact of weightings; if they are used to change the situation, the output may also be altered.

Abeysundara et al. (2009) give consideration to environmental, social and economic factors. A key element of this work which separates it from others considered was the assessment of social factors. The use of a survey to identify views on each of the construction methods from both end users and those involved in construction was identified as an effective method for determining acceptability in this work. The work presented by Abeysundara et al. (2009) demonstrates similarities with that by Emmanuel (2004). Scores are produced for environmental, economic and social impacts; however, they are presented in a profile format, comparable to that demonstrated by Harris (1999). As with other methods presented, the final selection is based on a visual assessment of the scores achieved by each option. A graphical representation was used by Abeysundara et al. (2009) to show how each option scored in terms of the performance factors. This was not considered effective when a large number of options are to be considered, as in this work.

The use of a modified version of the American LEED system for assessing the environmental performance of buildings, combined with an optimisation approach is demonstrated by Castro-Lacouture et al. (2009). The work presents a method for scoring and selection of materials which will result in the highest LEED score. The focus in the work by Castro-Lacouture et al. (2009) is balancing the requirements of the LEED rating system with cost. The assessment of each option is evaluated by use of an equation. The results of this are then compared to identify the optimal solution. The use of a similar method to examine construction materials and methods in relation to the Code for Sustainable Homes (CfSH) was considered. However, the CfSH considers construction method only in terms of the Green Guide to Specification rating and responsibility of sourcing (DCLG 2007a). This small number of categories makes a similar process ineffective. In addition, a Green Guide to Specification rating of A or A+ is achievable by all construction methods examined in this work, meaning there is very little differentiation between them (BRE Global Ltd 2008), therefore this could not be used as the basis for construction method selection. The use of an optimisation based approach was considered to be beneficial to this work. However, a greater number of options were to be considered. Therefore, a manual calculation and comparison of each would be impractical. The use of a genetic algorithm based optimisation programme was considered to be a more efficient approach. The ability to consider a range of criteria in the selection process, as demonstrated in the work by Castro-Lacouture et al. (2009) was desirable. In addition to the benefits of the optimisation process, a particular aspect of interest presented by Castro-Lacouture et al. (2009) was the use of constraints, placing a limit on some aspect of the construction. The best solution must be found, but within this limitation.

Some consideration was given to the topic of material selection from industries other than construction. Rao (2006) presents to design of a material selection tool for the manufacturing industry. The importance of material selection is discussed, in particular with respect to the performance of each of the options in a range of areas. This can be considered in relation to selecting a construction method for housing, as different options will result in different performance, for example in terms of durability, fire resistance, embodied energy. The use of database based selection tools is considered by Rao (2006) but identified as insufficient, with a mathematical approach being preferable. The method demonstrated by Rao (2006), based on the use of graph theory and matrices, combined with fuzzy logic, was not selected for use as optimisation using genetic algorithms was identified as a more efficient method for the large number of options to be assessed in this work. However, the creation of an equation, incorporating normalisation and weighting was used as the basis for the optimisation process adopted. Fuzzy set theory was used as the basis for a construction material selection method by Seo et al. (2004) and Li and Shen (2002). As with work by Rao (2006), weightings and normalisation were incorporated, the use of these was taken forward in this work although the fuzzy set theory method was not used. The normalisation method discussed by Rao (2006) was considered for use, however using an average value as a benchmark, as discussed by Emmanuel (2004) was selected as preferable to using the highest performing option (Rao 2006) or the method based on the best and worst scores presented by Seo et al. (2004).

Optimisation is essentially the act of identifying the optimal, or best, solution for the design (Goldberg 1989). It can be said that all previously discussed methods of material selection are forms of optimisation. However, they focus on assessing the options, leaving the final identification of the best option to the designer. While this method can be applied to a limited number of choices, if the aim is to select from many options this becomes inefficient. Numerical optimisation, for example, by use of genetic algorithms as discussed by Mourshed et al. (2011), is a more effective method.

Optimisation as considered in this work is a numerical method which uses a search technique to solve an equation and identify the variables which produce the optimal solution. The process is iterative; the search method will be repeated until the optimal solution is considered to have been found. Goldberg (1989) discusses a number of search techniques which can be used in optimisation; these include calculation based methods, hill climbing, enumerative methods, random search and genetic algorithms. In calculation based methods the equation is made to equal zero, the gradient which will occur at the maximum or minimal point. The solution of the equation will give the variable value that results in the maxima (or minima). This method becomes complicated when there are multiple peaks to consider, focusing on a local peak may cause a greater one to be missed. Hill climbing consists of evaluating the equation, then following the gradient to find the minimum or maximum value. As with calculation based methods there is the risk of missing a greater peak by focusing on a smaller one. Goldberg (1989) identifies these methods as ineffective in real world situations where multiple peaks commonly occur. Enumerative methods require all the options to be evaluated. The optimal value is identified from the results. This method is possible where the number of variables is small, but rapidly becomes inefficient with greater numbers of variables. The use of random searches evaluates randomly selected points to identify the optimal value. Goldberg (1989) describes these as little better than enumerative methods as many points will need to be calculated to determine the optimal solution has been identified. Genetic algorithms make use of the principle of natural selection, with the new variables being based on the most successful values from the previous iteration. Genetic algorithms use multiple values for each iteration, instead of a single value as used by other methods. This provides a more robust examination of the solution space. Genetic algorithms were chosen as the search method to be used in this work as they are more efficient and provide a more robust search than the other available techniques. The risk of missing the optimal solution by focusing on local minima is also reduced (Goldberg 1989). Genetic algorithms are discussed in greater detail in Chapter 2.4.3.

The use of optimisation in construction based decision making is considered by a number of authors. Examples include; Mourshed et al (2011) present optimisation as a method of finding the best location for luminares in a patient room; Diakaki et al (2010) use the method in building design for selection of the building envelope and services.

Diakaki et al. (2010) make use of multi objective optimisation in identifying the most energy efficient options when designing a building in terms of the envelope and building services. The model presented by Diakaki et al. (2010) uses a set of three equations, combined with optimisation procedures to identify the building combination which has the best compromise in terms of cost, energy use and annual carbon dioxide emissions. The use of optimisation was identified as a method in which many options could be assessed; this was taken forward for use in this work. However, a single objective problem was used, following work presented by Mourshed et al. (2011). No consideration is given by Diakaki et al. (2010) to other aspects which may be affected by a change in building envelope. Of particular interest in this work is the impact on acceptability. It will be seen later in this work that a material can perform very well in terms of operational energy, but have a low acceptability, impacting its public appeal. The optimisation by Diakaki et al. (2010) may identify this as the optimal solution; however the impact on economic viability is such that it is not the best solution to use. This relates to the comments made by Emmanuel (2004) regarding the subjectivity of what is considered sustainable in construction, and that no "best" can be identified, only the best for the situation examined.

A significant benefit of optimisation based on genetic algorithms as presented by Mourshed al. (2011) and Goldberg (1989) is the way in which it is able to cope with a large number of options. Considering large numbers of options visually would be a difficult and time consuming task. By use of a genetic algorithms and optimisation programming to assess the options this is simplified. More details are given on genetic algorithms in Chapter 2.4.3. The ability to consider multiple inputs, in the case of this work, construction method and front building dimension, is another area in which optimisation by use of genetic algorithms can be seen as advantageous over the other methods of construction method selection considered. The methods discussed above which do not make use of numerical optimisation would require a two stage process to deal with two variables, which would be a long and time consuming process. In addition, the work presented here can be adapted to allow a greater number of variables with minimal work, whereas with a visual selection method this would cause far greater complexity.

The possibility of selecting a sub-optimal solution was identified by Rao (2006), Seo et al. (2004) and Li and Shen (2002); who consider that additional factors may affect the final decision such that the best scoring option may not be selected for use. Ultimately, the final decision is made by those responsible for the design. This is noted in terms of optimisation by Mourshed et al (2011) and Goldberg (1989) who comment that the optimal solution may ultimately not be the best when other criteria are considered.

A benefit of using decision making tools such as those discussed is identified by Li and Shen (2002) as the increased transparency of the process. It becomes easier to justify and see why a particular option was selected. This is beneficial when explaining the decision to interested parties such as designers, financial stakeholders and customers. In the case of optimisation, the use of Phi arrays, as discussed by Mourshed et al (2011), provide a clear visual representation of the decision making process.

2.4.3. Optimisation by use of genetic algorithms

The background and details of optimisation using Genetic Algorithms are considered in greater detail as this method was selected for use in this work. In this work the use of genetic algorithms as the method used to search the solution space for the optimal value is considered. In optimisation using genetic algorithms the equation, or fitness function, is evaluated using a set of values at each evaluation, the population, rather than a single value as used with other methods. The advantage of this is that it allows a greater search of the solution space, reducing the risk of missing the optimal solution by focusing on local minima as can be the case with other search techniques.

The initial values are then adjusted following principles of natural selection based on those that occur in the natural world. The fitness function is evaluated again using the new values. This process is repeated either a set number of times or until the optimal solution is identified. This is more efficient than attempting to evaluate all possible values or using random search as the use of natural selection causes the values to move towards the optimum as the process proceeds.

Genetic algorithms are discussed in detail by many authors, including Gen and Cheng (1997), Mitchell (1996) and Goldberg (1989). The key to genetic algorithms is the way in which they mimic the process of natural selection. The initial run of the fitness function uses a random set of values, collectively referred to as Generation 0. These values are coded; binary is often a suitable method. This will convert the value into a string. For example, 01000 represents the value 8. Each member of Generation 0 will have a string and an output value of the fitness function.

The genetic algorithm is then used to create the next generation, Generation 1. This will be the second set of values that will be used in the fitness function, with the hope that these values will move closer to finding the optimal value. To create the next generation a combination of reproduction, crossover and mutation are used. The members of Generation 0 used as the basis (or parents) for Generation 1 are selected based on their score from the fitness function. Better scoring members of Generation 0 are more likely to be selected as “parents”. This mimics the “survival of the fittest” concept in the natural world, where the best members of the population are more likely to survive and pass their genetic code onto the next generation.

Once the “parents” have been selected from Generation 0 it is necessary to carry out crossover to mix the code and create new strings for Generation 1. A pair of “parent” strings is randomly selected. At a random point in the string a cut is made and the following data exchanged with the second parent string.

To avoid the issue of data being lost and points missed due to the genetic algorithm closing too rapidly on the solution, an occasional mutation is allowed. One of the characters in a string will be randomly selected and altered, or mutated. This changes its value. The impact of the mutation will be seen in the calculation of the fitness function. If the mutation has had a beneficial effect the change will be preserved in the next generation by the bias towards successful strings. Table 2.2 demonstrates the process of genetic algorithms visually using binary coded strings as the members of the population. Coloured text has been used to indicate crossover points and mutation.

Table 2.2: Visual representation of using a genetic algorithm to create a second generation

Generation 0			Generation 1		
String values	Fitness function score	Chosen as parents	After crossover	After mutation	Fitness function score
01001	10	**01001**	**01100**	**01101**	16
10001	4	**00100**	**00001**	**00001**	1
00100	6	**01001**	**01000**	**01000**	9
10000	3	**10000**	**10001**	**10001**	8

The process of creating a new generation is repeated until either a set number of generations have been worked or the improvement in fitness function score is below a set level, i.e. the optimal solution has been identified.

Using this method eliminates the need to calculate the score for every possible option and find the best score from this. The “survival of the fittest” theory allows the results to converge on the optimal solution without need for all values to be calculated. This results in significant savings in terms of computational time and associated cost.

The history of optimisation and the use of genetic algorithms to find the best solution is discussed by Goldberg (1989); from the beginnings of the method as a way of analysing biological science to the use of genetic algorithms in decision making from engineering, medical applications and human behaviour. More recently, the potential for using optimisation in design decisions is becoming more widely known. A number of authors have discussed the potential for applying optimisation to a range of problems in a range of disciplines. For example: Mourshed et al. (2011) discuss use of the technique to solve the placement of luminaries in a patient room; Diakaki et al. (2010) make use of multi objective optimisation in selecting energy efficiency improvements for buildings; Lagaros et al. (2005) consider the use of multi-objective optimisation to design space frames that will be subject to seismic loading.

Methods used by Mourshed et al. (2011) for identifying a suitable crossover probability, by varying the value and running the optimisation for a limited number of generations can be applied to this work.

The importance of sub optimal solutions is expressed by Mourshed et al. (2011); these values can give valuable information about the problem and may be a preferable solution when additional criteria, not in the algorithm, are considered, for example aesthetics. This echoes comments made by Goldberg (1989) that in human situations the optimal, or perfect, solution is rarely achieved. The target is to identify solutions which approach the optimal and perform better than others.

The use of Phi-arrays, a graph on which each point displays additional information about the fit of the point by its size and colour, is also discussed by Mourshed et al. (2011). Phi-arrays allow a visual representation of the solution space and can be used to identify locations with values which score well. Identifying these sub optimal, but good scoring, points can be useful in making decisions. Phi-arrays also demonstrate regions which have very poor scores. Identifying these gives information about unsatisfactory solutions to the problem. Unsatisfactory values can be removed from following optimisation runs, reducing the calculation time and associated cost. Phi-arrays can be generated from data calculated during the optimisation process; they are a by-product of the process, that provide useful information about the solution space. The use of a three dimensional graph to represent the solution space can also be used to give a visual impression of high and low scoring areas. This is an extension of the contour plots demonstrated by McKeown et al. (1990) that takes advantage of improved computer capabilities. However, the nature of three dimensional plots is that some data will be obscured, in particular the low values that are being aimed for. Using a Phi-array gives a clearer view of the solution landscape.

2.5. The level of user acceptability in construction decision making

The opinion of the housing user is given only limited consideration when construction method decisions are made. Roy and Cochrane (1998) consider this to be a result of the speculative nature of house building in England and Wales, with the end user not being identified until the house is complete. Price, rather than customer focus, is identified by Roy and Cochrane (1998) as the main motivator for the housing construction industry. Barlow (2000) compares the house building industry to other mass production industries, but notes that the housing industry has not developed a customer focus the way manufacturing has, restricting its efforts to minor details relating to fixtures and fittings. The need to consider the demands of the purchaser, by use of a customer focused, rather than cost focused business strategy is suggested by Roy and Cochrane (1998). Socio-economic impacts are also identified by Ravetz (2008) as being one of the factors that can affect the building stock.

A demonstration of the importance of end user acceptability is given by Cavill (1999) who discusses the impact of a 1984 television programme on timber framed construction. The programme suggested timber frame was at risk from rotting and fire, the loss of consumer confidence greatly reduced the number of houses built using this method in the following years (Cavill 1999). Therefore, it can be seen that householder support is essential for alternative methods of construction to be used on a large scale.

In addition to the primary purchaser, who buys the new build house, it is important to consider future users. Barlow (2000) comments that buildings which are undesirable, due to the type of land they are constructed on, may present future issues with value. This can be considered in relation to the desirability of construction method; if future purchasers are likely to consider a method undesirable there are implications for saleability and mortgage valuations.

Roy and Cochrane (1998) give some consideration to the use of alternative methods of construction. It is suggested that alternative methods may allow a more flexible interior layout, enabling the customer to determine how they want the building to look internally. Offering greater opportunities for customisation is also suggested by Barlow (2000) as a way to increase the appeal of houses.

The construction industry is widely viewed as resistant to change (Ravetz 2008). Methods that have been proven over time are preferred, as factors such as performance, cost, time to construct and durability are all known. In reality, this means the industry has a deep rooted preference for brick and block construction; the “typical” method used in England and Wales. Mackinder and Marvin (1982) note that the construction industry prefers experience over written information. It is also noted by Emmitt and Yeomans (2008) that when difficulties are experienced with construction decisions industry professionals will often opt for a familiar solution. Evidence of this resistance to change exists when it is considered that although a wide range of housing construction methods are available, brick and block construction was still used for 88% of dwellings in England between 1990 and March 2009 (DCLG, 2010). Timber framed construction was used for 7% of houses built in England during this time period with “other” methods of construction making up 5% of housing construction (DCLG, 2010). Combating this resistance to change is a key challenge for alternative construction methods.

The views of both the construction industry and the end user, the public who will purchase the houses, are an important consideration when choosing a construction method. If a particular method is not supported by the industry it is unlikely to be adopted. If a method is not supported by the public, houses built from it are unlikely to sell. If houses are not saleable they are not economically viable (Barlow 1999), this was demonstrated by the fall in timber framed construction after a negative television report in 1983 (Cavill 1999). Although the energy use and performance criteria of an alternative method of construction may be desirable, ultimately it must be acceptable to both of these groups to be economically viable, and therefore to be considered as a potential material for housing construction. In this work the views of both the end user (the public) and the construction industry have been considered. It was felt that neither of these could be ignored as they have a significant bearing on the viability of alternative construction methods in house building.

The need for consideration of social data is considered in a number of the papers previously discussed in relation to construction method selection. Li and Shen (2002) consider that housing decisions are too complicated to only consider in terms of quantitative data, that consideration must also be given to social aspects. For example, Li and Shen (2002) consider how the quality of life may be affected by construction decisions and state that these can be difficult to quantify as they may be imprecise. A number of social factors, including preference and convenience for occupants were considered in work by Seo et al. (2004). Acceptability was taken forwards in this work as the most significant social factor; however, the methodology demonstrated for incorporating acceptability could be adapted to include other qualitative factors. The importance of considering the views of all stakeholders is also considered by Li and Shen (2002), in this work the views of both the public, who will become the homeowners, and the construction industry, who will build the houses were considered.

2.6. Contribution to knowledge

It is the aim of this work to make the following contribution to knowledge based on gaps identified in the existing work.

- A review of the performance and energy associated with the construction methods studied; including identifying embodied energy issues with construction materials.
- Determining the acceptability of alternative methods of construction to the public and the construction industry.
- Identification of ways to increase the acceptability of alternative methods of construction allowing their benefits to be accessed
- An optimisation based methodology for the selection of construction methods that considers energy use, acceptability and performance to identify the best compromise for a given situation.

2.7. Summary

Elements identified during the literature review which are of particular relevance in achieving the intended aims of this work are summarised below.

- The potential for making savings in housing energy use and the associated emissions has been explored with consideration of the scale of new build housing. Even a small energy saving on each unit would make a significant contribution.
- Housing construction in England and Wales tends to be speculative; this increases the importance of acceptability.
- The typical aspect ratio for housing is in the region of 1:2

- Brick and block is the main construction method used for housing in England and Wales, timber frame has some use. Other methods are used very little.
- International use of alternative methods of construction is much higher.
- Ideally the minimum front dimension of housing should be 4.25m, it can be as low as 3.5m in some cases.
- Any method of construction can be used provided it meets the required Building Regulations.
- Typically no option will be the best on all counts, compromises must be made.
- The main impact of the Code for Sustainable Homes on this work is the need to minimise operational energy.
- Construction methods with good airtightness and U values are preferable as these will contribute to lower operational energy.
- Embodied energy should be considered when selecting a construction method.
- The use of different materials in construction has the potential to reduce embodied energy.
- Reducing embodied energy is beneficial as the saving is made at construction, unpredictable user behaviour will not affect the saving.
- Higher embodied energy construction methods may be acceptable if the method has improved performance in other areas.
- The impact on various aspects of performance should be considered when selecting a construction method.
- Options must be assessed based on some performance related criteria before the best option can be selected.
- A wide range of material, or construction method, assessments exist.
- Desirable criteria may be in direct conflict with each other, for example cost of construction and operational energy.
- Normalisation of the data is required to compare criteria of different sizes.
- Weightings should be included in the assessment method to allow different areas of concern to be highlighted as appropriate.
- Many existing works use visual inspection of a score for identifying the best option; this is considered insufficient for this work.
- Optimisation by use of genetic algorithms is able to cope with large number of options and multiple variables.
- Optimisation based on genetic algorithms was identified as a way to choose between methods for this work.
- Constraints can be incorporated using a penalty based method.

- A sub-optimal solution may be preferable to the identified optimal solution if other criteria are considered.
- Genetic algorithms make use of survival of the fittest concepts to determine the best solution.
- Optimisation by genetic algorithms eliminates the need to evaluate every option, saving time and reducing costs.
- Phi arrays and three dimension graphs can be used as a visual representation of the solution space. Sub-optimal solutions can be identified from these.
- It is not possible to identify a definitive best option, only the best option for the situation, out of those considered.
- Innovation is required for the use of alternative methods of construction to be adopted into the mainstream.
- Innovation requires one company to take the first step.
- Legislation to force innovation may be required.
- Education can encourage the use of alternative methods of construction.
- Decision making tools can increase the transparency of the process.
- Minimal consideration is currently given to customer acceptability when construction decisions are made.
- The construction industry is viewed as resistant to change.
- Public and construction industry acceptability should both be considered when selecting a construction method.
- Acceptability of a construction method must be high with both the public and construction industry for it to be economically viable.
- Combating the resistance to change is key to increasing acceptability of alternative method of construction.

3. Methodology

3.1. Introduction

The work carried out for this thesis builds on initial data collected through literature study, combined with primary data collected through the use of questionnaires and processed using optimisation techniques to create a design methodology with the potential to aid decision making. Each stage of this process requires a separate methodology.

For this work a limited number of construction methods were studied, the intention was to demonstrate techniques, which could be used for future expansion of the design methodology to create a functioning design tool.

3.2. Construction method selection

To find information on a range of construction options, a literature review was carried out. This allowed a wide range of construction methods to be identified and assessed for suitability. The construction methods were selected based on the following criteria:

- Prior use for housing in England or Wales.
- Availability of detailed information from academic literature and materials suppliers.
- Inclusion of at least one method perceived as unconventional and one or more modern methods of construction.
- Method suitable for use across England and Wales.
- Method to have an estimated lifespan in excess of 60 years.
- Suitable for large scale, speculative construction as carried out in England and Wales.

The methods used in this work were selected from the identified options based on the above criteria..

3.3. Construction method details

Methods were developed to assess the construction options for U value, embodied energy and three aspects of performance which it was considered could be affected by the changes in materials used across the methods. These were: air tightness, wall thickness and fire performance. These methods can be used to generate values for other methods of construction as required and for additional selection criteria such as cost, durability and construction speed.

3.3.1. U-value

U-values were calculated based on the specified set of materials for each method of construction. Published U-values, such as those produced by the BRE, were only used where the specified details exactly matched the ones used to generate the published values. This only occurred in the case of prefabricated straw bale construction.

The calculation of U values achieved by the wall systems were carried out using a combination of material thermal resistance values as shown in Equation 3.1 (British Standards Institution 2007, Anderson 2006, Chudley and Greeno, 2005).

(Eqn. 3.1)

$$U=\frac{1}{R_{SO}+R_1+R_2 \ldots + R_n + R_a + R_{si}}$$

Where

U = U value in W/m^2K

R_{so} = External surface resistance in m^2K/W

R_n = Thermal resistance of building component in m^2K/W

R_a = Thermal resistance of cavity air space in m^2K/W (if present)

R_{si} = Internal surface resistance in m^2K/W

A correction of 0.020 W/m^2K was applied to those walls using wall ties (Chudley and Greeno, 2005).

R values for building components are based on a combination of the thickness of material used and its thermal conductivity. They are calculated using Equation 3.2.

(Eqn. 3.2)

$$R = \frac{L}{\lambda}$$

Where

R = Thermal resistance in m^2K/W

L = thickness of material in m

λ = thermal conductivity of material in W/mK

Where a material system such as a SIP unit was specified, the R value provided by the manufacturer was used for the calculation. Values of thermal conductivity for other materials were sourced from a combination of British Standards Institution (2007), Anderson (2006) and Chudley and Greeno (2005). If the U value for the entire system was provided by the manufacturer, the given value was used in preference to calculating one. Where applicable the external leaf of mortar and brickwork were treated as a combined material due to the similarity in their thermal conductivity (Anderson 2006, Chudley and Greeno, 2005).

Values for external surface resistance (R_{so}), air space resistance (R_a) and internal surface resistance (R_{si}) were taken from Chudley and Greeno (2005); these are shown in Table 3.1. R_{so} is based on a normal level of exposure and a high surface emissivity. R_{si} takes the typical value for walls. R_a is the typical value for a cavity wall void.

Table 3.1- Surface and airspace R values used in U value calculations

Component	**R value**
R_{so}	0.055
R_a	0.180
R_{si}	0.123

3.3.2. Embodied energy

Embodied energy is the energy required to produce the materials and components of a construction system. There are a number of methods for the calculation of embodied energy. Input out-put analysis, process analysis, hybrid analysis and coefficients can all be used to evaluate the embodied energy of a component or system. A comparison of these methods by Hamilton-MacLaren et al (2009) showed that the most suitable method to use for this work was the one used by Hammond and Jones (2008) and

Buchannan and Honey (1993), where material quantities are combined with embodied energy coefficients to calculate the total embodied energy for the system. This method was chosen to give a balance between calculation requirements and accuracy.

Material quantities for 1m^2 of each construction type were calculated to allow comparison between the methods. Where a wall system used units greater than 1m^2 the amounts were calculated for a unit then divided by the unit area. Material quantities were based on the specification given for each construction method combined with manufacturer data. Values for material quantities were then combined with embodied energy coefficients for the materials used. Embodied energy coefficients were obtained from the Inventory of Carbon and Energy V 2.0 database produced by Hammond and Jones (2011). This was considered to be the most suitable source of data as the values included have undergone a careful screening process to ensure they are as suitable as possible for the UK situation and hence are most suitable for England and Wales. The generation of these values is discussed by Hammond and Jones (2008). Where a specific material value was unavailable the closest value for a similar material was substituted. Summing the individual material values provided the total embodied energy associated with the materials for 1m^2 of wall type. This process was carried out for both external and party walls for each construction method.

Morel et al (2001) demonstrate the effect that transportation of materials can have on the embodied energy of a project. However, as all materials can be sourced from within the UK and a precise location is not being examined in this work, the impact of transportation on energy use is considered to be the same for each construction method and hence is not included in the analysis. If the method were used in the assessment of a project with known location the transportation distances of materials could be calculated and these added to the embodied energy value used in the optimisation.

For this work, the impact of site activities and worker transportation has not been assessed. Records from actual case studies would be required to accurately calculate this. It was considered that the values would be similar in all cases, although it was noted that faster construction time may lead to lower requirements and hence lower associated emissions. This was identified as an area for further work.

3.3.3. Airtightness, wall thickness and fire performance

Three additional areas of performance were included in the optimisation procedure. These were air tightness, wall thickness and fire performance. All were considered to be affected by the use of alternative methods of construction when compared to typical construction methods.

Details of the performance achieved by each method were obtained from technical literature. A combination of manufacturers' product information and published works was used to provide the most applicable data for the products being considered.

3.4. Acceptability of construction methods

Acceptability of alternative methods of construction is a key theme of this work, in particular the way this affects their potential for use. Acceptability of the construction methods considered in this work was examined from two points of view, that of the construction industry, who would build the houses and of the public, who would buy the houses.

3.4.1. Data collection method

The aim of the questionnaire was to determine the awareness and acceptability of the construction methods under consideration to the public. This is an area which is not typically considered during construction planning, therefore the collection of primary data was required for this part of the work. To determine the views of the public on the methods being studied, a questionnaire was used. Kothari (2004) gives benefits of questionnaires as more cost effective; avoiding interviewer bias; ability to achieve larger samples; respondents can complete the questionnaire when it is convenient for them and have time to consider their answers. These factors were considered beneficial for this work.

Interviews were discarded as a method of collecting the required information as the number of sources required to give a representative view made interviews impractical. The main benefit of interviews in this situation is the potential to ask additional questions and obtain a greater depth of response. As discussed later in this chapter, the design of the questionnaire allowed for optional open-ended responses to some questions. This allowed a greater depth of response, achieving results similar to those which would have been achieved from a structured interview.

In addition, it was considered desirable to collect the views from different regions and determine whether the location of the respondents appeared to impact the acceptability of each construction method. The use of a questionnaire, as opposed to interviews, made it possible to collect sufficient responses from a diverse range of locations. Examples of work using questionnaires to obtain this type of data include Mahaptra et al. (2012), Osmani and O'Reilly (2009), Goodier and Gibb (2007), Pan et al. (2007), Lorenzoni et al. (2007), Stubbs (2002) and Chinyio et al. (1998).

Disadvantages associated with the use of questionnaires given by Miller and Salkind (2002) and Kothari (2004), such as ambiguous responses, missed questions, slow returns and inflexible questions were addressed with the use of careful questionnaire design and the use of an internet based distribution and response collection. This method allowed for compulsory questions, optional open ended responses and faster collection than would have been achievable by a postal questionnaire. The possibility of interviewer bias was avoided by careful wording of the questions, and where possible, the use of repeated questions styles, for example, the acceptability question for each construction method followed the same format, with a brief description and image.

3.4.2. Questionnaire design

The theory of questionnaire design is dealt with by a number of authors such as Fink (2006), Kothari (2004), Gillham (2000) and Oppenheim (1992). From these works it can be seen that the development of a questionnaire requires the following stages:

- Examination of research aims
- Interviews or background research to find suitable questions
- Deciding on the population and, if applicable, sample of participants
- Development of questions
- Testing of questions
- Layout of questionnaire
- Testing of questionnaire
- Pilot run
- Full run
- Follow up contact as required, e.g. to improve responses or debrief participants
- Analysis of data
- Reporting of results

It is considered by Gillham (2000) that all these stages are required to produce a high quality questionnaire, resulting in the best achievable response rates and providing meaningful data. In addition, the need for consideration of ethics and approval from an appropriate ethical committee is considered by Fink (2003).

The research aims of the house holder questionnaire were identified as:

- What factors are important to the public when considering a house to buy?
- Are the public aware of the construction techniques being examined?
- Would the public buy a house built using the construction techniques being examined?
- What would increase the public's interest in houses built using alternative methods?

The research aims of the house builder questionnaire were identified as:

- What factors are important to house builders when selecting a construction method?
- Are house builders aware of the options being examined?
- Do house builders have experience of using the methods being examined?
- Would house builders use the construction methods being examined?
- What would increase house builders' interest in alternative wall construction methods?

Questions were designed based on these aims and findings from the literature review discussed earlier in this work. The aim was to keep the questions simple and succinct in order to collect usable data and increase response rates by keeping the questionnaire short.

The importance of a range of factors was tested using a Likert scale. Factors were selected based on the perceived interests of the respondents. Each factor was scored from 1 (not important) to 5 (very important).

Awareness was determined with the use of simple yes/no responses. This was based only on the name of the construction method, with no additional information being supplied in order to identify the current situation. House builders were also asked if their company had any past experience with the method, with options of "Yes-housing", "Yes- other", "No" and "Not sure".

Acceptability was determined by providing a brief description; along with a labelled, full-colour, image of each method in turn. Respondents could indicate acceptability with a choice of "yes", "no" or "maybe" to the question "Would you buy a house built using this method?". The use of labelled, colour images, as opposed to technical drawings was intended to increase the accessibility of the questionnaire; technical knowledge was not required to understand the images. An optional, open ended, question allowed for further comments or explanation of the choice. This enabled an interview style response on a larger scale than could be achieved in person and limited the over-simplification of responding with only yes, no or maybe.

For the house builder survey, technical terms were used in the descriptions for each construction method, for example, use of the term leaf to describe the layers of the wall. House builders were asked "Would you build a house built using this method?"

To determine factors that may increase respondents' interest in alternative methods of construction a number of possible options were presented with a "yes/no" response option. An optional open-ended question was also included, allowing respondents to add any other factors they felt would increase their interest, as with the questions regarding acceptability, this allowed for an in depth response and avoided over-simplification.

The questionnaire was built and distributed using an online survey maker (Survey monkey 2011). This simplified the design process and allowed automatic collection of responses. This resulted in greater accuracy as the potential for transcription errors was removed. Additionally, it was possible to make certain questions compulsory, encouraging more complete surveys, with fewer missed questions.

A small pilot run was carried out. This allowed testing of the questions, layout and questionnaire as a whole and provided feedback which made it possible to develop the questionnaire further. As a result of comments received, the images of each method were altered from two dimensional cross-sections to labelled, axonometric images as shown in Figure 4.1. Some respondents felt they would have liked more information on each method of construction, in particular pros and cons. The decision was made not to alter this as the intention was to determine acceptability based on a combination of current knowledge and the given method description.

Ethical approval was sought for the questionnaire from Loughborough University's ethical approval committee. This was received provided the questionnaire respondents remained anonymous and any participant recruitment advertising was cleared with the committee. Conducting an anonymous survey was also considered to be beneficial in improving response rates.

Samples of the two questionnaires used can be seen in Appendix A and B.

3.4.3. Population and sample

The population for the public questionnaire included residents of England and Wales with the potential to purchase a house in the future. This was restricted to those aged 18 or over at the time of responding to the survey to avoid the ethical considerations of working with minors. No upper age limit was set. Based on estimated figures for 2010 from the Office of National statistics (2011), this gives a population of approximately 48 million individuals. The use of online survey distribution limited the sample to those UK residents with computer access. This is estimated to be 82.9% of the population (Internetworldstats, 2004), which was considered to be an acceptable limitation.

Calculation of the required number of respondents to achieve a 95% confidence level with a confidence interval of 5 following the method described by Bartlett et al. (2001) indicated 384 responses were required. This means that values from the survey will contain the true mean value 95% of the time if this number of respondents was achieved. A small confidence interval, such as 5, indicates the sample values will be close to the true mean values. 384 was taken to be the minimum acceptable number of responses, with a greater number being considered to improve the quality of findings by reducing the confidence interval and allowing for partial responses.

The population for the industry survey was considered to be all house construction firms working in England and Wales, and therefore their employees who would answer the survey based on a combination of their own perceptions and their company's views and strategies. The varying size of construction firms meant that a target population was difficult to set. A minimum of twenty five responses was considered to be acceptable as it would allow a range of opinions and provide sufficient responses for some statistical analysis.

3.4.4. Questionnaire distribution

In order to distribute the survey, a website was designed for the project. This provided a brief explanation of the work, as well as a link to the survey. A list of frequently asked questions and a contact sheet was provided to give respondents further information if required. Wording of all sections was crafted carefully to avoid introducing bias into the results.

Willingness to participate places a limitation on survey responses, therefore a range of participant recruitment methods were adopted, this included:

- Use of personal contacts via email
- Professional networking websites www.linkedin.com and www.graduatejunction.com
- The social networking website www.facebook.com
- Staff and student contacts through the University mailing lists.

To increase the distribution, respondents were asked to complete the questionnaire and to pass details of the website onto their own contacts. This makes use of the "small world theory", more commonly known as the "six degrees of separation" whereby any two individuals can be connected by six or fewer other individuals (Schnettler, 2009). By use of this theory it would be possible to contact all those residents of England and Wales who have computer access if all individuals were willing to participate.

The potential exists for this type of distribution to result in bias due to self selection. Those who are interested in the subject or hold a strong opinion are most likely to respond, whereas those who have little opinion may not complete the questionnaire. To reduce the impact of this bias, the target sample for the public survey was increased to a minimum of 500. The range of distribution methods was also aimed at reducing bias in the results by accessing a range of respondents.

The larger sample size also allowed for sampling from within the responses if necessary. To enable sampling, questions such as region and age band were asked. Income level was considered as a question but was discarded as it was felt it would reduce the response rate.

Distribution of the industry survey followed the same method used for the public survey (See 4.2.3). Two additional methods of distributing the survey were used to increase the industry response rate, these were:

- The forum section of the online construction magazine “Building”
- Emails to the top twenty house building firms in the UK for 2009 as given by McMeeken (2009)

3.4.5. Response analysis

To analyse the public survey the number of respondents for each region was compared with the regional population distribution for England and Wales. The difference in distribution between respondents and the actual population was assessed using a chi squared test. This indicated that the distributions were not comparable so sampling was carried out within the responses to create sub-samples which mirrored the actual population distribution of England and Wales. Five sub-samples were created and used in the statistical analysis of importance factors.

To determine the importance of factors to respondents, percentage scores, modal and median scores for the Likert scales were calculated. From visual inspection of the resulting graph and table it was possible to create a ranking for the importance of the factors. Principal component analysis was carried out on the householder survey results to group the factors into a smaller number of categories about which it is felt householders are concerned. It was not possible to carry out principal component analysis on the house builder survey due to the lower number of responses.

Awareness of the construction methods being considered and ways to increase interest were not divided by region, they were considered for the area of study as a whole. Graphical representation of the results was used to analyse responses.

Acceptability was considered by region. Visual examination of tables and graphs were used to analyse these responses. Views expressed in the optional open-ended question were coded, based on content and whether it was negative or positive. Where a query was made about performance, it was coded as a negative view as it was considered to indicate a concern about that aspect of the method; e.g. “How does this perform in fire” was felt to indicate a concern about the fire performance. This allowed the perceived benefits and disadvantages of each method to be identified.

3.5. Optimisation based selection methodology

The final element of this work was the creation of a design methodology to aid with the selection of construction methods. This combines data collected in the previous sections and uses optimisation to identify the best option for use.

Sub-optimal solutions can also be identified as they may provide valuable information as discussed by Mourshed et al. (2011) and Goldberg (1989). The optimisation process and the use of genetic algorithms have been discussed in detail in the literature review that forms part of this work (Chapter 2.4). The optimisation based design methodology in this work requires an equation which produces a single value as its output, the single objective equation. The single objective equation forms part of the fitness function. This is a programme which evaluates the input variables and produces a single value to indicate their performance in terms of the factors considered.

Use of the fitness function allows the investigation of a range of factors, including energy use, acceptability and performance, combined with weightings. Entering values for each variable in the fitness function allows a single situation to be assessed by creating a single value that incorporates these factors. This can be compared with a second situation by repeating the process and comparing the output values from the fitness function.

Optimisation uses this process on a large scale to assess a range of situations and identify the optimal combination of variables. Variables are selected to be altered during the process, in this work two have been used, all others are fixed. The design methodology will run the fitness function multiple times, altering the input values each time based on a genetic algorithm, until the optimal solution is found.

3.5.1. Problem definition

The design of the optimisation based methodology focused on the data collected throughout this work. Factors selected for the basis of the decision were embodied energy, operational energy, public acceptability, industry acceptability, air tightness, fire performance and wall thickness. It was the intention of this work to demonstrate the potential of this methodology, rather than to create a fully functional design tool. Expansion to include other factors which would affect construction method selection is intended as further work.

As part of the fitness function it was necessary to generate values for energy use, both operational and embodied. Data collected and generated in Chapter 3 was combined with user inputs to calculate these values. To allow the combination of factors with different scales all values were normalised by use of benchmark figures. A weighting was applied to each factor and the values combined to generate the single objective equation. The output of this is a single value that combines all of the inputs plus weighting to show their importance- the single objective value. Details of the fitness function development are given in Chapter 7.

3.5.2. The use of optimisation

The background and details of optimisation using genetic algorithms have been discussed in Chapter 2.4.3. Optimisation allows the calculation of values which approach the optimal, eventually identifying the optimal value.

The initial run of the optimisation uses a number of randomly selected variable values. Subsequent runs use variable values that are based on the most successful values from the previous run. These values are selected based on a genetic algorithm that uses the principles of natural selection to identify the best values in the first run and carry them through to the second run or "generation". Crossover and mutation are applied to the values, altering them before the second run of the equation. After the single objective equation has been evaluated using the second generation of values, the process will be repeated. This continues until the optimal value is identified by no improvement in single objective value between the generations or until a set number of generations have been run. Examples of previous work using this methodology include Mourshed et al. (2011), Diakaki et al. (2010) and Lagaros et al. (2005).

3.5.3. Optimisation method

To carry out the optimisation a Matlab based optimisation programme was used. This method uses the Matlab computer programme (Mathworks Inc. 2012). The optimisation programme used in this work was provided by M. Mourshed, following the methods used in Mourshed et al. (2011) and Mourshed et al. (2003).

To run the programme for it is necessary to set values for crossover and mutation probabilities, population size and number of generations. Calculation of mutation and crossover probabilities was carried out using the method described by Mourshed et al.

(2011) using the case study values presented in Chapter 3.6.1, values for mutation and cross-over can be seen in Chapter 3.6.3. The maximum number of generations and the population size was investigated using the case study values, the result of this can be seen in Chapters 3.6.4 and 3.6.5 respectively.

3.6. Case study development

3.6.1. Case study design

Values were chosen for the case study based on housing data for England and Wales. Data from 2006 was used for numbers of houses constructed, as pre-recession data was considered to be more representative of the construction industry in a "healthy" state, which is likely to return as the economy improves. Table 3.2 shows the number of residences constructed by type for England and Wales.

Table 3.2: Number of residences constructed in England and Wales during 2006 by type of housing (NHBC 2007)

Country	Detached	Semi detached	Terraced	Flats and maisonettes
England	23728	20762	29660	72667
Wales	2508	1320	1122	1716
Total	26236	22082	30782	74383
Percentage of total	17.09	14.38	20.05	48.46

Only houses were considered for this work, flats and other forms of multi-residence construction were not included due to the different styles of their construction, in particular, the greater number of storeys used in multi-house residences. The maximum number of storeys considered in this work was three. Therefore, the next most frequently constructed type of housing was terraced.

Table 3.3 shows the number of houses constructed by number of bedrooms for England and Wales during 2009/10. Figures are shown as a percentage of all housing constructed.

Table 3.3: Percentage of all housing constructed in England and Wales during 2009/10 by number of bedrooms (DCLG 2012b and Rees 2011)

Number of bedrooms	**Percentage of all housing**	
	England	**Wales**
1	1	1
2	10	13
3	25	35
4 or more	19	20

From this it can be seen that the most frequently constructed number of bedrooms is three. Table 3.4 shows the average floor areas for housing by number of bedrooms. Values for England and Wales were not available, so this figure was based on data for the UK as a whole.

Table 3.4: Floor areas by number of bedrooms for the UK, values from Scott Wilson Ltd. (2010)

Number of bedrooms	**Mean floor area (m^2)**
1	64.30
2	71.20
3	95.60
4	120.60
5	163.50

Using the data from Tables 73.2, 3.3 and 3.4, a case study was designed based on a terraced, three bedroom house with a floor area of 95.6m^2. The East Midlands was selected as the location for the case study as this region had the most robust results for acceptability as a result of having the greatest response rate for the questionnaire. All other values adopted the optimisation programme default values. The values entered into the optimisation programme are shown in Table 3.5.

Table 3.5: Constant values for case study optimisation

Factor	Value
Total building area	$95.6m^2$
Number of storeys	2
Height of each storey	3m
Number of external doors	2
Region	2 (East Midlands)
Building type	3 (Terraced)
Maximum window percentage	25
Door size	$2.42m^2$

3.6.2. Optimisation variables

The optimisation process was run using the values given in Table 3.5 as constant values. The variables for the optimisation process were wall construction method and value of dimension *(a)*. These values were altered by the optimisation process to find the optimal combination, which produces the lowest value of the fitness function. This represents the best compromise in terms of energy use, acceptability and performance. To maintain integer values in the optimisation, dimension *(a)* was given in millimetres, this was converted to metres in the fitness function calculation. It was necessary to specify a minimum and maximum value for each variable, the optimisation programme used values between these bounds. The bounds for the case study are given in Table 3.6.

Table 3.6: Variables and bounds for case study optimisation

Variable	Lower bound	Upper bound
Construction method	1	6
Dimension a	3600	13278

Material values are bounded by the number of options. The minimum value for dimension a is based on the smallest length that will allow a 1.1m wide door and a 1.0m window plus wall area to support these. This is taken to be 3600mm. In addition, Chown (1999) suggests that the minimum front dimension that can be practically used for housing is 3.5m, with 4.25m being preferable. The maximum value of *a* is based on Equation 3.3.

(Eqn. 3.3)

$$Maximum\ a = (Area/(\#\ storeys))/3600$$

3.6.3. Mutation and crossover probabilities

Mutation and crossover probabilities affect the way in which the optimisation process alters the input variables with each successive run. The crossover probability is input into the optimisation by use of the crossover function, a value between 0 and 1. To determine the most effective value of crossover function (P_c), the value was increased from 0.0 to 1.0 in steps of 0.05. The maximum number of generations was set to fifty to reduce the running time of the experiment. Five optimisation runs were carried out for each value. The value of best fitness was plotted against crossover function. This graph can be seen in Figure 3.1.

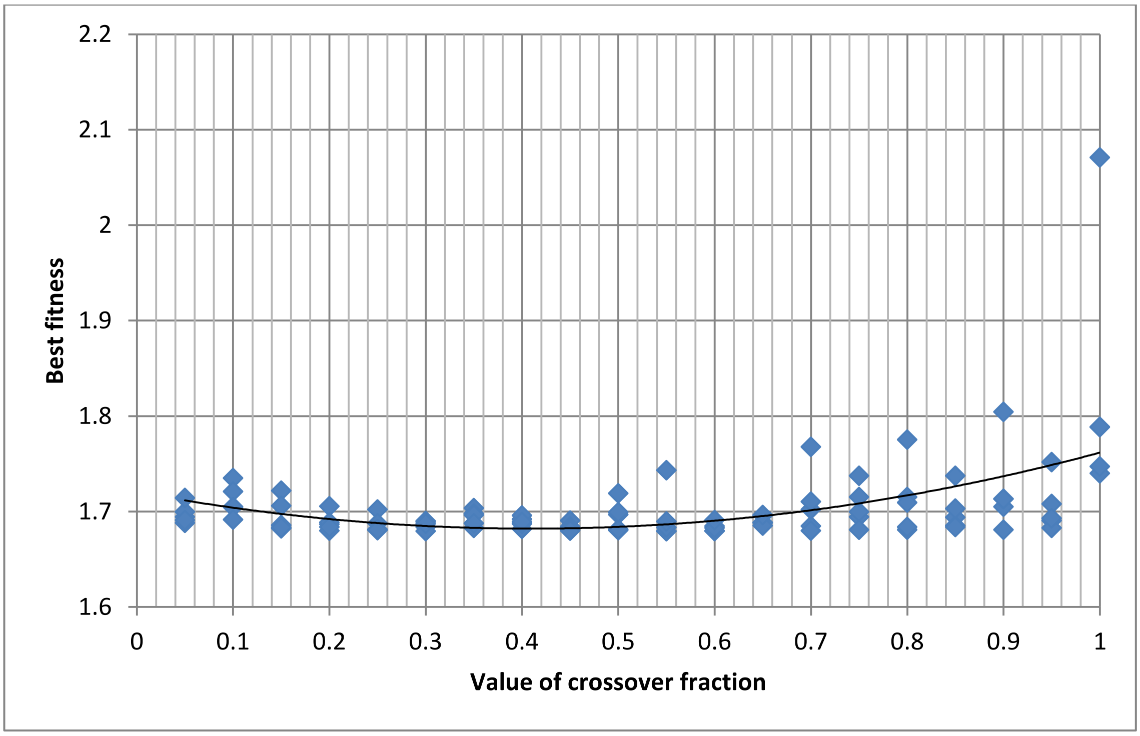

Figure 3.1- Crossover fraction against best fitness value for the case study runs.

A quadratic curve was fitted to the results produced. The best value of crossover function was the one that resulted in the lowest value of best fitness. This is because the optimal combination of construction method and dimension *(a),* is the one which produces the lowest value from the fitness function. It can be seen from Figure 3.1 that this occurs at a value of P_c=0.4. This was used in the case study run. Lower values of

P_c result in a slightly higher best fitness so are less suitable. As P_c increases from 0.4 the value of best fitness achieved increases noticeably, indicating that higher values of P_c are less suitable. It can be seen that at values of P_c greater than 0.5 the spread of best fitness results increases, including the outlier seen at a crossover fraction value of 1.0. From this it was determined that a high degree of mutation is necessary for this programme to achieve accurate values of best fitness.

The mutation probability (P_M) is set as a result of the crossover fraction. The mutation rate comes from subtracting the crossover fraction from unity; therefore, it was set to P_M= 0.6.

3.6.4. Number of generations

The number of generations determines the maximum number of times the optimisation programme will alter the input variables and run the fitness function. If the improvement in fitness function value calculated is less than the specified value at any point, the optimisation programme will cease to run, as the optimal solution is considered to have been achieved.

It was noted when running the optimisation programme to determine the best value of crossover fraction that none of the runs were completed in fewer than the fifty generation maximum. Therefore, the number of generations needed to be higher than fifty to allow for a complete optimisation run.

To determine the number of generations, the value was initially set at 300. The optimisation process was run five times, with a note of when the process completed if it stopped prior to 300 generations. The number of generations was decreased to 200 and then to 150 and a further five optimisation runs carried out for each value. Population size was set at 50 for the trial runs, crossover fraction to 0.4. The results of the trial runs are shown in Table 3.7.

Table 3.7- Number of generations to complete the optimisation run compared to maximum number of generations.

Maximum number of generations	Number of generations to complete optimisation	Best fitness
300	89	1.69067
300	82	1.68103
300	96	1.68440
300	143	1.68729
300	160	1.68199
200	85	1.69646
200	Max. number exceeded	1.68055
200	100	1.68296
200	135	1.68922
200	194	1.68103
150	113	1.68199
150	Max. number exceeded	1.68296
150	95	1.68922
150	109	1.68199
150	101	1.68103

Table 3.7 shows that 93% of the optimisation trials completed in fewer than 200 generations. When the number of generations was decreased to 150, only 73% completed within the maximum number of generations. As a result, 200 was chosen as the number of generations for the case study.

3.6.5. Population

The population is the number of individual values in each generation. The size of the population can have a significant effect on the time taken for the optimisation programme to complete its search for the optimal value, which can result in high costs (Mourshed et al. 2011). A small population may result in a rapid convergence on a solution, which risks missing important values.

The optimisation considered in this work has a relatively small runtime; therefore, a number of trial runs were carried out using varied population sizes (25, 50, 100, 150). For these runs the number of generations was set at 200, the crossover probability used was 0.4. The results of these trial runs can be seen in Table 3.8.

Table 3.8- Impact of varying population size on the optimisation methodology results.

Population size	Number of generations to complete optimisation	Best fitness
25	83	1.70032
25	140	1.68922
25	95	1.71675
25	133	1.68922
25	171	1.6926
50	89	1.68006
50	144	1.68826
50	143	1.67958
50	160	1.68826
50	88	1.68440
100	93	1.68006
100	106	1.68392
100	175	1.68199
100	125	1.68006
100	108	1.67958
150	90	1.67958
150	148	1.68055
150	131	1.68537
150	132	1.68199
150	149	1.68055

It was noted that a slight improvement (decrease) in the value of best fitness occurs as the population increases. The time taken for the optimisation to complete at higher values of population was noticeably longer, in particular once the population reached 150. A population size of 100 individuals was selected as a compromise between runtime, speed of convergence and value of best fitness achieved.

Examination of the number of generations taken to complete the optimisation in Table 3.7 further supports the use of 200 generations, as all runs completed within this time.

3.7. Summary

The nature of this work means that each section required a very different approach, including the use of both primary and secondary data, with the final element being the combination of all data collected and generated along with optimisation techniques to create the construction method selection methodology. The use of this methodology was then demonstrated with the case study described in Chapter 3.6. The results for each section can be found in Chapters 4-8.

4. Construction methods

4.1. Introduction

Throughout this work the phrase "construction method" is used to refer to the system used to construct the house wall, including all materials contained therein. The materials used will have an impact on the way in which the wall is built, including the processes involved.

To allow a comparison and identify possible alternatives to brick and block construction for the walls of new build housing, six construction methods were selected to be studied in depth. The selection justification and the construction method details are discussed below. For the work, each construction method used was evaluated using a set of specified materials, details of these are given in 4.4-4.9. Altering the material specifications has the potential to affect the comparison between construction methods. This provides an area for further work.

4.2. Selected methods

Construction methods studied were:

- Brick and block construction ("typical" method)
- Structural Insulated Panels (SIPs)
- Insulating Concrete Formwork (ICF)
- Prefabricated straw bale and lime plaster panels
- Thin joint block work
- Timber framed construction with brick cladding

Brick and block was included as the baseline for comparison as this is the most frequently used method of construction in the area of study. Structural Insulated Panels, Insulating concrete formwork and Thin joint block work were included as examples of Modern Methods of Construction, Prefabricated straw bale panels were included as an unconventional material, timber frame was included as an alternative method of construction which some people may have experience with.

It was considered desirable, although not essential, to maintain a brick external appearance across as many of the methods as possible. This follows comments made by Roy and Cochrane (1998) that more than half their survey respondents preferred traditional styling when considering a house purchase. This would allow housing built using alternative methods to blend in visually with existing properties, a fact considered important for planning purposes as well as to achieve high public acceptability. A brick finish was achieved for five of the options; prefabricated straw bale panel construction has a plastered external appearance.

4.3. Discarded methods

As a result of the criteria in Chapter 3.2 some of the options initially considered were eliminated as they were unsuitable for the work. These were:

- Off-site modular or “pod” construction- It was considered that this method would not be comparable with the other options considered in this work as it deals with components other than wall materials.
- Rammed earth construction- This construction method is very site specific, relying on the availability of suitable soil types for use in construction. As a result of this it could not be used in all areas of England and Wales so was not included in the work.
- Local materials- It was considered the definition of what is a local material and the complexities of creating a methodology including these applicable to the entire area of study was too great for inclusion at this stage.
- Steel frame and cladding- Expected to have similar levels of acceptability to timber frame, although with variation in performance values.
- Recycled materials- The use of recycled materials is often considered to be a particularly sustainable option as it makes use of materials which already exist (Calkins, 2009). The most common use of recycled construction materials is in steelwork, as steel framed housing was not included in the work recycled steel was also discarded.
- Reused materials- differ from recycled materials as it involves use of the materials in the original form, rather than after reprocessing (Calkins, 2009). Reused materials can potentially be incorporated into most types of construction provided the materials can be recovered. The variable availability of materials for reuse across the area of study meant they were not considered as a universal option.
- Load bearing straw bale construction- it was considered that this method is not sufficiently standardised for large scale speculative construction.

- Natural materials- Typically based on one of the considered methods, such as brick and block or timber frame with natural alternatives for elements such as insulation. Not included at this stage due to the limited difference between this option and the included ones.

The optimisation based design methodology developed in this work (Chapter 6) has been designed to allow for further expansion at which point some or all of the discarded options could be incorporated.

4.4. Brick and block

Brick and block was included as a reference construction method. It is the most commonly used method in the area of study. As an example it was used for 88% of all dwellings constructed in England from 1990 to March 2009 (DCLG, 2010). If alternatives are to replace this “typical” construction method they must show significant benefits over it.

4.4.1. Construction details

Brick and block walls are constructed using a double leaf system. An external leaf of brick work is separated from the internal concrete block work leaf by a cavity. Both leaves are constructed simultaneously, with components held together using mortar. The cavity contains insulation against the concrete leaf and an air space against the brick leaf. Wall ties set into the mortar during construction link the leaves. Internally the wall is finished with plasterboard, a plaster skim and paintwork. This construction method is shown in Figure 4.1.

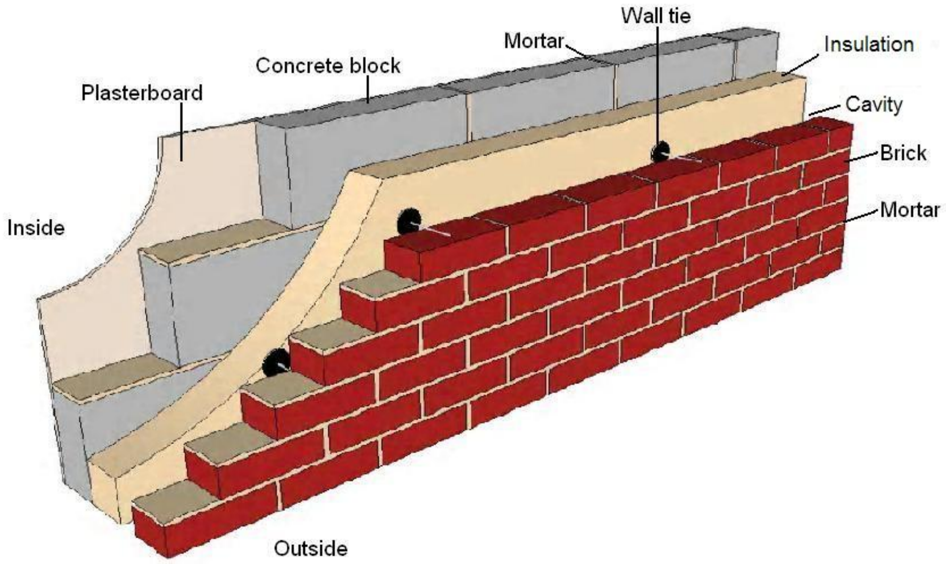

Figure 4.1- Axonometric view of brick and block construction

To allow the consideration of terraced and semi-detached properties a party wall specification was also created. This consists of a fully filled and sealed construction to minimise thermal loss between properties. The wall was taken to be constructed from a double layer of lightweight concrete blocks, with insulation between the layers. On both sides the walls are finished with plasterboard, a plaster skim and paint. Material specifications for both external and party walls are given in Table 4.1.

Table 4.1- Material specification for brick and block construction

Component	Specification
Brick	Fired clay red brick, dimensions- 102.5 x 65 x 215mm
Mortar	1:3 cement sand mix, 10mm joints
Wall ties	Stainless steel wire, plastic insulation retainer, 2.5 ties per $1m^2$ wall
Air space	25mm width
Insulation	Mineral wool insulation, 100mm
Block	8MPa compressive strength, 100 x 215 x 440
Plasterboard	12.5mm thickness
Plaster skim	6mm skim
Paint	Double coat of water based paint
Party wall blocks	100 x 215 x 440 lightweight blocks
Party wall ties	Stainless steel tie, no insulation retainer
Party wall insulation	75mm mineral wool

4.4.2. U value calculation

Current Building Regulation requirements place a maximum value of 0.30W/m^2K on external walls (HM Government, 2010). Calculation of the U value for this system was based on values for thermal conductivity given by British Standards Institution (2007), Anderson (2006) and Chudley and Greeno (2005). These are given in Table 4.2.

Table 4.2- L, λ and R values for brick and block components

Component	L (m)	λ (W/mK)	R (m^2K/W)
Mortared brickwork	0.1025	0.84	0.12
Air space	0.025	0.18	0.14
Mineral wool	0.1	0.038	2.63
Block	0.1	0.18	0.56
Plasterboard	0.0125	0.16	0.08
Plaster skim	0.006	0.57	0.01

These values, combined with the values for R_{so}, R_a and R_{si} in Table 3.1 give U=0.257W/m^2K.

Corrected for wall tie placement in accordance with Chudley and Greeno (2004) this results in a value of U=0.277W/m^2K for use in this work.

The fully filled design of the party wall, with no cavity as described above, results in a U value of U=0W/m^2K in accordance with Part L of the Building Regulations (HM Government, 2010). Therefore, heat loss through party walls is not considered in this work.

4.4.3. Embodied energy

The embodied energy (EE) value for brick and block work was expected to be high due to the processes involved in making the materials, for example firing of clay bricks and the creation of cement.

Material quantities were based on the specification given in Table 4.1. The values used in the calculation of embodied energy for 1m^2 of brick and block wall are shown in Table 4.3 and Table 4.3 for external and party wall respectively. The values for volumes of material are based on the specification given in Table 4.1, values for the embodied energy coefficients were taken from the Inventory of Carbon and Energy V2.0 database developed by Hammond and Jones (2011).

Table 4.3: Material quantities and embodied energy coefficients for1m^2 brick and block work external wall

Component	**Volume (m^3)**	**Density (kg/m^3)**	**Mass (kg)**	**EE (MJ/kg)**	**EE per 1m^2 wall area (MJ)**
Brick	0.085	1700	144.330	3.00	432.99
Mortar	0.018	1750	30.800	1.33	40.96
Wall tie	N/A	N/A	0.513	56.70	29.09
Insulation retainer	N/A	N/A	0.061	76.70	4.67
Insulation	0.100	25	2.500	16.60	41.50
Block	0.093	1400	130.760	0.59	77.15
Mortar	0.007	1750	2.067	1.33	2.75
Plasterboard	0.013	950	11.875	6.75	80.16
Plaster skim	0.006	1300	7.800	1.80	14.04
Paint	N/A	N/A	N/A	N/A	21.00
					744.30

Summing the values from Table 4.4 gives a value of 744.30MJ for the embodied energy associated with 1m^2 of brick and block work external wall. It can be seen that the energy intensive process of brick manufacture has a significant impact on the embodied energy, contributing over half the total value. The embodied energy of concrete blocks is lower than expected, although the mass of blocks is high the low value of embodied energy per kg results in a low overall value.

Table 4.4: Material quantities and embodied energy coefficients for 1m^2 brick and block work party wall

Component	Volume (m^3)	Density (kg/m^3)	Mass (kg)	EE (MJ/kg)	EE per 1m^2 wall area (MJ)
Paint	N/A	N/A	N/A	N/A	21.00
Plaster skim	0.006	1300	7.800	1.80	14.04
Plasterboard	0.013	950	11.875	6.75	80.16
Lightweight Block	0.093	600	56.040	3.50	196.14
Mortar	0.007	1750	11.494	1.33	15.29
Wall tie	N/A	N/A	0.513	56.70	29.09
Insulation	0.075	25	1.875	16.60	31.13
Lightweight Block	0.093	600	56.040	3.50	196.14
Mortar	0.007	1750	11.494	1.33	15.29
Plasterboard	0.013	950	11.875	6.75	80.16
Plaster skim	0.006	1300	7.800	1.80	14.04
Paint	N/A	N/A	N/A	N/A	21.00
					713.46

The party wall specification for brick and block construction has an embodied energy value of 713.46MJ for 1m^2 of wall. It can be seen that the high embodied energy of the lightweight blocks results in a higher total embodied energy, even though their mass is low.

4.4.4. Airtightness, wall thickness and fire performance

The airtightness of brick and block wall relies on good quality construction, in particular good pointing and plastering of the internal wall face (Lecompte 1987). The airtightness value used was based on the testing of a number of buildings constructed using the same method given in the specification for this work. The average value of airtightness found during this testing over a range of house types was 4.5m^3/hr.m^2 at 50Pa (Miles-Shenton et al 2007). This value was used for brick and block in the optimisation procedure. The Building Regulations maximum value for airtightness is 10m^3/hr.m^2 at 50Pa (HM Government 2010).

The wall thickness for this construction method was calculated from the values of L in Table 4.3. This method was considered to have a wall thickness of 0.346m.

The fire performance of brick and block walls has been demonstrated many times over the years. Testing has shown it will satisfy the Building Regulations requirement of 60 minutes burn time resistance for external walls over 5m in height (HM Government

2011), this is supported by anecdotal evidence. A value of 240 minutes burn time was used in the optimisation procedure based on values given by British Standards Institution (2005) and The Brick Industry Association (2008).

4.5. Structural Insulated Panels (SIPS)

4.5.1. Construction details

Structural Insulated Panels are composed of two layers of engineered timber with a foam layer sandwiched between them. Commonly used foam types are expanded polystyrene (EPS) and extruded polystyrene (XPS), fixed to the boards with adhesive, and polyurethane foams which do not require adhesives (Morley, 2000). Oriented Strand Board (OSB) is typically used for the timber layers. Foam thickness can vary, allowing a range of performance values.

Erection of the building is often done by hand, however, mechanical lifting devices are required if large sized panels are used. Panels are placed in position before external cladding or brickwork is constructed.

It is necessary to provide impact and weather protection to the panels. This is achieved by a breathable membrane applied to the external face of the SIP and either external cladding or, as in this work, by an external leaf of brickwork. Wall ties link the SIP panels to the external brickwork leaf. To avoid damage to the panels a small air filled cavity is maintained between the breathable membrane and the brickwork. Internally the wall is finished with two layers of plasterboard, a plaster skim and paint. This construction method is shown in Figure 4.2.

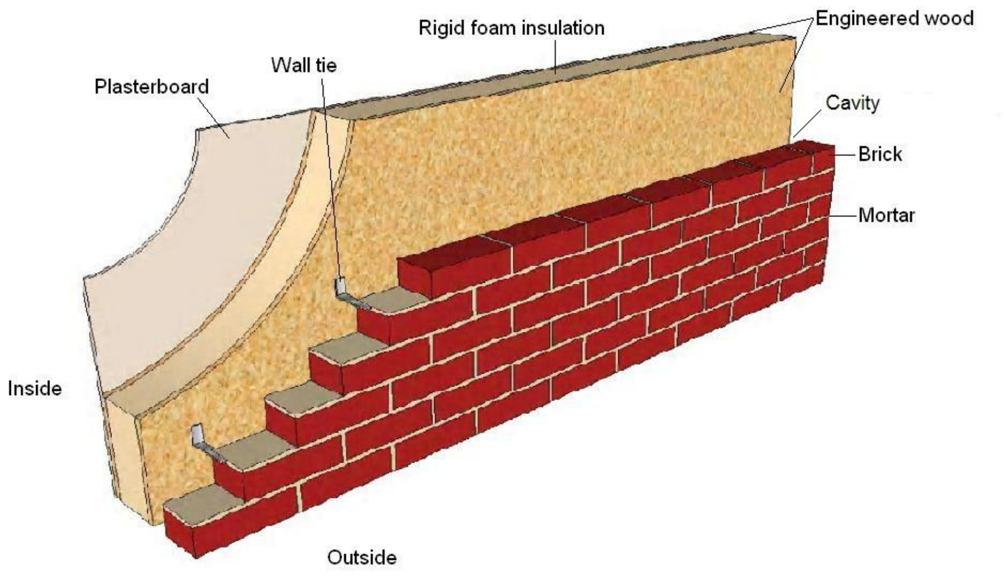

Figure 4.2- Axonometric view of SIP construction

Party wall construction for this type of dwelling can be either timber stud work or SIP panel. SIP panels were chosen for this work to limit the crossover between construction types. The method consists of a layer of SIP panel, finished on both sides with a vapour control membrane, two layers of plasterboard, a plaster skim and paint. The material specification used in this work is given in Table 4.5.

Table 4.5: Material specification for SIP construction

Component	Specification
Brick	Fired clay red brick, dimensions- 102.5 x 65 x 215mm
Mortar	1:3 cement sand mix, 10mm joints
Wall ties	Stainless steel, 2.5 ties per 1m^2 wall
Air space	50mm width
Breather membrane	Kingspan Nilvent breathable membrane
SIP panel	Kingspan Tek SIP, 142mm wide (2 x 15mm OSB sheets, 112mm urethane foam)
Plasterboard	2 x 12.5mm thickness
Plaster skim	6mm skim
Paint	Double coat of water based paint

4.5.2. U value calculation

SIPs are considered to have very good thermal performance as the thickness and type of insulation is selected with this in mind. Dye and McEvoy (2008) state that U values of 0.2W/m^{2}K are easily achieved and White (2007) gives a value of 0.17-0.18W/m^{2}K. In addition, a report by the Department for Communities and local Government (2009) notes that additional insulation can be added to the SIP, with an extra 50mm of insulation resulting in a U value of 0.14W/m^{2}K. Values used to calculate the U value of the SIP wall system are given in Table 4.6. These values are taken from information supplied by Kingspan (2009), British Standards Institution (2007), Anderson (2006) and Chudley and Greeno (2005). The impact of the breathable membrane was discounted due to the very low value of L for this component.

Table 4.6: L, λ and R values for SIP components

Component	L (m)	λ (W/mK)	R (m^{2}K/W)
Mortared brickwork	0.1025	0.84	0.12
Air space	0.050	0.18	0.28
OSB	0.015	0.03	0.50
Urethane foam	0.112	0.023	4.87
OSB	0.015	0.03	0.50
Plasterboard	0.025	0.16	0.16
Plaster skim	0.006	0.57	0.01

From the values given in Table 4.6, the values for R_{so}, R_a and R_{si} in Table 4.1 and the correction for wall ties given by Chudley and Greeno (2005) a U value of 0.167W/m^{2}K was calculated for SIP construction using the materials specified in Table 4.5.

The solid construction of the party wall allows it to have a U value of 0 based on Part L1A of the Building regulations (HM Government, 2010). Therefore, heat loss through party walls is not considered in this work.

4.5.3. Embodied energy

Material quantities and embodied energy coefficients for $1m^2$ of SIP construction as detailed in Table 4.5 are shown below in Table 4.7 for external walls and Table 4.8 for party walls.

Volumes of material are based on the specification given in Table 4.5, values for the embodied energy coefficients were taken from the Inventory of Carbon and Energy V2.0 database developed by Hammond and Jones (2011).

Table 4.7: Material quantities and embodied energy coefficients for $1m^2$ SIP external wall

Component	Volume (m^3)	Density (kg/m^3)	Mass (kg)	EE per kg (MJ)	EE per $1m^2$ wall area (MJ)
Brick	0.085	1700	144.330	3.00	432.99
Mortar	0.018	1750	30.800	1.33	40.96
Wall tie	N/A	N/A	0.150	56.70	8.51
Breather membrane	N/A	N/A	0.140	95.89	13.43
Oriented Strand Board	0.015	680	10.200	15.00	153.00
Urethane foam insulation	0.112	41.07	4.600	101.50	466.88
Oriented Strand Board	0.015	680	10.200	15.00	153.00
Plasterboard	0.025	950	23.750	6.75	160.31
Plaster skim	0.006	1300	7.800	1.80	14.04
Paint	N/A	N/A	N/A	N/A	21.00
					1464.12

Summing the values from Table 4.7 gives an embodied energy value of 1464.12MJ for $1m^2$ of SIP wall with a brick outer leaf as detailed above. Elements which have a large impact on the value of embodied energy include bricks, the OSB sheets and the urethane foam core. OSB sheets were expected to have a low value of embodied energy due to their organic nature. However, they are highly processed, resulting in a high value of embodied energy per kilogram.

Table 4.8: Material quantities and embodied energy coefficients for 1m^2 SIP party wall

Component	Volume (m^3)	Density (kg/m^3)	Mass (kg)	EE per kg (MJ)	EE per 1m^2 wall area (MJ)
Paint	N/A	N/A	N/A	N/A	21.00
Plasterboard	0.025	950	23.750	6.75	160.31
Breather membrane	N/A	N/A	0.140	95.89	13.42
Oriented Strand Board	0.015	680	10.200	15.00	153.00
Urethane foam insulation	0.112	41.07	4.600	101.50	466.88
Oriented Strand Board	0.015	680	10.200	15.00	153.00
Breather membrane	N/A	N/A	0.140	95.89	13.42
Plaster skim	0.006	1300	7.800	1.80	14.04
Paint	N/A	N/A	N/A	N/A	21.00
					834.77

The party wall as specified for the SIP construction has an embodied energy of 834.77MJ for 1m^2 of wall. The high energy requirements of the OSB and the foam core raise the value. The effect of removing the brick outer skin on the total embodied energy can be seen. This suggests systems which use cladding other than brickwork may perform better in terms of embodied energy.

4.5.4. Airtightness, wall thickness and fire performance

A number of authors such as Barista (2008), Morley (2000) and Greeley (1997) consider the airtightness of SIPs to be very good as a result of the large panel sizes with a small number of joints and therefore low potential for air leakage. This is quantified by Dye and McEvoy (2008) as 1.6 air changes per hour at 50Pa and by Gaze (2008) as 1.27m^3/h.m^2 at 50Pa, both an improvement on the building regulations requirement of 10m^3/hr.m^2 at 50Pa (HM Government 2010). Rudd and Chandra (1994) discuss testing carried out to compare the airtightness of a SIP house with an identical timber framed house and found the SIP construction to be significantly more airtight. However, it is noted by Morley (2000) that good workmanship on joints is of particular importance with this construction method to avoid air leakage. For this work a value of 1m^3/hr.m^2 at 50Pa was used based on data supplied by the SIP manufacturer (Kingspan 2009).

The wall thickness for the SIP system was based on the material specification given in Table 4.5. The SIP method of construction was considered to have a wall thickness of 0.326m.

It is noted that the components of SIPs are susceptible to fire by Calkins (2009), Barista (2008) and Griffen et al. (2006). Particular issues associated with the burning of SIPs are noted by Griffen et al. (2006); these include the possibility of the OSB skin separating from the core, the ability of fire to spread throughout a building via the panel cores, the production of dense smoke during burning and the low melting point of EPS.

In order to minimise fire risk the industry standard is the application of plasterboard to the internal surface of the SIP, to separate the SIP from sources of ignition and provide sufficient time for occupants to exit the house before the structure is compromised. Depending on use the requirement is given as one or two 12.5mm sheets of plasterboard by Hairstans and Kermani (2007). Bregulla and Enjily (2004) state that the use of a plasterboard lining enables the Part B of the Building Regulations for England and Wales to be met for SIP structures. The performance of SIPs from each manufacturer is tested by the British Board of Agrément (BBA) and must achieve set levels before they can be sold for use in the UK. Based on the use of two 12.5mm sheets of plasterboard to provide fire protection the fire resistance of the SIP system used in the work is 73 minutes, given by the manufacturer (Kingspan 2009).

4.6. Insulating Concrete Formwork (ICF)

4.6.1. Construction details

ICF can take the form of large panels, or smaller blocks. This work focuses on the block system. Blocks consist of two layers of expanded polystyrene (EPS) or extruded polystyrene (XPS) foam, held apart at fixed dimensions by plastic or metal ties. The foam thickness varies with the choice of product, allowing a range of insulation values to be obtained as required.

Blocks are stacked by hand to form the walls, they commonly have indentations in the top and bottom surfaces to ensure correct placement (Davies 2006). Rebar is often not required but can be added if necessary; it is positioned using the ties which hold the leaves of the block apart. Concrete is poured into the cavity in the centre of the blocks and gently vibrated where rebar has been placed to ensure compaction (Insulating Concrete Formwork Association, ICFA 2009). The concrete pouring stage is generally carried out at a maximum of one storey per day to avoid over loading the formwork. During the concrete pour additional support may be required in the form of bracing and trestles to ensure the walls remain true, this is removed once the concrete has set

(Davies 2006, Evans 2006). Construction of the following layer or roof can begin the next day (ICFA 2009).

ICF systems require cladding to protect the insulation from mechanical damage and the impact of UV radiation which can result in degradation of the foam (ICFA 2009). A wide range of finishes can be used. Plaster, render and cladding can be applied directly to the ICF (Barista 2009, ICFA 2003). For this work a brick skin has been used to maintain the traditional appearance used in housing construction in England and Wales. Wall ties to connect the brickwork to the ICF are inserted in the ICF before the concrete pour (Davies 2006, Evans 2006). A small air cavity is maintained between the ICF foam and the brickwork. Internally the wall is finished with plasterboard, a plaster skim and paint. This construction method is shown in Figure 4.3. Table 4.9 gives the material specification used for the ICF construction considered in this work.

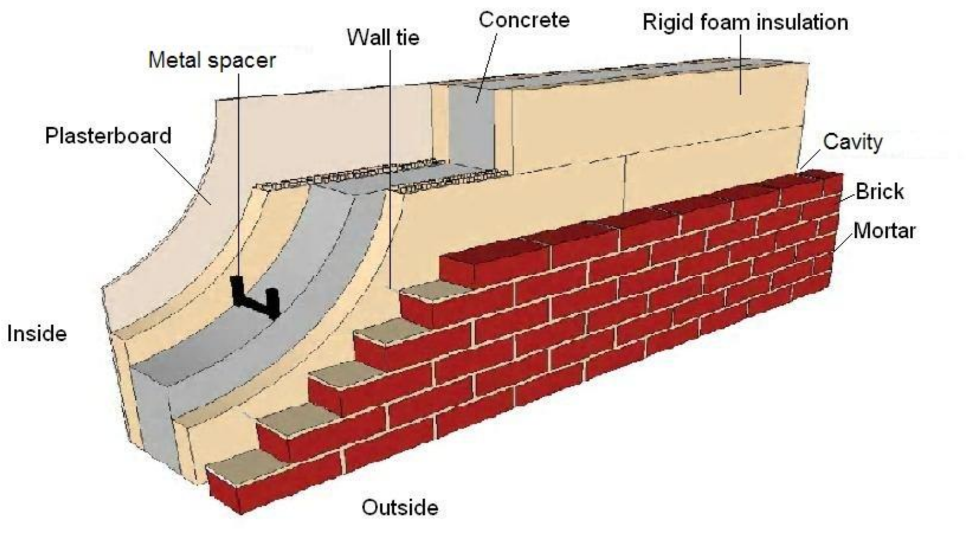

Figure 4.3: Axonometric view of ICF construction

Party walls are constructed using the ICF firewall 313 system. The walls are finished on both sides using one layer of plasterboard, a plaster skim and paint.

Table 4.9: Material specification for ICF construction

Component	Specification
Brick	Fired clay red brick, dimensions- 102.5 x 65 x 215mm
Mortar	1:3 cement sand mix, 10mm joints
Wall ties	Stainless steel, 2.5 ties per 1m^2 wall
ICF system	Beco Wallform 313 Firewall
Concrete	Pumpable RC 25 concrete, 10mm aggregate
Plasterboard	12.5mm thickness
Plaster skim	6mm skim
Paint	Double coat of water based paint

4.6.2. U value calculation

ICF has good thermal properties with U values of 0.10-0.30 W/m^{2}K given by ICFA (2009). A value of 0.25 W/m^{2}K without finishes is given by Funke (2006) and 0.25-0.13W/m^{2}K for filled but unclad blocks depending on size by Evans (2006). Greeley (1997) notes that the good thermal performance of the foam insulation compensates for the poor performance of concrete, resulting in a good overall value.

ICF blocks can be provided with a range of insulating options to suit the project requirements, insulation leaves can be of different thicknesses to achieve desired values (ICFA, 2009). Additional insulation can also be added to either face of the ICF after the concrete pour, before finishings are applied to increase performance. Table 4.10 gives the values of thickness, thermal conductivity and thermal resistance used to calculate the U value for the specified system, values were taken from Beco Products Ltd. (2008), British Standards Institution (2007), Anderson (2006) and Chudley and Greeno (2005).

Table 4.10: Values of L, λ and R used to calculate the U value for the ICF wall system

Component	L (m)	λ (W/mK)	R (m^{2}K/W)
Mortared brickwork	0.1025	0.840	0.122
Air space	0.0150	0.180	0.083
Concrete filled ICF	0.3130	0.0657	4.764
Plasterboard	0.0125	0.160	0.078
Plaster skim	0.0060	0.570	0.011

A U value of 0.204W/m^{2}K was calculated for ICF construction using the data in Table 4.10, Table 3.1 and the wall tie correction given by Chudley and Greeno (2005).

The solid construction of the party wall allows it to have a U value of 0W/m^{2}K based on Part L1A of the Building regulations (HM Government, 2010). Therefore heat loss through the party walls was not considered in this work.

4.6.3. Embodied energy

Concrete has a high value of embodied energy due to the energy required to create its components, in particular cement. Calkins (2009) notes the high energy inputs and associated carbon dioxide emissions of this process as a disadvantage of using concrete in construction. This relates directly to the use of ICF as large volumes of concrete are required. Pierquet et al. (1998) also state that the concrete component of ICF results in the system having a high embodied energy and that this results in a long payback period; i.e. the time it takes for the operational energy savings to outweigh the greater embodied energy cost is long.

A number of measures can be taken to reduce the embodied energy and therefore the negative environmental impact of concrete use. Calkins (2009) and Johnston and Gibson (2008) suggest the use of concrete containing elements such as fly ash to reduce the cement content and hence lower the embodied energy. The use of recycled aggregates in the concrete is also suggested by Calkins (2009) and Anink et al. (1996) as a way to improve the environmental impact of concrete. These measures rely on availability of materials and test results to prove the acceptability of the materials for use.

Material quantities and embodied energy coefficients for 1m^2 of external and party wall constructed using the ICF system are shown in Table 4.11 and Table 4.12 respectively.

Material volumes are based on the specification given in Table 4.9, values for the embodied energy coefficients were taken from the Inventory of Carbon and Energy V2.0 database developed by Hammond and Jones (2011).

Table 4.11: Material quantities and embodied energy coefficients for 1m^2 ICF external wall

Component	Volume (m^3)	Density (kg/m^3)	Mass (kg)	EE (MJ/kg)	EE per 1m^2 wall area (MJ)
Brick	0.085	1700	144.330	3.00	432.99
Mortar	0.018	1750	30.800	1.33	40.96
Wall tie	N/A	N/A	0.513	56.70	29.09
Polystyrene	N/A	N/A	5.180	87.40	452.73
Concrete	N/A	N/A	335.620	0.78	261.78
Metal spacers	N/A	N/A	3.210	36.00	115.56
Plasterboard	0.013	950	11.875	6.75	80.16
Plaster skim	0.006	1300	7.800	1.80	14.04
Paint	N/A	N/A	N/A	N/A	21.00
					1448.31

Summing the values from Table 4.11 gives an embodied energy value of 1448.31MJ for 1m^2 of ICF wall to the specification in Table 4.9. Components which have a high impact on the embodied energy value of SIP construction are bricks, polystyrene, concrete and the metal spacers which form the ICF units. If a lower fire resistance is acceptable polystyrene spacers can be used which would reduce the embodied energy of this system.

Table 4.12: Material quantities and embodied energy coefficients for 1m^2 ICF party wall

Component	Volume (m^3)	Density (kg/m^3)	Mass (kg)	EE (MJ/kg)	EE per 1m^2 wall area (MJ)
Paint	N/A	N/A	N/A	N/A	21.00
Plaster skim	0.006	1300	7.800	1.80	14.04
Plasterboard	0.013	950	11.875	6.75	80.16
Polystyrene	N/A	N/A	5.180	87.40	452.73
Concrete	N/A	N/A	335.620	0.78	261.78
Metal spacers	N/A	N/A	3.210	36.00	115.56
Plasterboard	0.013	950	11.875	6.75	80.16
Plaster skim	0.006	1300	7.800	1.80	14.04
Paint	N/A	N/A	N/A	N/A	21.00
					1060.47

Party walls constructed using the specified ICF system are calculated to have an embodied energy value of 1060.48MJ per 1m^2. The impact of removing the brick and the associated energy is high; indicating that alternative cladding options may be more competitive in terms of embodied energy. The embodied energy value remains high for

ICF party walls due to the energy requirement for making polystyrene, concrete and metal spacers.

4.6.4. Airtightness, wall thickness and fire performance

The continuous nature of the concrete when ICF is used has the potential to produce a very airtight building. A number of authors note the high level of airtightness achieved by the use of ICF (ICFA 2009, Barista 2009, Mosey et al. 2009 and Ross 2005). This is quantified in examples given by Moedinger-Clay (2007) of 0.8ACH and Kośny et al (1998) of 0.257-0.051ACH with an average of 0.147ACH. Information provided by Beco, manufacturers of the Wallform system specified here, give the achievable airtightness as 0.5 to 1.0 $m^3/hr.m^2$ at 50Pa (Miller 2012). For this work the higher value of $1.0m^3/hr.m^2$ at 50Pa has been used, an overestimation was felt to be fairer for comparison than an underestimation.

Wall thickness was calculated from the material specifications given in Table 4.9 and the thicknesses given in Table 4.10. The ICF system being examined was found to have a wall thickness of 0.449m.

The fire performance of ICF is considered to be very good. Fire retardants are used in the foam to limit the risk of burning. Concrete will not burn and the continuous nature of the concrete achieved using this method means there is little risk of building collapse in the event of a fire (ICFA, 2003). Design details are also important for reducing fire risk. Internally lining the ICF with gypsum plasterboard improves the fire performance of the building (ICFA 2009, Barista 2009). Barista (2009) also notes that the foam should not be continuous across floors to limits risks. Beco class the 313 Wallform Firewall system as F90 –AB, indicating a fire resistance of 90 minutes (Beco Products Ltd. 2008). The firewall version of the Wallform 313 system was selected for this work in order to achieve this higher fire rating. The standard 313 system has a slightly lower value of λ, resulting in a better U value for the system; however, it only achieves 30 minutes of fire resistance, making it unsuitable for buildings over 5m.

4.7. Prefabricated straw bale and lime plaster panels

4.7.1. Construction details

Straw bale buildings can be constructed using a number of methods, including load bearing bales and the use of bales as an infill for a timber frame. For this work, the system created by ModCell™ was used as it was felt this produces a more standardised construction than the load bearing method and presents a different method to the timber framed construction considered later in this work. The system uses timber framed panels which are filled with bales and covered with lime plaster, or render, off site. Construction of the units takes place under cover, near to the final building site, often in a large barn or similar building. The units are then transported to site and installed as prefabricated panels with a finishing coat of lime plaster on both sides after placement (Modcell 2012a). This construction method is shown in Figure 4.4.

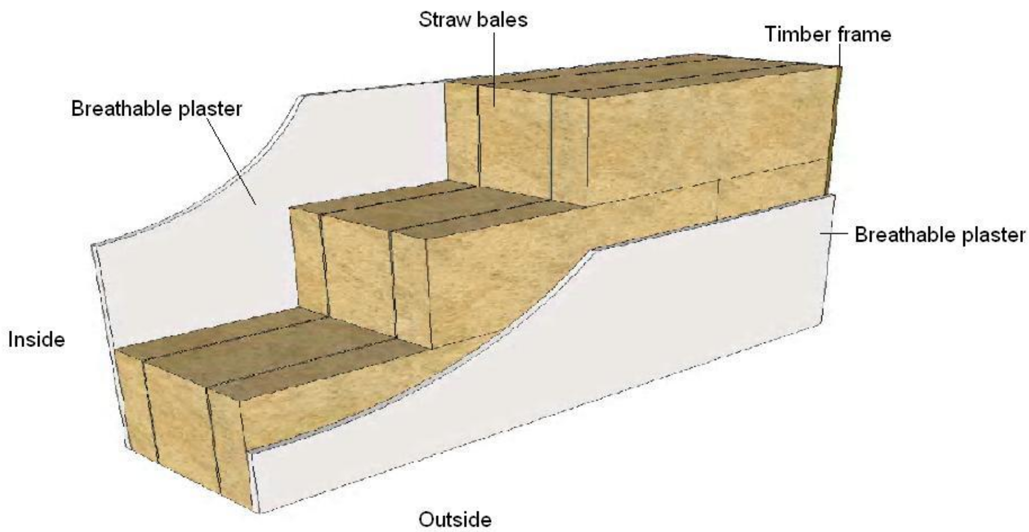

Figure 4.4- Axonometric view of prefabricated bale wall construction

Party wall construction can be carried out either by using an insulated timber stud wall or by use of the same method as for external walls. For this work, the prefabricated bale panel system was selected for use in party walls. Material specification for the prefabricated straw bale system is given in Table 4.13.

Table 4.13: Material specification for prefabricated bale wall construction

Component	Specification
Timber framing	480mm wide,100m thick, length as required. PEFC timber
Straw bale	420mm wide straw bale
Lime plaster	Lime:Sand 1:3, 27mm thick
Lime plaster skim	3mm

4.7.2. U value calculation

Straw bale construction is considered by many authors such as Arnaud et al (2009), Calkins (2009) and Lawrence et al. (2009b) to have very good thermal properties. Jones (2007) and Yates (2006) both give a U-value of 0.13W/m^{2}K for a 450mm wall. The low U values achievable are credited to the large amount of air trapped in the bales which act as insulation.

Modcell^{TM} provide a U value of 0.13 to 0.19W/m^{2}K for the 0.48m straw bale system being used in this work (Modcell 2012a). The higher value, 0.19 W/m^{2}K, was used in the optimisation process as it was felt over estimating the energy requirement was fairer that under estimating. As the party wall construction is solid it is considered to have a U value of 0 W/m^{2}K (HM Government, 2010). Therefore heat loss through party walls is considered to be zero and is not calculated as part of the operational energy requirements.

Information supplied by Modcell, including thermal imaging of an existing building constructed using this method, demonstrates that thermal bridging through the timber framing is not an issue (White 2011).

4.7.3. Embodied energy

Straw bale construction has a low value of embodied carbon. During growth of the plant material, carbon is stored in the stems which ultimately become straw. This will be retained until it is released, for example by decomposition or burning. This carbon storage is considered to be one of the potential benefits of straw bale construction by Arnaud et al (2009), Lawrence et al (2009) and Apte et al (2008). The stored carbon can be offset against the production, transportation and installation energy carbon emissions, resulting in a low net value of embodied energy. However, Calkins (2009) notes that while carbon storage is a benefit, straw cannot be considered carbon neutral as energy is put into its production, for example, to bale the straw. Energy is also required for the other materials used. As a result of this the embodied energy value of the system is low, but not zero or a negative value.

The material quantities for 1m^2 of wall constructed using prefabricated, lime plastered, bale panels and relevant embodied energy coefficients are given in Table 4.14.

Values for volumes of material are based on the specification given in Table 4.13, values for the embodied energy coefficients were taken from the Inventory of Carbon and Energy V2.0 database developed by Hammond and Jones (2011).

Table 4.14: Material quantities and embodied energy coefficients for 1m^2 prefabricated bale wall construction

Component	**Volume (m^3)**	**Density (kg/m^3)**	**Mass (kg)**	**EE (MJ/kg)**	**EE per 1m^2 wall area (MJ)**
Lime plaster	0.027	1650	44.550	1.386	61.74
Straw	0.420	304	127.680	0.240	30.64
Timber	0.074	529	39.220	7.400	290.23
Lime plaster skim coat	0.027	1650	44.550	1.386	61.74
Lime wash	0.006	1650	9.900	1.386	13.72
					458.06

Summing the values from Table 4.14 gives an embodied energy value of 458.61MJ for 1m^2 of prefabricated, lime plastered, straw bale panel.

It can be seen from Table 4.15 that the main energy input for the construction of prefabricated bale panels is the timber used to make the frame. The straw bales have a very low energy requirement. Although the lime plaster accounts for a small volume it is a dense and energy intensive material, resulting in a significant value of embodied energy.

As party walls are constructed using the same technique this value is used for the embodied energy of party walls as well as external walls.

4.7.4. Airtightness, wall thickness and fire performance

Yates (2006) discusses the need for a good finish with a high degree of airtightness to help prevent moisture entering the walls and hence avoid the high moisture levels that would lead to rotting. The Canada Mortgage and Housing Corporation (2000a) notes that the use of a plaster finish aids airtightness. This is particularly the case with the prefabricated panel system as the final plaster skim applied onsite creates an opportunity for a continuous plaster barrier to limit airflow. The airtightness value given for the straw bale system is $0.86m^3/hr.m^2$ at 50Pa (Modcell 2012b).

The wall thickness of the prefabricated straw bale system is dictated by the width of the bales used in the construction of the panels. Plaster adds a small amount to the width, both in the prefabricated panels and the additional plaster layer applied on site. The system selected for use in this work has a wall thickness of 0.48m (Modcell 2012a).

Straw bales are perceived to burn easily, presenting a considerable fire risk if used in construction. However, this perception has been shown to be incorrect for plastered bales in a number of tests. Testing by Apte et al. (2008) showed the importance of render in restricting ignition by limiting air availability. Values were also obtained for risk of ignition at various levels of fire intensity. Lower levels of fire intensity showed temperatures too low to cause ignition, however higher intensity fire resulted in temperatures capable of causing ignition after 40 minutes. Ignition did not occur due to the low levels of oxygen inside the plastered bale; however smouldering did occur, resulting in ignition when the plaster was cut open and the straw exposed to the air.

Testing discussed by Jones (2007) into fire resistance of straw bale walls shows that plastered bales have a resistance of at least 2 hours 40 minutes under standard construction material fire tests of up to 1000°C. Although these test results, combined with tests and anecdotal evidence from other countries such as that produced by Apte (2008), have been sufficient to allow construction of straw bale buildings within the UK it is noted by Jones (2007) that a lack of funding has resulted in an inability to produce a British Standard for the fire performance of lime plastered straw bales. This is because the testing rig used was smaller than that required to obtain results to British Standard level. A fire resistance of 135 minutes was used for the optimisation work; this value was taken from data published by Modcell (Modcell 2012a).

4.8. Thin joint block work

4.8.1. Construction details

Thin joint block work is similar in construction to standard brick and block work. The potential for differences between the two methods, in terms of Embodied energy due to reduced mortar, increased construction acceptability due to perceived faster build time and expected minimal impact on consumer acceptability due to similarities with brick and block construction led to its inclusion in this work.

A double skin construction is used with an external leaf of mortared red brick. An air cavity and insulation separate the leaves. The internal leaf is constructed from large, lightweight blocks with a maximum of 3mm mortar between them. The mortar bed is reinforced with a thin stainless steel or nylon mesh placed on the block before the mortar is applied. This mesh compensates for the reduced strength of thin mortar. Internally the walls are finished with plasterboard, a plaster skim and paint. The internal leaf can be constructed prior to the external leaf. Wall ties between the two leaves are inserted into the blocks after construction of the internal leaf as the external brickwork is placed. This construction method is shown in Figure 4.5.

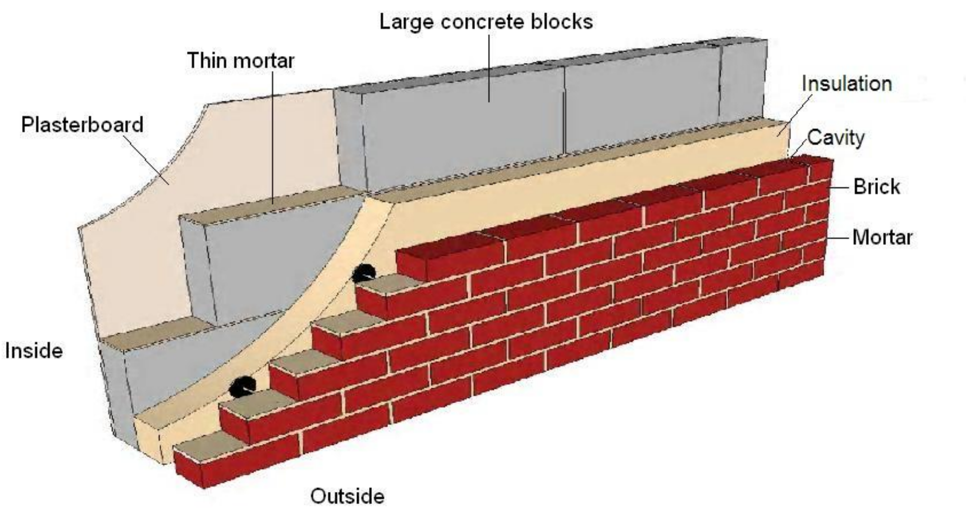

Figure 4.5- Axonometric view of thin joint block work construction

Party wall construction uses a thin mortared double layer of lightweight concrete blocks with mortar reinforcement. A 75mm layer of mineral wool insulation is used between the layers. On both sides the walls are finished with plasterboard, a plaster skim and paint. The material specification used in this work is given in Table 4.15.

Table 4.15: Material specification for thin joint block work construction

Component	Specification
Brick	Fired clay red brick, 102.5 x 65 x 215mm
Mortar	1:3 cement sand mix, 10mm joints
Wall ties	Stainless steel, 2.5 ties per 1m^2 wall
Insulation	100mm mineral wool
Thin joint blocks	Durox top block System 600, 100 x 299 x 620mm
Thin joint mortar	1:3 cement sand mix, 3mm joints
Reinforcement mesh	Galvanised, 90mm wide, 1.5mm flat wire. Murfor EFS/Z used
Plasterboard	12.5mm thickness
Plaster skim	6mm skim
Paint	Double coat of water based paint
Party wall insulation	7mm mineral wool

4.8.2. U value calculation

Values for material thickness and thermal conductivity were taken from Tarmac Topblock Ltd. (2006), British Standards Institution (2007), Anderson (2006) and Chudley and Greeno (2005), these, along with the calculated value of thermal resistance, are given in Table 4.16.

Table 4.16- L, λ and R values for thin joint block work components

Component	L (m)	λ (W/mK)	R (m^{2}K/W)
Mortared brickwork	0.1025	0.84	0.12
Air space	0.025	0.18	0.14
Mineral wool	0.1	0.038	2.63
Mortared block work	0.1	0.16	0.63
Plasterboard	0.0125	0.16	0.08
Plaster skim	0.006	0.57	0.01

The values from Table 4.16 and Table 3.1, adjusted for the effect of wall ties as recommended by Chudley and Greeno (2004) give U = 0.272W/m^{2}K for the thin joint block work wall using the materials specified in 4.16.

The U value of the party walls is taken as 0W/m^{2}K as it is fully filled and sealed (HM Government, 2010). Therefore heat loss through the party walls is considered to be zero.

4.8.3. Embodied energy

The embodied energy of thin joint block work walls was expected to be high as a result of the energy intensive materials used. Calkins (2009) notes the high energy requirements of both bricks and concrete blocks. Table 4.17 gives values of material quantities and embodied energy coefficients for 1m^2 of external thin joint block work wall. Table 4.18 gives values of material quantities and embodied energy coefficients for 1m^2 of thin joint block work party wall.

The values for volumes of material are based on the specification given in Table 4.15, values for the embodied energy coefficients were taken from the Inventory of Carbon and Energy V2.0 database developed by Hammond and Jones (2011).

Table 4.17: Material quantities and embodied energy coefficients for 1m^2 thin joint block work external wall

Component	**Volume (m^3)**	**Density (kg/m^3)**	**Mass (kg)**	**EE (MJ/kg)**	**EE per 1m^2 wall area (MJ)**
Brick	0.085	1700	144.330	3.00	432.99
Mortar	0.018	1750	30.800	1.33	40.96
Wall tie	N/A	N/A	0.513	56.70	29.09
Insulation retainer	N/A	N/A	0.061	76.70	4.67
Block	0.099	600	59.280	3.50	207.48
Reinforcement mesh	N/A	N/A	0.622	22.60	14.06
Mortar	0.002	1750	2.348	1.33	3.12
Plasterboard	0.013	950	11.875	6.75	80.16
Plaster skim	0.006	1300	7.800	1.80	14.04
Paint	N/A	N/A	N/A	N/A	21.00
					847.56

Summing the values from Table 4.18 gives an embodied energy value of 847.56MJ for 1m^2 of wall using the thin joint block work system as specified in Table 4.16. Bricks are the main contributor to the embodied energy. The lightweight blocks used also make a significant contribution to the value as they have a higher value of embodied energy per kilogram than standard blocks. However, the low mass of the blocks prevents this value being too high.

Table 4.18: Material quantities and embodied energy coefficients for $1m^2$ thin joint block work party wall

Component	Volume (m^3)	Density (kg/m^3)	Mass (kg)	EE (MJ/kg)	EE per $1m^2$ wall area (MJ)
Paint	N/A	N/A	N/A	N/A	21.00
Plaster skim	0.006	1300	7.800	1.80	14.04
Plasterboard	0.013	950	11.875	6.75	80.16
Block	0.099	600	59.280	3.50	207.48
Mortar	0.002	1750	2.348	1.33	3.12
Reinforcement mesh	N/A	N/A	0.622	22.60	14.06
Wall tie	N/A	N/A	0.513	56.70	29.09
Insulation	0.075	25	1.875	16.60	31.13
Reinforcement mesh	N/A	N/A	0.622	22.60	14.06
Mortar	0.002	1750	2.348	1.33	3.12
Block	0.099	600	59.280	3.50	207.48
Plasterboard	0.013	950	11.875	6.75	80.16
Plaster skim	0.006	1300	7.800	1.80	14.04
Paint	N/A	N/A	N/A	N/A	21.00
					739.92

The value of embodied energy calculated for 1 m^2 of party wall built using the thin joint block work system was 739.93MJ. Removing the brick skin caused a reduction in embodied energy. However, including a second layer of lightweight blocks increased the value. Lightweight blocks have a higher embodied energy per kilogram than standard concrete blocks as a result of the additional manufacturing processes.

4.8.4. Airtightness, wall thickness and fire performance

The reduced number of joints resulting from the use of larger blocks was expected to improve the airtightness achievable with this method when compared with the traditional use of small blocks. Product information provided by the manufacturer indicates an airtightness for the Durox blocks of $0.12m^3/hr.m^2$ at 50Pa (Tarmac Topblock Ltd. 2006). However, testing of a building constructed using the method as specified in Table 3.16 showed an airtightness of $4m^3/hr.m^2$ at 50Pa (Zero Carbon Hub 2011), this higher value was used in the optimisation as it is based on actual construction values and includes all elements of the wall construction, not just the thin joint blocks. This is lower than the value achieved by traditional brick and block construction. It is important that the quality of workmanship is high to allow this value to be achieved.

The value of wall thickness was calculated from Table 4.16. For the system as specified for this work the wall thickness was 0.346m.

Fire performance of thin joint block work was expected to be similar to that shown by standard brick and block construction. Information supplied by the manufacturer indicates that 100mm thickness of System 600 blocks, as specified for this work, will provide two hours of fire resistance for load bearing walls (Tarmac Topblock Ltd. 2006). A fire resistance time of 180 minutes was used during the optimisation procedure.

4.9. Timber frame with brick cladding

Timber frame construction is the second most commonly used method of construction, used for 7% of the houses constructed in England from 1990 to March 2009 (DCLG 2010). Historically this construction method experienced increased popularity during the 1960s and 1970s, however, bad publicity resulting a television programme stating it was at risk from rotting and fire severely damaged the public acceptability of this construction method and reduced its use (Cavill 1999).

It was included as an alternative method that is considered to have had some level of mainstream exposure.

4.9.1. Construction details

Timber frame construction uses a load bearing timber frame with external cladding and infill to provide insulation and internal finishing.

For this work an external finish of mortared brickwork was used to maintain a traditional appearance and provide the necessary waterproofing for the building. To control the movement of moisture and heat the internal system is composed of an air filled cavity, a waterproof membrane, wood boarding, insulation, a breathable vapour control membrane and plasterboard, finished internally with a plaster skim and paintwork. Details for this construction method are based on those provided by Knight et al (2009) and Hastings (2010). This construction method is shown in Figure 4.6.

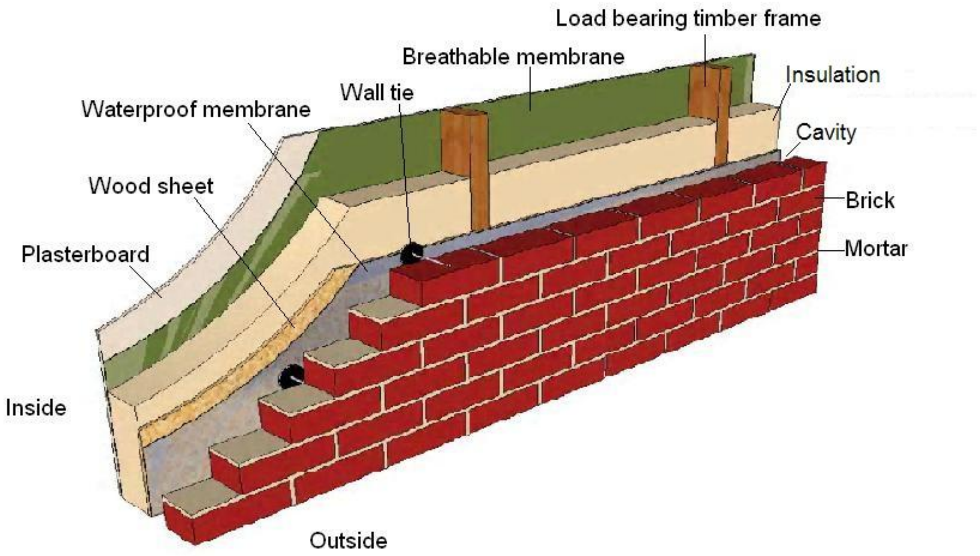

Figure 4.6- Axonometric view of timber framed construction

Party walls are constructed using a double thickness layer of frame and infill with additional insulation between the two layers. Material specification used in this work is given in Table 4.19, unless stated specification applies to external and party walls.

Table 4.19- Material specification for timber frame construction

Component	Specification
Brick	Fired clay red brick, 102.5 x 65 x 215mm
Mortar	1:3 cement sand mix, 10mm joints
Wall ties	Stainless steel, plastic insulation retainer, 4.4 ties per $1m^2$ wall
Air space	60 mm ventilated
Waterproof membrane	Glidevale Protect TF200 Breather Membrane
Wood sheet	OSB sheet, 9mm thickness
Insulation	Mineral wool insulation, 120mm between studs
Breathable membrane	Glidevale VC foil ultra with cavity clips to reduce thermal bridging
Timber frame	140 x 45mm timber studs at 500mm spacings
Services void	20mm, interrupted by studs to allow placement of cavity clips. Services can also be run in these voids.
Plasterboard	25mm thickness, two sheets of 12.5mm
Plaster skim	6mm skim
Paint	Double coat of water based paint
Party wall timber frame	90 x 45mm timber studs at 500mm spacings
Party wall cavity	60mm
Party wall insulation	Mineral wool insulation, 70mm between studs, 60mm in cavity

4.9.2. U value calculation

Values of material thickness and thermal conductivity for the timber framed construction method shown in Table 4.20 were taken from Kingspan (2009), British Standards Institution (2007), Anderson (2006) and Chudley and Greeno (2005). The impact of the vapour barrier and waterproof membrane are ignored due to their low thickness (1mm) as suggested by the manufacturer (Hastings 2010). The U value is calculated for the insulated section of wall.

Table 4.20- L, λ and R values for timber frame construction components

Component	Thickness (m)	Thermal conductivity (W/mK)	Thermal resistance (m^2K/W)
Mortared brickwork	0.1025	0.84	0.12
Air space	0.060	0.18	0.14
Wood sheet	0.009	0.03	0.30
Mineral wool	0.120	0.038	3.16
Services void	0.020	0.18	0.11
Plasterboard	0.025	0.16	0.08
Plaster skim	0.006	0.57	0.01

Values from Table 4.20 and Table 3.1 were summed then adjusted for the effect of wall ties as recommended by Chudley and Greeno (2004) to give U= 0.249W/m^2K for the insulated section of timber framed construction as specified in this work.

Timber framed construction carries the risk of thermal bridging, where heat can be transferred from inside the building, through the timber to the outside, bypassing the insulation layer and resulting in significant heat loss. The selection of Glidevale VC foil ultra with cavity clips as the vapour control membrane was intended to reduce this issue to an acceptable level. The cavity clips cover the internal face of the timber studs and reduce the heat transfer into the timber (Hastings 2010). Although some depth of insulation is lost to allow for the clips the reduced thermal bridging is considered to be of greater importance.

The specified construction of party wall enables the U value of the party wall to be considered as 0W/m^2K (HM Government, 2010). Therefore heat loss through the party walls is considered to be zero.

4.9.3. Embodied energy

Table 4.21 gives quantities of material components for 1m^2 of external timber framed wall to the specification given in Table 4.19 and the associated embodied energy values. Table 4.22 contains material and embodied energy values for 1m^2 timber framed party wall.

The values for volumes of material are based on the specification given in Table 4.19, values for the embodied energy coefficients were taken from the Inventory of Carbon and Energy V2.0 database developed by Hammond and Jones (2011).

Table 4.21- Material quantities and embodied energy coefficients for 1m^2 timber framed external wall

Component	Volume (m^3)	Density (kg/m^3)	Mass (kg)	EE (MJ/kg)	EE per 1m^2 wall area (MJ)
Brick	0.085	1700	144.330	3.00	432.99
Mortar	0.018	1750	30.800	1.33	40.96
Wall tie	N/A	N/A	0.903	56.70	51.19
Insulation retainer	N/A	N/A	0.107	76.70	8.22
Waterproof membrane	N/A	N/A	0.140	155.00	21.70
OSB sheet	0.009	680	6.120	15.00	91.80
Mineral wool	0.109	25	2.730	16.60	45.32
Breathable membrane	N/A	N/A	0.100	95.89	9.59
Timber studs	0.013	529	6.665	7.40	49.32
Plasterboard	0.025	950	23.750	6.75	160.31
Plaster skim	0.006	1300	7.800	1.80	14.04
Paint	N/A	N/A	N/A	N/A	21.00
					946.45

Summing the values from Table 4.21 gives an embodied energy value of 946.45MJ for 1m^2 of wall using the timber framed wall construction specified in Table 4.17. Brickwork was the main contributor to the total embodied energy for this method of construction. Using an alternative method of cladding could reduce the total embodied energy of the construction.

Table 4.22- Material quantities and embodied energy coefficients for 1m^2 timber framed external wall

Component	Volume (m^3)	Density (kg/m^3)	Mass (kg)	EE (MJ/kg)	EE per 1m^2 wall area (MJ)
Paint	N/A	N/A	N/A	N/A	21.00
Plaster skim	0.006	1300	7.800	1.80	14.04
Plasterboard	0.025	950	23.750	6.75	160.31
Breathable membrane	N/A	N/A	0.100	95.89	9.59
Timber studs	0.008	529	4.285	7.40	31.71
Mineral wool	0.064	25	1.593	16.60	26.44
OSB sheet	0.009	680	6.120	15.00	91.80
Mineral wool	0.090	25	2.250	16.60	37.35
OSB sheet	0.009	680	6.120	15.00	91.80
Mineral wool	0.064	25	1.593	16.60	26.44
Timber studs	0.008	529	4.285	7.40	31.71
Breathable membrane	N/A	N/A	0.100	95.89	9.59
Plasterboard	0.025	950	23.750	6.75	160.31
Plaster skim	0.006	1300	7.800	1.80	14.04
Paint	N/A	N/A	N/A	N/A	21.00
					747.12

The value calculated for the embodied energy of 1m^2 of timber framed party wall was 747.12MJ. The removal of the brick outer skin reduced the embodied energy. However, the second layer of insulated timber frame required to construct a suitable party wall caused a significant increase in the value.

4.9.4. Airtightness, wall thickness and fire performance

High quality of workmanship is particularly important in achieving an airtight building with timber framed construction. The nature of the method, with multiple layers and components increases the potential for gaps which will allow the passage of air.

The selection of a vapour barrier with cavity clips helps to improve the airtightness of the system by creating a continuous layer within the wall. Joints must be sealed with tape to achieve this (Hastings 2010). The estimated airtightness for a timber framed wall following the above specification is 3 to 5m^3/hr.m^2 at 50Pa (Glidevale 2012). Hastings (2011) gives an example of a perfectly sealed system achieving 3m^3/hr.m^2 at 50Pa in testing. The higher value of 5m^3/hr.m^2 at 50Pa has been used in the optimisation process as it was considered achieving a perfect seal in site conditions was unlikely.

To calculate wall thickness the component thicknesses given in Table 4.19 were summed. This gives a value of 0.295m for the wall constructed to the specification used in this work.

The presence of wood in timber framed construction is often considered to present a high fire risk. The fire resistance of timber framed buildings is discussed by Lennon et al. (2000) with the conclusion that good workmanship is required to achieve good fire performance. The testing of the TF2000 timber framed housing discussed by Lennon et al (2000) showed that timber framed construction meets the Building Regulations fire performance standard of 60 minutes, this value was used in the optimisation. Two layers of plasterboard, as specified in Table 4.17 are typically required to achieve this.

4.10. Summary

Six construction methods were chosen to be studied in detail- brick and block, structural insulated panels (SIPs), insulating concrete formwork (ICF), straw bale and lime plaster panels, thin joint block work and timber framed construction. Brick and block construction was included as the "typical method". Alternative techniques were selected to cover a range of available options. All methods considered had been previously used in England or Wales, meaning they are capable of passing the Building Regulations for England and Wales and can be constructed and maintained in the temperate climate experienced. Details of the method and performance associated with each of the six construction methods have been given. Values for U value, embodied energy and performance for the construction method specifications studied are summarised in Table 4.23.

Table 4.23- U values, embodied energy and performance values for each of the methods of construction and Building Regulations

Construction method	U value (W/m^2K)	Embodied energy External wall (MJ)	Embodied energy Party wall (MJ)	Air tightness ($m^3/(h.m^2)$ at 50Pa)	Wall thickness (m)	Fire performance (minutes)
Brick and block	0.277	744.30	713.46	4.50	0.346	240
SIP	0.167	1464.12	834.77	1.00	0.326	73
ICF	0.204	1448.31	1060.47	1.00	0.449	90
Prefabricated bale unit	0.190	458.61	458.61	0.86	0.480	135
Thin joint block work	0.272	847.56	739.92	4.00	0.346	180
Timber frame	0.249	946.45	747.12	5.00	0.295	60
Building Regulations	0.300	N/A	N/A	10.00	N/A	60

A visual comparison of Table 4.23 shows that all the options perform better than the requirements of the Building Regulations where applicable. A comparison of the alternative methods of construction with the “typical” construction method of brick and block and each other is difficult to achieve visually as each material performs better on some elements, but worse on others. Because of this the optimisation carried out later in this work (Chapters 7 and 8) is particularly suitable for identifying the best option. Identifying the values in Table 4.23 enabled the calculation of embodied energy, operational energy and performance characteristics during the optimisation procedure.

It can be seen from the embodied energy calculation table for each construction method that bricks contribute significantly to the total embodied energy for those methods that include them. It is possible that alternative methods of cladding would reduce the embodied energy of construction. However, if a brick finish is desired other methods of cladding may be unacceptable. Materials such as brick slips, which provide a brick appearance but use significantly less material and hence have a lower embodied energy, may be a solution to this issue. This has been identified as an area for further work as this work focused on maintaining a brick appearance where possible. Foam insulation, such as that used in SIPs and ICF has a higher than expected embodied energy, however, these methods of construction achieve high performance in terms of U value and airtightness, therefore the embodied energy cost can be balanced by the potential operational energy savings.

5. Public acceptability of construction methods

5.1. Introduction

It was considered important to determine the public acceptability of alternative construction methods. An option that was not supported by the public would be unlikely to be a successful construction option, even though it may have benefits such as low embodied energy or good thermal performance. In this chapter the acceptability of the end user, the public who will live in the finished houses was examined. The opinions of the public on the construction methods being studied were examined by the use of a survey. Views were collected on factors which the public consider to be important when choosing a house, as well as the acceptability of each method.

5.2. Questionnaire results and discussion

The view of house purchasers was considered to be of particular importance to this work. In order for a type of housing construction to present an economical solution it must be acceptable to the purchaser. If a house is constructed using a method in which people are not prepared to invest it is unlikely to sell. Even if such a house performs well in terms of embodied and operational energy it cannot be considered to be a viable solution. The survey aimed to evaluate this acceptability and to identify factors about which purchasers were concerned when selecting a house.

5.2.1. Response rate

A total of 593 responses were received. Of these, twenty one responses were fully blank, with only the permission to use information question completed; these were removed. For the analysis 573 responses were used; partial responses were retained as it was felt they could provide information about those questions which were completed.

5.2.2. Geographical representativeness of responses

The distribution of respondents by region was examined and compared with the geographical population distribution for England and Wales. This is shown in Figure 5.1.

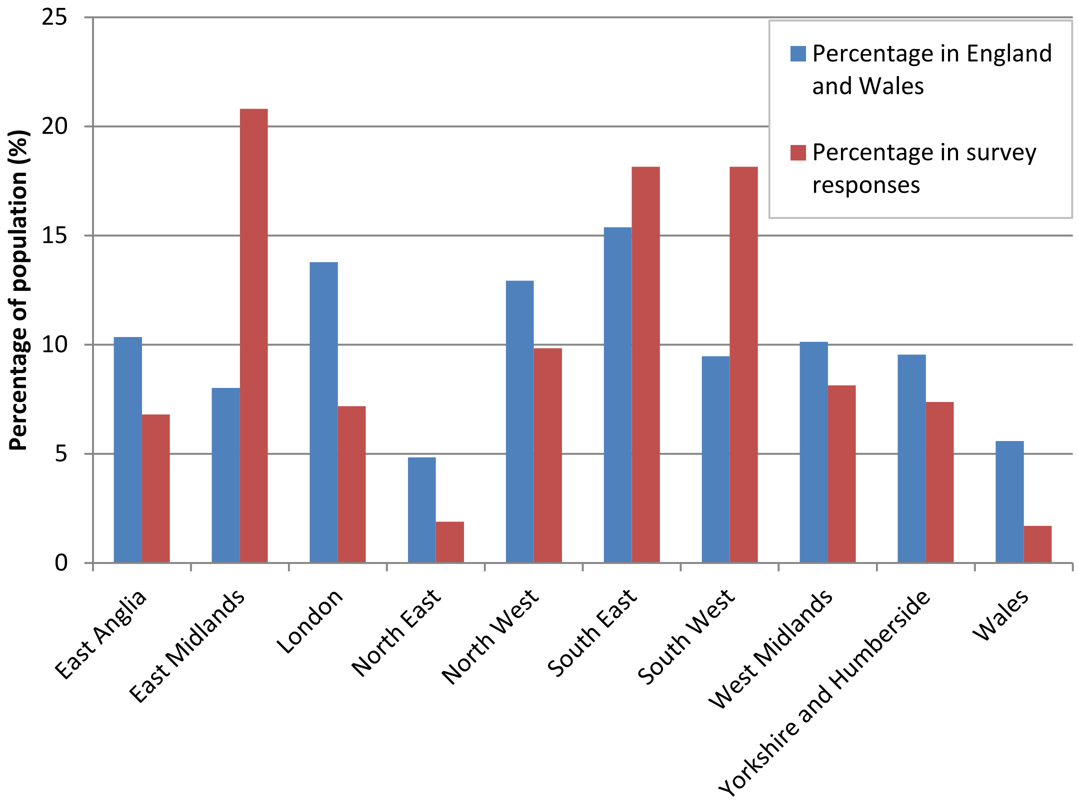

Figure 5.1- Percentage distribution of respondents and population of England and Wales by region

Visual inspection of Figure 5.1 indicates a higher percentage of responses from the East Midlands, South East and South West than exist in the actual population, with lower than actual values for all other regions. A Chi squared test of the values shows the distributions are not sufficiently similar for the values to be used nationally (X^2= 39.88, $X_{0.95}{}^2$= 16.92. Therefore, sampling was carried out within the survey responses to mirror the geographical distribution of the population. The sub-samples created were used for statistical analysis of the responses regarding importance of factors when choosing a house. As each region is considered separately for acceptability it was not necessary to sample within the data for this.

5.2.3. Sampling of data

Sampling was carried out from within the survey responses to create subsamples that correctly mirrored the geographical distribution of England and Wales.

SPSS was used to draw five different samples from the data; the use of multiple samples allowed a comparison between the results. The number of respondents from each region was calculated to mirror the geographical distribution of population in England and Wales.

It was desirable to maximise the number of responses in the sample; therefore, the region with the smallest population to total response ratio was used as the limiting region. This was identified as Wales; all subsamples used all responses from Wales and a reduced number from each of the other regions.

To calculate the number of samples required from each region, the number of responses for Wales was divided by the percentage of the actual population who live in Wales. This value was multiplied by the percentage in the population for each region. All values were rounded to the nearest whole number, as survey numbers are a discrete value. The number of responses from each region is shown in Table 5.1.

Table 5.1- Number of responses taken from each region to form the sample

Region	**Percentage of England and Wales population**	**Total number of survey responses**	**Number of responses in sample**	**Percentage of the sample**
East Anglia	10.35	36	17	10.35
East Midlands	8.02	110	13	8.02
London	13.78	38	22	13.78
North East	4.83	10	8	4.83
North West	12.93	52	21	12.93
South East	15.37	96	25	15.37
South West	9.47	96	15	9.47
West Midlands	10.12	43	16	10.12
Yorkshire and Humberside	9.54	39	15	9.54
Wales	5.58	9	9	5.58
Totals	100	529	161	100

Five subsamples containing the correct number of responses from each region to mirror the actual population distribution of England and Wales were drawn randomly from the survey responses. Analysis of importance factors was carried out on these subsamples.

5.2.4. Importance of characteristics in house purchase

The importance of each factor when considering buying as house is displayed as a percentage score in Figure 5.2. A score of 1 was equivalent to not at all important, a score of 5 meant very important.

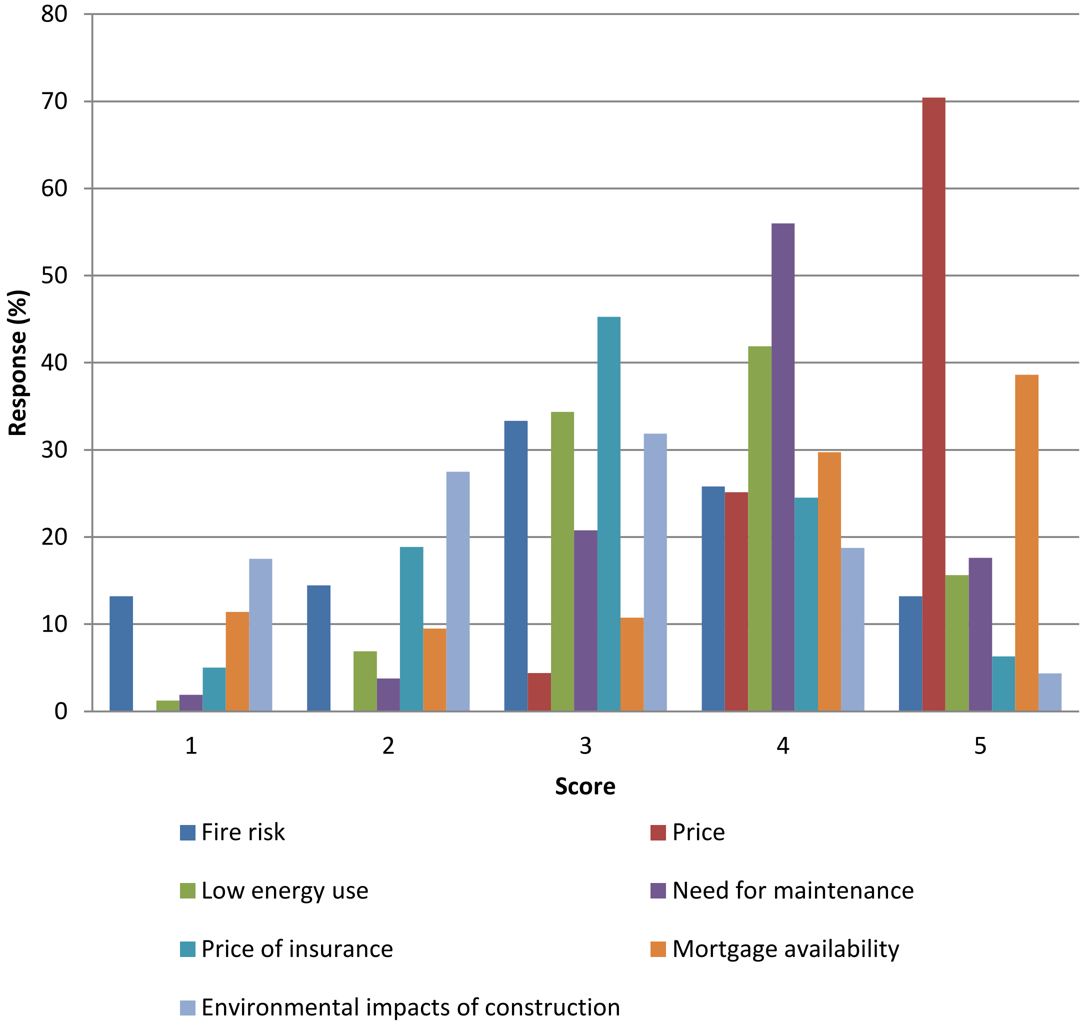

Figure 5.2- The importance of each factor when considering a house purchase, from Sample 1.

Values are shown for Sample 1 only as the graphs produced for all samples were similar.

The most frequent value (modal) and the middle value when all responses were arranged in numerical order (median) values are given in Table 5.2. These values were the same for all samples.

Table 5.2- Modal and median values of importance for the characteristics considered

	Importance score	
Characteristic	**Mode**	**Median**
Fire risk	3	3
Price	5	5
Low energy use	4	4
Need for maintenance	4	4
Price of insurance	3	3
Mortgage availability	5	4
Environmental impacts of construction	3	3

From visual inspection of the graphs and consideration of the modal and median values, the factors can be given the following importance ranking (most to least):

1) Price
2) Need for maintenance
3) Mortgage availability
4) Low energy use
5) Price of insurance
6) Environmental impacts of construction
7) Fire risk

It can be seen from Figure 5.2 that all factors have some importance to the public. The impact of any changes such as wall construction method on these should be considered carefully as a positive impact, such as reducing price, may result in good public support for the method. A negative impact, for example increasing price, will reduce the attractiveness of the method and the potential for its use.

Principal component analysis was used to reduce the seven categories scored using Likert scales into a smaller number of themes. These identify areas about which the public are concerned, for example financial issues, rather than focusing on specific aspects, such as house prices. Connections between the factors are identified by the use of a rotated component matrix.

For each of the five samples drawn from the data, principal component analysis was carried out on the seven sets of data produced by the Likert scales for the questionnaire. This allowed linked factors to be grouped into a smaller set of issues that should be considered when designing houses. Each question asked was considered to be a variable. To determine the suitability of the data from the questionnaire for principal component analysis, two tests are carried out, the Kaiser-Mayer-Olkin measure and Bartlett's test of spherecity. The Kaiser-Mayer-Olkin measure for each sample was in excess of 0.6, which is considered acceptable (Field 2009). The correlation of items was tested using Bartlett's test of spherecity, the values for this are shown in Table 5.3.

Table 5.3- Values for Bartlett's test of spherecity for each sample

Sample	Values for Bartlett's test of spherecity
1	$\chi^2(21) = 169.703$, $p < .001$
2	$\chi^2(21) = 213.911$, $p < .001$
3	$\chi^2(21) = 194.821$, $p < .001$
4	$\chi^2(21) = 212.300$, $p < .001$
5	$\chi^2(21) = 214.802$, $p < .001$

Values of $p < .05$ indicate there is a relationship between the variables that can be explored by principal component analysis (Field 2009). The values in Table 5.3 show that all samples satisfy this requirement, therefore, the data is suitable for this analysis as there is a significant relationship between the variables.

Eigenvalues for each "theme", or component, were calculated. However, only those considered to be significant are retained. This dictated by the minimum eigenvalue that is accepted. All samples produced two factors with eigenvalues greater than 1, which would satisfy Kaiser's criterion, however, it was decided to use Joliffe's criterion of factors with eigenvalues above 0.7 being retained (Field 2009). Using Joliffe's criterion resulted in four factors for all subsamples and created a more logical division of categories when examined. The four components are initially labelled 1-4; determination of their meaning is carried out after examination of the results.

Scree plots can be used to examine the eigenvalues for each component identified. A plot of the eigenvalue calculated against the component number can be used to identify the number of components to retain. Typically such plots will fall sharply and demonstrate a noticeable point of inflexion. Components with eigenvalues greater than this point of inflexion are retained; those with eigenvalues below the point of inflexion below are discarded. The point of inflexion itself may be retained or discarded, depending on preference and the results achieved (Field 2009). Scree plots were generated for each sample in this work. However, they produced ambiguous results, with the point of inflexion difficult to identify. Therefore, Joliffe's criteria was used.

When a principal component analysis is carried out it is desirable that the components identified account for the maximum possible variance. The variance represents the spread of the data. Each component identified will account for some percentage of the variance. The cut off point for the number of components should be such that an acceptable amount of variance is accounted for. The variance accounted for by the use of four factors for each sample was in excess of 78% for all five samples, considered to be acceptable.

To improve the clarity of results by making each variable impact most strongly on a single component, rather than on many, a technique called rotation can be used. The results are referred to as the rotated component matrix. For this work Orthagonal rotation (varimax) was used (Field, 2009). The results of the principal component analysis for Samples 1 to 5 are shown in Tables 5.4 to 5.8 respectively.

Table 5.4- Rotated component matrix for Sample 1 Likert scale principal component analysis

Question	Component 1	2	3	4
When considering a house for purchase how important are the environmental impacts of its construction to you?	0.868			
When considering a house for purchase how important is low energy use to you?	0.785			
When considering a house for purchase how important is mortgage availability to you?		0.861		
When considering a house for purchase how important is price to you?		0.793		
When considering a house for purchase how important is fire risk to you?			0.855	
When considering a house for purchase how important is the price of insurance to you?			0.698	0.483
When considering a house for purchase how important is the need for maintenance to you?				0.916

Consideration of the variables which affect each component leads to the components being identified as:

- Component 1- Environmental factors
- Component 2- Financial factors
- Component 3- Risk
- Component 4- Running costs

Table 5.5- Rotated component matrix for Sample 2 Likert scale principal component analysis

Question	Component 1	2	3	4
When considering a house for purchase how important is the need for maintenance to you?	0.811			
When considering a house for purchase how important is the price of insurance to you?	0.773			
When considering a house for purchase how important is fire risk to you?	0.644			
When considering a house for purchase how important are the environmental impacts of its construction to you?		0.913		
When considering a house for purchase how important is low energy use to you?		0.795		
When considering a house for purchase how important is mortgage availability to you?			0.933	
When considering a house for purchase how important is price to you?				0.960

Consideration of the variables which affect each component leads to the components being identified as:

- Component 1- Risk and associated costs
- Component 2- Environmental factors
- Component 3- Mortgage availability
- Component 4- Purchase price

Table 5.6- Rotated component matrix for Sample 3 Likert scale principal component analysis

Question	Component 1	2	3	4
When considering a house for purchase how important are the environmental impacts of its construction to you?	0.811			
When considering a house for purchase how important is low energy use to you?	0.773			
When considering a house for purchase how important is mortgage availability to you?	0.644			
When considering a house for purchase how important is price to you?		0.913		
When considering a house for purchase how important is the price of insurance to you?		0.795		
When considering a house for purchase how important is fire risk to you?			0.933	
When considering a house for purchase how important is the need for maintenance to you?				0.960

Consideration of the variables which affect each component leads to the components being identified as:

- Component 1- Environmental factors
- Component 2- Financial factors
- Component 3- Risk
- Component 4- Maintenance

Table 5.7- Rotated component matrix for Sample 4 Likert scale principal component analysis

	Component			
Question	1	2	3	4
When considering a house for purchase how important is fire risk to you?	0.720			
When considering a house for purchase how important is price to you?				0.973
When considering a house for purchase how important is low energy use to you?	0.811			
When considering a house for purchase how important is the need for maintenance to you?		0.915		
When considering a house for purchase how important is the price of insurance to you?		0.735		
When considering a house for purchase how important is mortgage availability to you?			0.930	
When considering a house for purchase how important are the environmental impacts of its construction to you?	0.865			

Consideration of the variables which affect each component leads to the components being identified as:

- Component 1- Environmental factors
- Component 2- Running costs
- Component 3- Mortgage
- Component 4- Price

Table 5.8- Rotated component matrix for Sample 5 Likert scale principal component analysis

Question	Component 1	2	3	4
When considering a house for purchase how important are the environmental impacts of its construction to you?	0.888			
When considering a house for purchase how important is low energy use to you?	0.819			
When considering a house for purchase how important is the price of insurance to you?		0.857		
When considering a house for purchase how important is fire risk to you?		0.742		
When considering a house for purchase how important is price to you?			0.861	
When considering a house for purchase how important is mortgage availability to you?				0.814
When considering a house for purchase how important is the need for maintenance to you?				-0.636

For the results of Sample 5 maintenance achieved a negative value. As a result of this it was removed from the analysis of this sample. Consideration of the variables which affect each component leads to the components being identified as:

- Component 1- Environmental factors
- Component 2- Risk
- Component 3- Price
- Component 4- Mortgage

The four components identified from each of the five samples above were compared to identify the “themes” about which it was considered the public are concerned when considering a house for purchase. Energy use and environmental impact of construction are always grouped into a single factor; therefore, it is considered that environmental factors can be considered as a “theme” about which the house purchasing public are concerned. Purchase price and mortgage appear either grouped together or individually, with no other factors. Therefore, a second “theme” about which it can be said the purchasing public is concerned is financial factors. Other elements appear grouped in a variety of ways across the samples; they all indicate a level of concern for different types of risk and the associated costs. Risk management is considered to be the best way to categorise the remaining elements into a single "theme" about which the house purchasing public is concerned. Environmental factors, financial factors and risk should all be considered when making decisions about housing construction. At this point in the survey the questions were about house purchase in general, rather than the specific topic of wall construction method. Therefore these themes can be applies to any housing related decision.

5.2.5. Awareness of alternative construction methods

The respondents were asked if they had heard of each of the six construction types being considered. At this stage no further details were given about the methods. The results from this question are shown in Figure 5.3.

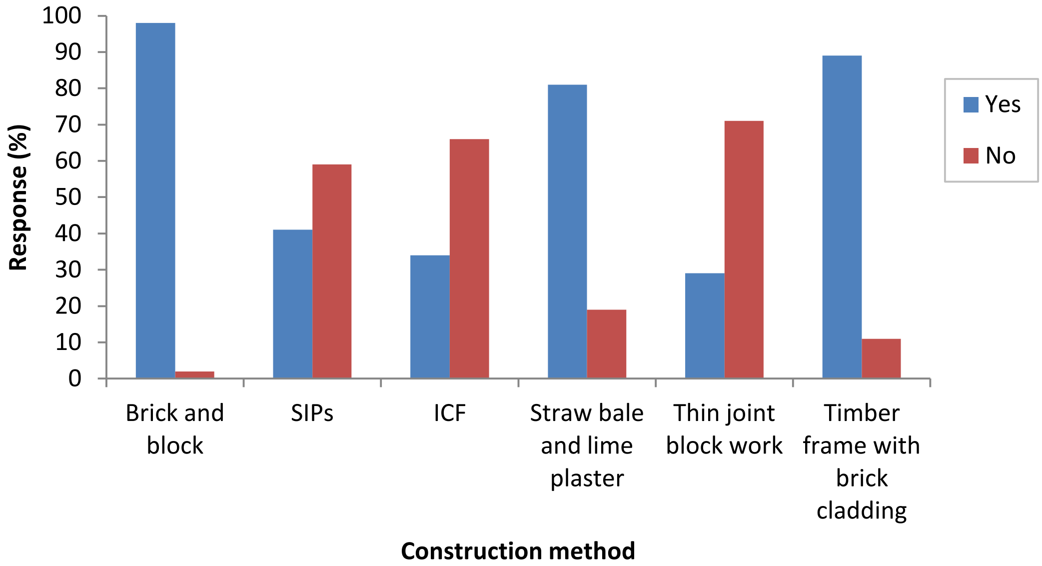

Figure 5.3- Percentage of respondents who have heard of each type of construction.

There is a high level of awareness of brick and block amongst the public; this was expected as it is the most commonly used housing construction method. For example, brick and block was used to construct 88% of dwellings in England between 1990 and March 2009 (DCLG, 2010).

Timber frame had the second highest level of awareness. A high level of awareness was expected as timber frame is the second most common method of housing construction. From 1990 to March 2009 7% of houses built in England were built using timber frames (DCLG, 2010).

Awareness of straw bale and lime plaster construction was higher than expected. Later in the questionnaire a number of respondents made comments about having seen this type of construction on the Channel Four television programme “Grand Designs”. It is felt this, combined with the unusual nature of the method making it memorable, has increased public awareness. ICF and SIPs have both also featured on “Grand Designs”, but have a lower awareness.

SIPs, ICF and Thin joint block work all have low levels of awareness. It is possible that as no illustration of the wall types was given when this question was asked in the survey a number of respondents may be aware of the construction technique, for example through media exposure, but be unfamiliar with the name. It would be desirable to increase the awareness of these methods through education as this is viewed as the first step to their potential increased usage.

5.2.6. Acceptability of Brick and block

The acceptability of each method is considered by region as the data indicated the respondents' regional structure was not a reflection of that found in England and Wales. Visual inspection of the acceptability data when sorted by region indicated there was a strong variation in the acceptability of construction methods by location which supported the argument for considering the data for each region separately. In addition, later use of the data in optimisation procedures required a regional separation to make it compatible with other data. Comments made expressing views and concerns about each option were not divided by region as it was felt they could be applied nationally.

In the survey, the question regarding the acceptability of brick and block was presented first with the intention that later alternative options would not bias respondents against brick and block by feeling they may have been shown a better option. It also allowed respondents to familiarise themselves with the layout of the questions and diagrams on a type of construction that it was more likely they would recognise.

Percentage responses to the question “Would you buy a house built from this material?” for the brick and block question are shown in Figure 5.4. Numerical values for the responses can be found in Appendix C. Answers to this question are sorted by region; no subsamples were taken as acceptability remained divided by region throughout the work.

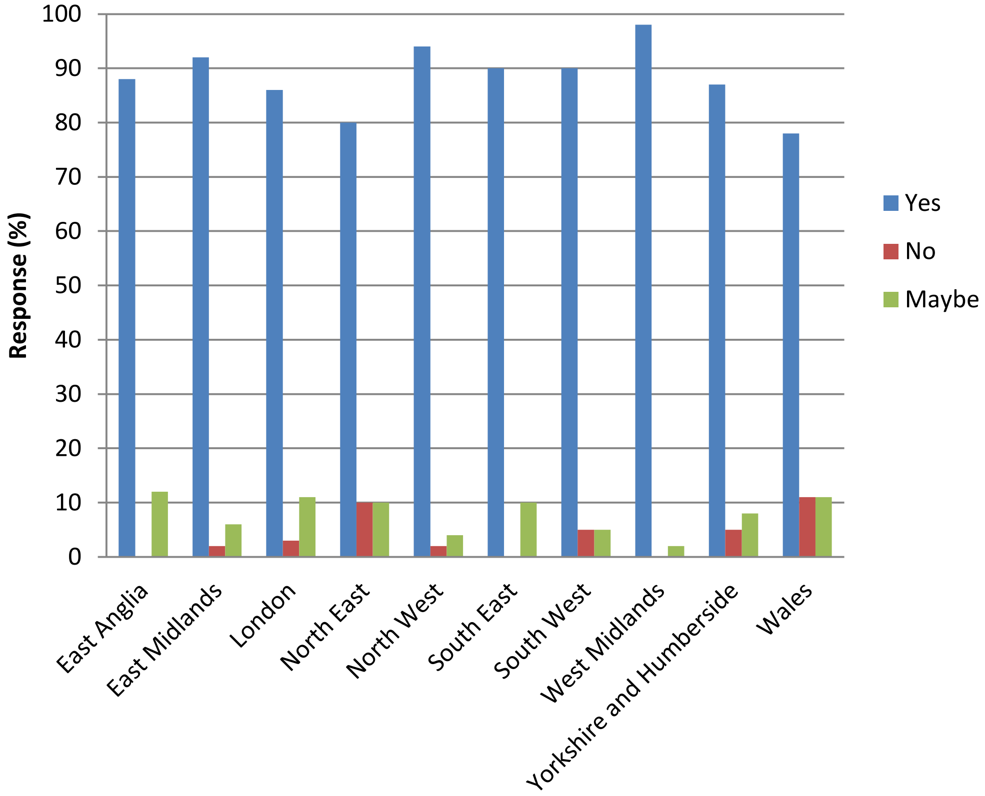

Figure 5.4- Acceptability of brick and block construction by region

Figure 5.4 shows that brick and block has a high acceptability for purchase in all regions, with the highest in the West Midlands at 98%. A high acceptability for this construction method was expected as it is the most commonly used type of housing construction; used for 88% of dwellings in England between 1990 and March 2009 (DCLG, 2010). This data was intended to act as a control group, enabling acceptability of the "typical" method to be compared with that of alternative options. It also demonstrates that there is not 100% acceptability of brick and block in any region.

The lowest acceptability for this type of construction was seen in Wales and the North East; these values may have been artificially lowered by fairly low response rates from these regions. All other regions had "yes" responses in over 85% of cases.

Of the remaining respondents, "maybe" answers make up the majority, with very few "no" responses seen in any region. The highest values of "no" responses were seen in the North East and Wales. Again this may have been impacted by low response rates for these regions.

The acceptability question was followed by an optional open question allowing respondents to add any comments they wished regarding the construction type. These comments have not been divided by region as it is felt the views expressed can be applied nationally.

The most common comment relating to brick and block construction was that it was the typical housing method. The high acceptability combined with the number of comments describing brick and block as “typical” or “traditional” indicates that the respondents have a significant preference for wall types with which they are familiar.

Factors such as insulation, strength and durability received positive comments. The fact that it is a proven method was also presented as a positive feature by a number of respondents. The high acceptability of this type of construction may indicate that these are factors which must be emulated by alternative methods of construction in order for them to be accepted.

Few negative comments were presented by respondents for this method of construction. The respondents who said they would not purchase this type of building expressed a preference for other types of construction, such as stone, or a dislike of brick as an exterior material. Alternative exterior skin materials may have been acceptable to these respondents; this provides an opportunity for alternative construction methods such as SIPs and ICF, where a range of finishes can be achieved more easily than with a dual skin system.

5.2.7. Acceptability of Structural Insulated Panels (SIPs)

Percentage responses to the question "Would you buy a house built from this material?" for SIPs are shown in Figure 5.5, divided by region. Numerical values can be found in Appendix C.

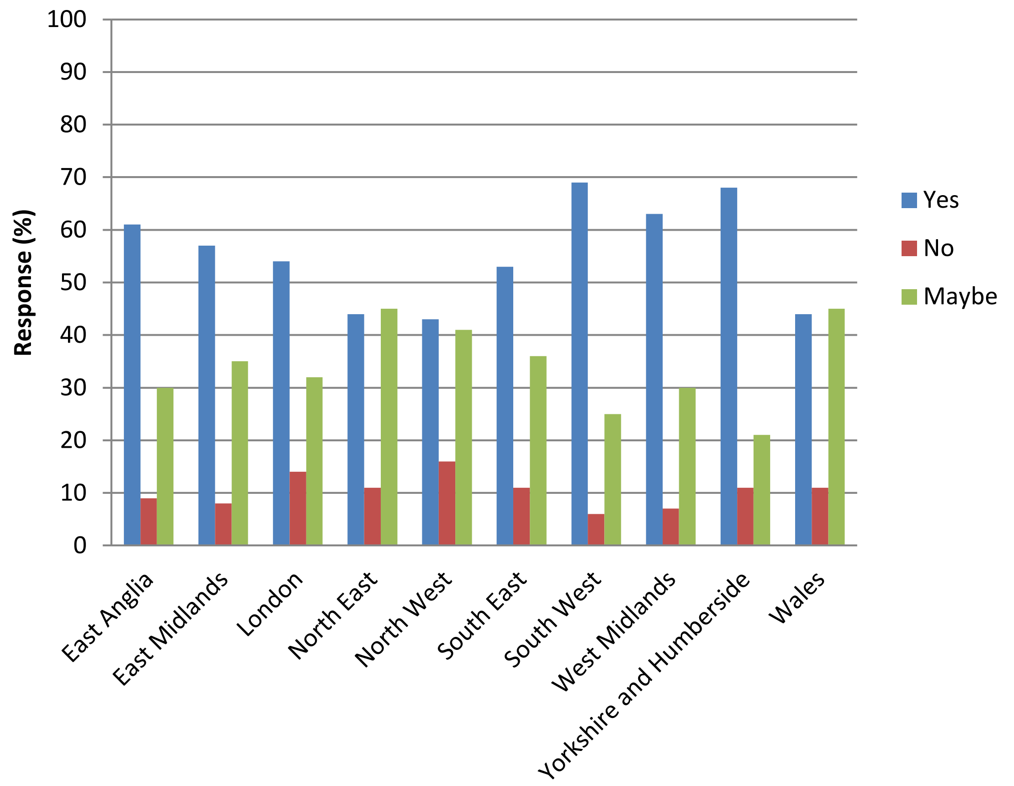

Figure 5.5- Acceptability of SIP construction by region

Compared with brick and block, SIPs have a significantly lower acceptability, ranging from 43% to 69%. However, the percentage of "maybe" responses is much higher, with a range of 6-16%. If the issues which result in a "maybe" response, rather than a "yes" response could be solved then there is the potential for this method to move from a medium to a high level of acceptability. The level of "no" responses ranges from 6% to 14%, indicating the method is unlikely to be as universally accepted as brick and block even if the perceived issues can be solved. These results may relate to the lack of awareness indicated in 5.2.4, those respondents who had not previously heard of the construction method may have selected "maybe" or "no" due to a lack of prior knowledge.

SIPs received positive comments in two areas. Respondents felt that the appearance of the finished building would be similar to that achieved by brick and block construction and indicated that this was a benefit. As with brick and block, a few respondents indicated a dislike of brick as a finish. Although not discussed in the survey, SIPs can be finished in a range of ways, which may appeal to those who indicated they would not purchase this type of construction because they disliked the appearance of brickwork. The presence of insulation in the construction method and the associated reduction in energy use resulting from this was the other positive aspect raised by respondents.

In contrast to brick and block, a number of negative points were raised. This was expected due to the unusual nature of the construction method, and presents an opportunity to see which issues concern the respondents. The most frequently expressed negative point was that the method would not be sufficiently strong to perform the duties of a house wall, in particular when compared to the previously viewed option of brick and block. The strength of SIPs has been tested, both in laboratory conditions and by use in existing structures, it is found to be better than that for comparable timber frame structures in work done by Mosey et al. (2009), Hairstans and Kermani (2007) and Morley (2000).

Durability, in particular with respect to the effects of moisture on the timber elements of the construction, was the second most commonly stated negative point. It is noted by the Department for Communities and Local Government (DCLG) BRE authors (2008) that there is little long term evidence for the durability of SIP construction in the UK. However, anecdotal evidence for the durability of SIPs exists in the USA, where early examples of SIPs from the 1950s are cited by Morley (2000) and Cathcart (1998). More recent examples which are still in use after thirty years are cited by Hairstans and Kermani (2007). These examples suggest a significant durability; however, the presence of timber will present a risk that must be managed by the use of suitable finishes and good workmanship.

The presence of timber in the structure led to concerns regarding the fire performance of the construction method. Barista (2008) and Griffen et al. (2006) note that timber elements of the construction method result in a susceptibility to fire. To achieve the necessary level of fire protection, it is necessary to use a plasterboard lining. Bregulla and Enjily (2004) state that this allows SIPs structures to satisfy Part B of the England and Wales Building Regulations. Good workmanship must be achieved to ensure this is the case, as gaps would greatly reduce the fire performance of the structure.

Some respondents felt that this type of construction would result in difficulties attaching fixtures and fittings to the walls. In fact, the OSB skin allows for placement of small loads such as picture hooks and light weight shelving across the face, giving a greater flexibility. However, it is noted by DCLG BRE authors (2008) that it is desirable to minimise damage to the OSB layer as damage potentially reduces its strength. Larger items, such as kitchen units, should be attached to framing or freestanding, rather than fixed to the OSB.

5.2.8. Acceptability of Insulating Concrete Formwork (ICF)

Percentage responses to the question "Would you buy a house built from this material?" for ICF are shown in Figure 5.6, divided by region. Numerical values for the results can be found in Appendix C.

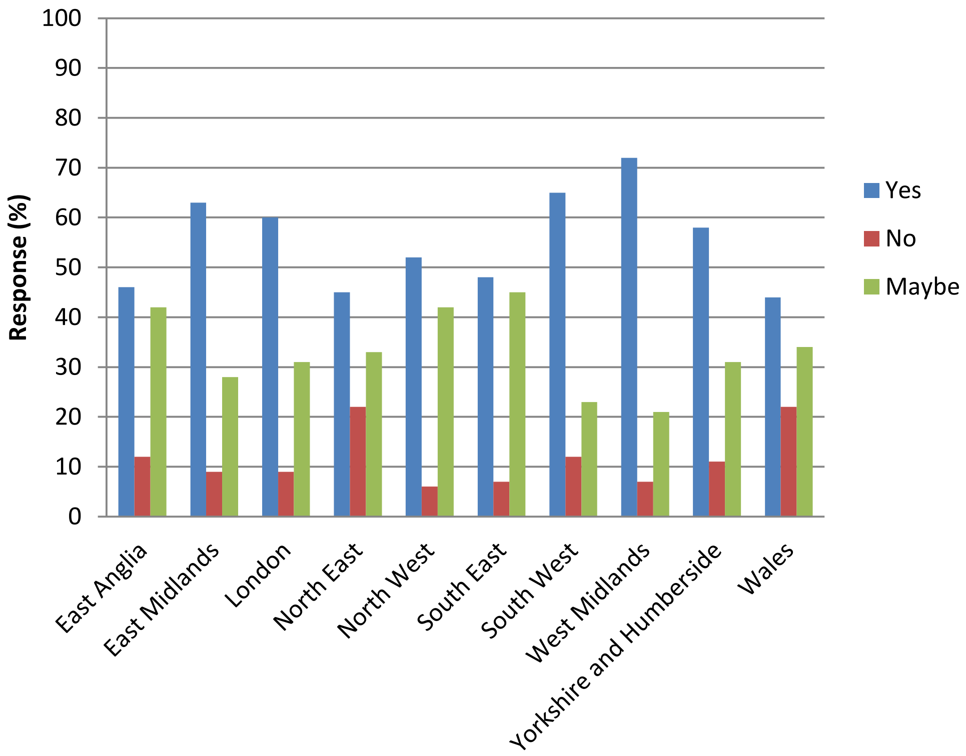

Figure 5.6- Acceptability of ICF construction by region

The acceptability for purchasing a house built using ICF is similar to that of SIPs, with fewer "yes" responses, but more "maybe" responses than seen with brick and block. There appears to be a regional variation, with the "yes" percentages ranging from 44% to 72%, the lowest in Wales and the highest in the West Midlands. This provides an argument for considering construction methods by region rather than adopting a national view. As with other questions, the low questionnaire response rates from Wales and the North East may have skewed the results for these regions, however, they have similar rates to those seen in other areas such as East Anglia and the South

East. Results seen for the acceptability of ICF might be connected the level of awareness of the method shown in 5.2.4. As with SIPs, this construction method had a low level of awareness, which may have resulted in more “maybe” or “no” responses as respondents were not familiar with the method.

In the open ended question, the respondents were divided in their opinions on the durability of ICF. Some felt that the concrete would produce a durable structure, whereas others were concerned about the lifespan, in particular with respect to the foam insulation. Past examples from the USA provide anecdotal evidence for durability, demonstrating a lifespan of thirty years (ICFA, 2003). Predictions for lifespan vary from sixty years (ICFA 2009) to two hundred years (Griswold, 2007) which is comparable with traditional construction. Another divided issue was the potential for attaching fixtures and fittings to walls made from this type of construction. Some respondents felt that the concrete would easily support any loads applied, whereas others were concerned about the ease of fixing items to the walls.

Positive factors commented on by questionnaire respondents included the presence of insulation; the strength of the construction resulting from the use of concrete; and the appearance. That the finished building looks like brick and block construction was given as a positive aspect. In a few cases respondents indicated a dislike of a brick finish, as with SIPs, it is possible to use alternative finishes with this construction method to produce a range of appearances to suit the consumer. This has the potential to increase acceptability.

The main concern expressed by respondents was that the use of concrete has a negative environmental impact. Although the production of cement requires large amounts of energy and results in the release of carbon dioxide, the environmental impacts should be balanced with other factors such as lifespan and performance data. In addition, it is possible to reduce the negative environmental impacts of concrete production by the use of alternative component materials such as fly ash and recycled aggregates (Calkins 2009; Johnston and Gibson, 2008; Anink et al., 1996).

The potential for ICF to be more expensive than other construction methods was noted. Research by Denzer and Hedges (2007) and Al-Homoud (2005) indicates that ICF is indeed more expensive than other forms of construction, quantified as 5-20% more by Griswold (2007). As with environmental impacts, the additional cost of construction should be balanced against performance data to determine if the initial investment is economical. However, unlike environmental issues which are balanced across the entire lifespan, the savings must balance the increased purchase price in the potentially shorter time period of ownership, which may only be a few years.

The thickness of walls constructed from ICF was also a concern to some respondents. Other methods of finishing, such as rendering, have the potential to reduce the wall thickness as the air gap and brick skin would be eliminated. This was not examined in the work as it was decided to maintain a traditional finish with the methods examined where possible.

5.2.9. Acceptability of Prefabricated straw bale and lime plaster panels

Percentage responses to the question “Would you buy a house built from this material?” for straw bale and lime plaster construction are shown in Figure 5.7, divided by region. Numerical values are given in Appendix C.

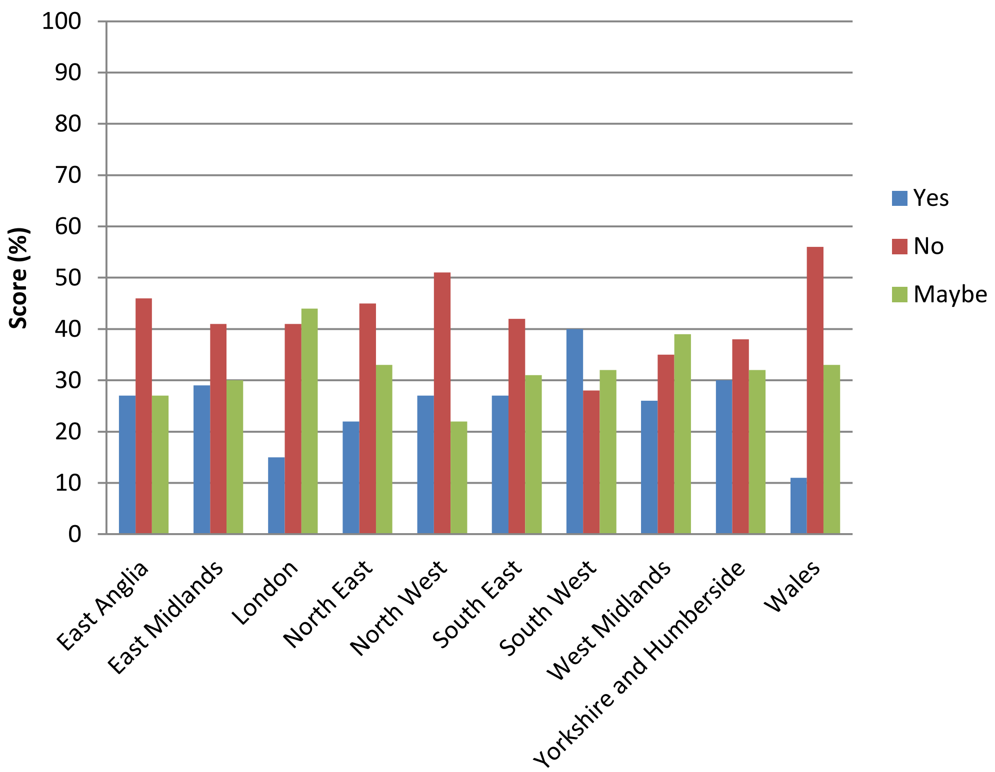

Figure 5.7- Acceptability of Prefabricated straw bale construction by region

Straw bale construction received the greatest proportion of “no” responses of all the construction methods examined, with a range of “yes” responses at only 11-40%. This option scored particularly low in London and Wales; a low acceptability was expected in London due to its urban nature, however, Wales, being more rural, was expected to have a higher acceptability. As with other methods, this may have been a result of an insufficient response rate or due to other, unexplored, factors for example, farming in Wales tends to be less crop-focussed due to the terrain.

The South West was the only region to have more “yes” responses than “no”. It is thought that this indicates a significant regional divide in acceptability, and further supports the case for considering each region separately. It is considered that this greater acceptability may be a result of the South West being a rural area, with a large amount of farming, which may have made a more easily identifiable connection between straw bale construction and support for the local economy.

The levels of “maybe” responses is not dissimilar to that seen for SIPs and ICF, supporting the case that a large number of purchasers would be interested in alternative methods of construction, of all sorts, even methods perceived as unusual, if purchasers’ concerns are dispelled. A large number of comments were given in the open ended question for this method which provides valuable information on the concerns held by the respondents. Identifying these concerns and addressing them has the potential to greatly improve the acceptability of the method, in particular for those respondents who answered “maybe”.

Comments indicated that opinion was divided over the appearance of lime plastered straw bale construction. This was the only option in the survey that did not have a brickwork appearance, as the typical construction method does not allow for this. Views on appearance are largely a matter of personal preference; however, if a greater range of finishes was available, then the acceptability might increase. Lime based plaster is typically considered an integral part of the straw bale construction and the most effective solution to weatherproofing, whilst still allowing moisture to exit the wall. A solution may be to create a “fake brick” finish using coloured plaster. However, this has significant implications for increasing costs and maintenance requirements.

Several comments indicated respondents had seen straw bale construction on the UK Channel Four Television programme “Grand Designs”. This can be credited with raising awareness of the method and some of its advantages, as the majority of respondents reflected that their views were positive from this experience. Positive comments on the use of straw in house building mainly focused on the environmentally friendly nature of the construction method. The lower impact of the materials used compared to those in other types of construction was commented on. The word “sustainable” was used frequently by respondents who identified the rapidly renewable nature of straw and perceived it as a benefit. The potential for straw bales to act as a good insulator was commented on by many respondents, which has implications for both environmental and financial factors. Positive financial implications were identified with respect to cost, in that it may be a cheaper construction option than the others presented due to the use of low-price components.

Straw bale construction received a large number of comments classed as negative, either because they expressed a direct dislike or because they indicated a concern that the respondent held regarding the method. This was expected, due to the unusual nature and the limited exposure the method has had, particularly in relation to performance details. The “Three Little Pigs” story, in which the house built from straw is blown down, received a number of mentions; fortunately this was balanced to a degree by more recent media exposure. However, neither gives a great deal of reliable performance data to the mildly interested consumer. To obtain quality information, it would be necessary to research the method, adding an extra step to the already long process of house purchase.

The main focus for concern when respondents considered straw bale construction was fire performance and the perception that straw is highly susceptible to fire damage. In the case of plastered straw bale, the fire resistance of plastered straw bale is given by Jones (2007) as two hours and forty minutes which satisfies the England and Wales Building Regulations for fire performance. The tightly-packed nature of the bales combined with the plaster skin limits the air available for combustion and reduces the risk of burning. However, to convince people of this would be a substantial task. The greatest fire risk is during the construction phase as loose straw will burn fairly easily and there is a greater risk with unplastered bales. Good site practices should minimise the risk and this should not affect the end user.

Another frequent area of concern was the durability of the walls, in particular with respect to moisture and the risk of bales rotting. This is a genuine concern, as high levels of moisture can result in rotting as discussed by Carfrae et al. (2009), Lawrence et al. (2009), Goodhew et al. (2007), Summers (2006), Goodhew et al. (2004) and Canada Mortgage and Housing Corporation (2000b). To limit the risk of this, it is essential that good workmanship and quality control is maintained throughout the construction phase. The impact on the end user should be minimal, although there would be the option of monitoring the moisture content of the wall using moisture meters. In the USA straw bale buildings between fifty and one hundred years old exist, they are presented by Seyfang (2010), Smith (2007) and Yates (2006) as evidence of durability. In the UK there is much less of a tradition of using straw bales in construction; Jones (2007) states that the earliest examples date from 1994. Although this is not as long as the evidence from the USA, it still demonstrates the durability of the method if good construction practices are followed. The possibility of damage by pests was another way respondents suggested durability could be compromised; however, Jones (2007) indicates there is minimal risk of this as the straw contains little nutritional value and once the bales are plastered access for pests is difficult.

The third most frequent concern was that the bales would have insufficient strength to support applied loads. In the prefabricated unit, construction loads are carried by a combination of the timber and plaster, with the straw acting largely as infill and insulation. However, King (1997) demonstrates that even without the timber frame the composite nature of the bales and plaster skin are sufficient to carry the loads. The strength of plastered bales when used in this way has also been examined by the Canada Mortgage and Housing Corporation (2008); their conclusion was that it is possible to carry the loads associated with construction even when quite low quality bales are used.

Wall thickness was noted by a few respondents. The nature of the construction means that thick walls are unavoidable; however, thick walls provide the opportunity for architectural features such as window seats, as demonstrated by Lacinski and Bergeron (2000). In addition, as the thickness of insulation in brick and block construction is increased to achieve better U values, the difference in wall thickness reduces. One respondent stated that the additional thickness would make the method unsuitable for use in London where space is a premium. This manner of regional variation should be considered as in other areas wall thickness may be less of a concern.

Issues raised by smaller numbers of respondents included a high need for maintenance and potential difficulty relating to financial matters. The unusual nature of the construction means it is more difficult to obtain mortgages and insurance for the building. Specialist companies will provide the required financial assistance, however the lack of competition has the potential to increase costs. Since price and other financial issues rate highly in consumer concerns, this is an issue that would need to be addressed to make this method of construction viable on a large scale. It is true that the lime plaster requires a greater level of maintenance than other construction methods as the external surface must be repainted to maintain its condition. This is an unavoidable factor which is likely to reduce the acceptability of the method to a number of consumers.

5.2.10. Acceptability of thin joint block work

Percentage responses to the question “Would you buy a house built from this material?” for thin joint block work are shown in Figure 5.8, divided by region. Numerical values are given in Appendix C.

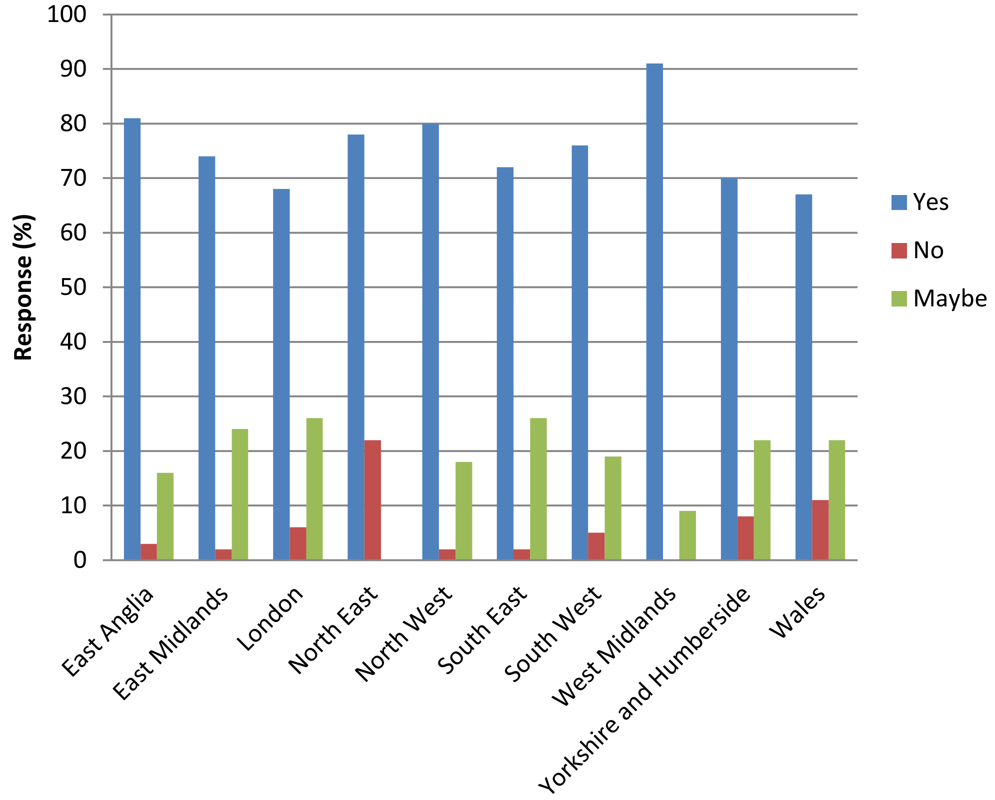

Figure 5.8- Acceptability of thin joint block work construction by region

A high acceptability of this construction method was expected due to its similarities with brick and block construction. However, it can be seen that it has a slightly lower acceptability than brick and block; it is felt that this may be an indication of purchasers' reluctance to consider new and alternative options, preferring to remain with the familiar.

Most regions had very low levels of “no” responses, the main exception being the North East. The low response rate in this region may have affected the data. For other regions the level of “no” responses was similar to that seen with brick and block, this is expected due to the similarities between the two methods.

The number of “maybe” responses was a little higher that that seen for brick and block. Comments in the open-ended questions mostly expressed a desire for more information regarding the benefits and disadvantages of this option over brick and block. This is considered to have increased the number of “maybe” responses. Unlike SIPs and ICF, a lack of awareness of the method did not seem to greatly affect the acceptability of this method. This may be because of the similarities, both visually and in the description, to brick and block construction.

The most frequently expressed comment related to the similarities between this type of construction and brick and block construction. This view was typically expressed by respondents who stated that they would purchase a house built using this method, so was taken to be a positive comment. Additional positive comments reflected those seen in the brick and block question: the presence of insulation, strength, proven nature, ease of hanging fittings and appearance were all given as positive aspects. It is considered that these views, combined with the high acceptability levels seen above, support the case that purchasers’ favour options that are familiar or have high levels of similarity with standard options, over those that are different and unknown.

The method received very few negative comments. The most frequently expressed concern was a dislike of concrete; in some cases this was tied to the perceived high environmental impact of concrete. However, in others it was not tied to any other specific view, just stated as an issue. The environmental impact of concrete use varies greatly, depending upon the composition and the specifics of the individual use. In this case, the blocks used would be light weight, containing a significant proportion of air and reducing the volume of concrete used in their construction. If alternatives such as fly ash are used to replace a portion of the cement then the environmental impact can be further reduced (Calkins, 2009). When considered in combination with performance factors such as expected lifespan, the environmental impact of concrete use is often lower than expected. A lack of familiarity was noted, in particular several respondents stated that more information would be needed to determine the advantages and disadvantages over standard brick and block construction.

5.2.11. Acceptability of timber frame with brick cladding

Percentage responses for the question “Would you buy a house built from this material?” for timber frame construction are shown in Figure 5.9, divided by region. Numerical values are given in Appendix C.

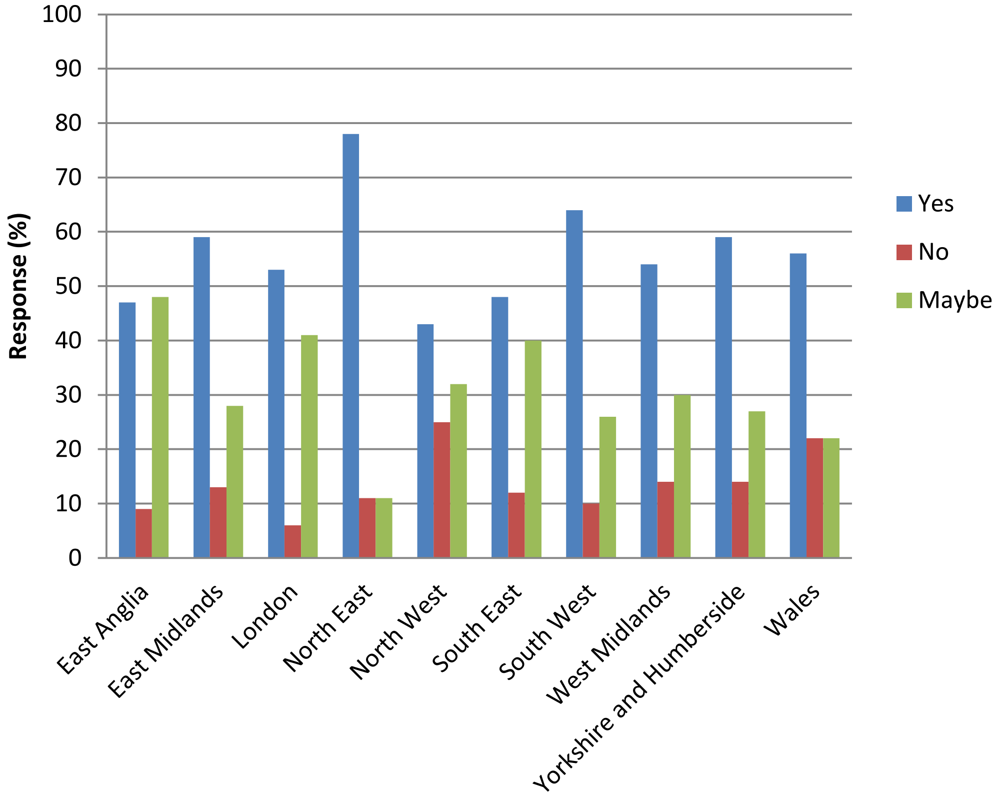

Figure 5.9- Acceptability of timber frame construction by region

Timber frame construction is the second most commonly used method for building houses in England, with 7% of houses built in England from 1990 to March 2009 using this method (DCLG, 2010). Considering this, a higher acceptability was expected for timber frame as a construction technique than was seen in the responses. However, as noted in the literature review, the popularity of timber frame construction was seen to fall during the nineteen eighties after bad publicity regarding the potential for rotting and fire (Cavill 1999), this may have impacted responses from those who were aware of the programme.

For most regions, the responses for timber frame are comparable with those seen for SIPs and ICF; there are noticeably fewer “yes” responses than for brick and block, but more “maybe “ responses, indicating issues which it may be possible to solve in order to increase acceptability. Numbers of “no” responses are similar to, or slightly higher than, those seen for brick and block. A high level of “yes” responses was seen in the North East. As previously commented upon, the response rate from the North East was fairly low, therefore, the results may have been skewed as a result of this. Alternatively it may be that there is a greater acceptability in this region. Timber frame is used more extensively in Scotland in the construction of housing which may indicate a more positive view of the construction method in more Northerly regions, for example due to differences in the construction process and the way this is impacted by different climates. However, the noticeably lower acceptability in the North West does not appear to support this.

This was a method of which a few of the respondents had experience, with both positive and negative comments. Positive views indicated that the respondents had lived in timber framed housing and were happy with the performance, while negative views stated that problems had been experienced with houses built using the timber framed methods. Often, the cause of problems was identified as poor workmanship; due to the multilayer nature of this construction method it is essential that the highest quality standards are achieved.

Positive comments made regarding timber framed construction were similar to those seen for brick and block, SIPs and ICF. The majority of respondents felt that the appearance of the construction method and its similarity to “typical” construction was a benefit. For those who noted a specific dislike of brick as an external finish, it is possible to use this construction method with other cladding options. Although this was not stated in the questionnaire, it has a potential to further increase acceptability. That the method is “tried and tested” was given as a positive aspect by some respondents, particularly some of those who had positive past experience of houses constructed using timber frames. The presence of insulation in the construction method was noted by a number of respondents as a positive aspect. Government schemes such as the “Warm Front scheme” have focussed on connections between insulation, the environment and heating costs which has increased public awareness of the need for insulation. The final positive point for timber framed construction was that several respondents noted that it appeared to be of high strength.

Durability was the main concern, in particular with respect to moisture and the potential for rotting of the timber components. This is discussed by Hutton (1992) who concludes that avoiding the conditions in which rotting occurs reduces the risk. The possibility of damage to the waterproof membrane and the difficulty of inspecting the timber once covered by the brick and plaster are valid points raised. However, as stated above, by adopting the highest quality of workmanship, issues associated with moisture can be avoided. The process of attaching fixtures and fittings to the walls was identified as an issue due to the potential for damaging the membranes and causing moisture issues. This should be carried out with care to minimise the risk. The chance of insect infestation causing damage to the timber was identified as another risk that could seriously reduce the longevity of the construction. This is of minor concern in the UK and can be further limited by the treatment of the timber components if required.

The presence of timber in the construction led to many respondents indicating concerns regarding the fire performance of timber framed construction. The presence of plasterboard and a plaster skim finish on the internal surface of the construction provide sufficient protection to meet the England and Wales Building Regulations; again the importance of good workmanship can be seen as poor quality work would leave the frame susceptible to fire; this is discussed by Lennon et al. (2000).

5.2.12. Methods of increasing interest in alternative construction methods

Responses to this question were not divided by region as it was considered that suggestions could be applied nationally to improve the image of alternative methods of construction.

The possibility of financial savings scored highly on the potential for increasing interest. Low prices would increase interest for 89% of respondents and 99% of respondents said that low running costs would increase their interest. Alternative methods of construction have the potential to save on either, or both, of these elements, which could greatly increase their appeal. However, these need to be quantified and publicised to persuade purchasers that they can make savings which would make it worth trying their something different. Where construction costs are cheaper, it would be necessary that a significant portion of the saving is passed on to the purchaser, rather than being retained as a larger profit by the initial investor, allowing a lower price that would attract purchasers. For running costs the annual savings compared to an equivalent brick and block house presents an ideal way to demonstrate the potential of alternative construction techniques.

A low environmental impact had the lowest percentage of “yes” responses, but still scored highly, with 86% of respondents indicating that this would increase their interest in alternative construction methods. This is somewhat in contrast with responses to questions ranking the importance of factors when choosing a house, where environmental impact received low scores, placing it at the bottom of the list. However, when combined with other factors during factor analysis, environmental impact as a whole was one element about which it is considered house purchasers are concerned. Increasing media focus on the environment and climate change has resulted in a much greater awareness of the need for change which may have encouraged the “yes” response. In addition, the Government focus on operational energy has led to an implied connection between low environmental impact and financial savings which may have led to a favourable response.

The need for more information about the construction methods was identified from both the 90% “yes” response to this section and from the comments sections across the questionnaire, where a “maybe” response was often accompanied by a query. These queries typically related to performance and could often be answered by existing research. For example, queries relating to the fire performance of straw bale construction which can be answered from existing research, demonstrating straw bale construction to be more than satisfactory for Building Regulation requirements (Jones, 2007). Having that information could turn a maybe into a yes and greatly increase the acceptability of alternative construction options.

The open ended question offered respondents a chance to state what they felt would increase their interest. Many of the comments can be tied to the need for information, for example, the need for methods to be durable and proven. Information exists relating to many of the factors queried, both anecdotal and from laboratory testing, however it is not widely disseminated and is sometimes of restricted availability. In order to increase the acceptability of alternative construction methods, this information needs to be shared in an easily understandable manner. Without this, the public will always favour materials they are familiar with, and therefore trust, as suggested by the high acceptability and comments relating to the use of brick and block.

Guarantees were suggested in this section as a method of increasing the acceptability of alternative construction methods. The purchase of a house is a large financial investment, and a guarantee would reassure not only the purchaser, but also companies providing mortgages and insurance. This could be a route to greatly increasing the acceptability of alternative construction techniques and therefore achieving the associated benefits such as lower embodied energy and better performance.

Respondents also commented that the construction method is not the only important factor when selecting a house. A wide range of other factors would affect the choice, for example location. This is not a subject that has been examined as it does not relate to wall construction methods, which is the focus of this work. It would have been beneficial to eliminate these comments from respondents' answers by stating in the introduction to the construction methods section of the questionnaire that they should consider the construction method only; as if each option were used to construct an identical house with identical non-construction related benefits such as location, view, proximity to services etc.

5.3. Summary

- The top three concerns for house purchasers were: price; need for maintenance and mortgage availability.
- Factors about which the public are concerned when considering a house purchase include environmental factors, financial factors and risk management.
- The public has a high awareness of brick and block, timber frame and straw bale. There is low awareness of SIPs, ICF and thin joint block work.
- Brick and block and thin joint block work construction methods have a high acceptability.
- There is the potential for good acceptability of SIPs and ICF if concerns are addressed.
- Straw bale and timber frame construction methods have a low acceptability, although some respondents found them acceptable.
- The acceptability of construction methods varies noticeably with location.
- Respondents indicated a preference for familiar or traditional options.
- Desirable characteristics of a construction method include: insulation, strength, durability, proven performance, brick appearance externally.
- Many of the concerns about construction methods identified can be disproved by existing research and anecdotal evidence.
- More information, financial benefits and good environmental performance would increase public interest in alternative methods of construction.

6. House builder acceptability of construction methods

6.1. Introduction

In addition to determining the existence of a market for houses constructed using alternative methods it was felt that the views of those who would be producing the houses were important. A reluctance to use a particular method would make it difficult to promote. Information from past experience with the construction methods being examined was also felt to be helpful. Construction industry views were collected by use of a questionnaire, similar to that used to collect public views, but with an industry focus.

6.2. Questionnaire results

6.2.1. Response rate

Fifty responses were received for the house builder survey. Of these twenty were fully blank, with only the permission to use information question completed, these were removed from the data. Thirty surveys were used in the analysis. Partial responses were retained as they provided a level of information about the topic.

6.2.2. Representativeness of responses

Many of the respondents work for companies with a wide geographical spread. It was therefore decided not to divide responses by region. All regions had multiple respondents.

All areas of the construction process were represented, with multiple respondents in the design, planning and construction categories. In addition, Building Control was represented by one respondent.

6.2.3. Importance of characteristics in construction method selection

To determine the importance of a range of factors when choosing a construction method, respondents were asked to score the importance of each factor on a Likert scale. The scale ranked from 1- Not at all to 5-Very much. All the factors included can be affected by the construction method. The percentage scores for each characteristic are shown in Figure 6.1. Modal and median scores are shown in Table 6.1.

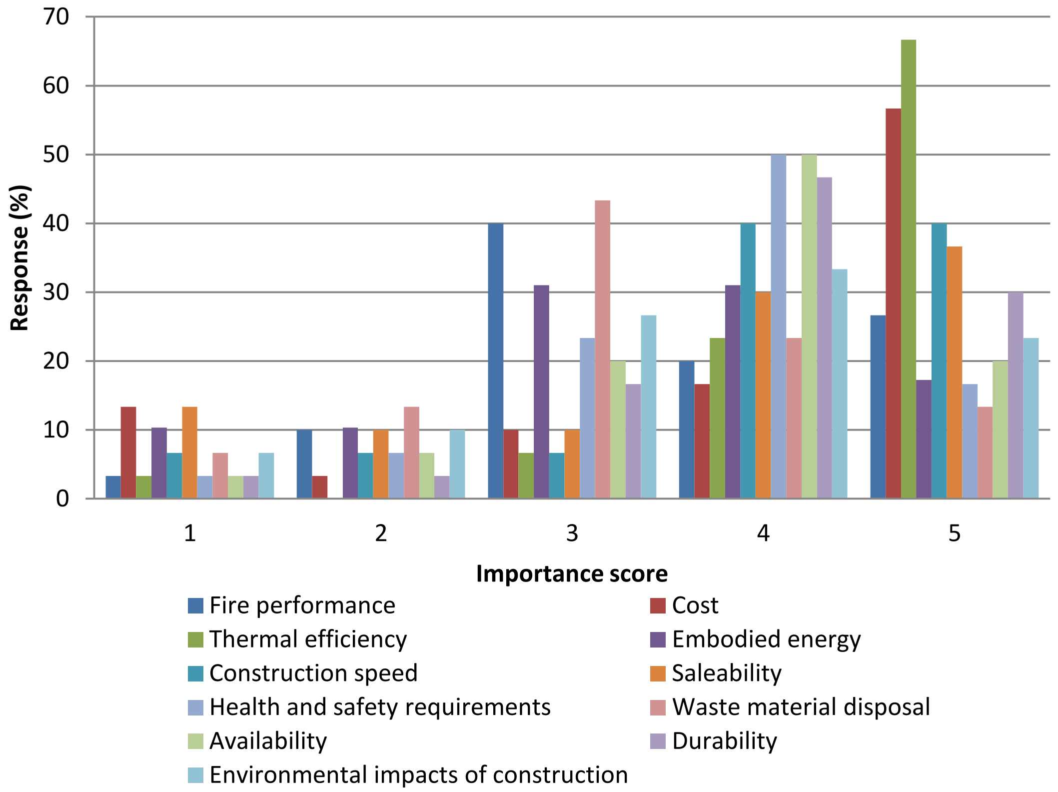

Figure 6.1- Percentage scores for the importance of each characteristic

Table 6.1- Modal and median scores for the importance of each characteristic

	Importance score	
Characteristic	**Mode**	**Median**
Fire performance	3	3
Cost	5	5
Thermal efficiency	5	5
Embodied energy	3-4	3-4
Construction speed	4-5	4
Saleability	5	4
Health and safety requirements	4	4
Waste material disposal	3	3
Availability	4	4
Durability	4	4
Environmental impacts of construction	4	4

From a visual inspection of Figure 6.1 and Table 6.1 these factors were given the following importance ranking, from most to least.

1. Thermal efficiency
2. Cost
3. Construction speed
4. Saleability
5. Health and safety
6. Availability
7. Durability
8. Environmental impacts of construction
9. Embodied energy
10. Waste material disposal
11. Fire performance

These characteristics were all indicated to be important to the respondents, so should be considered when making decisions. The top ranked characteristics of thermal efficiency, cost, construction speed and saleability are of the most importance. The high ranking of saleability indicates that construction methods supported by the public, as indicated by the results of the questionnaire, have a good chance of being accepted by the construction industry.

6.2.4. Awareness of construction techniques

As with the public it was desirable to determine the level of awareness of alternative construction methods within the construction industry. At this stage in the questionnaire no details of the methods were given, only the names. Higher levels of awareness were expected compared to those seen with the householder survey as ongoing training, press releases and continuing professional development encourages awareness of changes in the industry such as new construction methods.

The survey results indicated a high awareness of the alternative methods in the construction industry. ICF was the only method to receive any "no" responses, with 7% of respondents not having heard of it. All other methods had a 100% "yes" response. High awareness is beneficial in encouraging greater usage. However, being aware of a construction method does not necessarily indicate a high level of knowledge of its performance; this was examined to some degree in later questions regarding acceptability.

6.2.5. Past experience of construction methods

To determine the past use of the construction methods being considered respondents were asked if their company had used each of the methods in the past. Options included ``yes- housing'', ``yes-other'', ``no'' and ``don't know''. It was possible for respondents to select multiple categories for this question. The results of this question are shown in Figure 6.2.

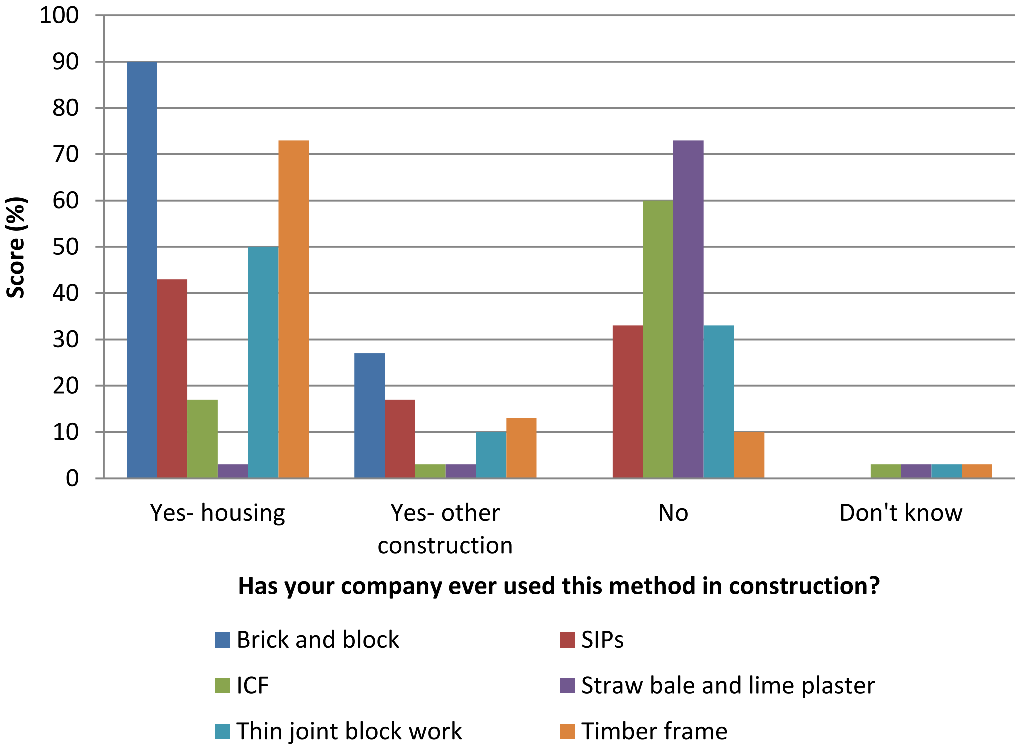

Figure 6.2- Past usage of the construction methods by respondents' companies

Responses indicated that all the methods had been used for both housing and ``other construction'' in the past by at least one of the respondents' companies.

Brick and block had the highest level of past usage. It had been used for housing (90%) or "other construction" (27%) by all respondents. This high level of past usage was expected due to it being the most frequently used construction method in England and Wales.

The level of past usage for SIPs was higher than expected, 43% of respondents had experience of the method in housing and 17% in other construction. This method currently has a low level of usage in England and Wales, so a lower level of past experience was expected.

ICF had a fairly low level of past usage, although this was higher than expected considering how few buildings are currently constructed using this method in England and Wales. For housing, 17% of respondents had past experience of this method and 3% in other construction. No past experience was indicated by 60% of respondents.

Straw bale had the lowest past usage. It had been used for housing by one respondent and "other construction" by a second respondent. Although this is lower than other methods it is higher than was expected due to the unusual nature of the method. The remaining 73% of respondents had no past experience of using this construction technique.

Thin joint block work showed some level of past usage, with 50% having used it in housing and 10% in other construction. The similarity of this method to brick and block construction meant some past usage was expected. However, as with SIPs and ICF this was higher than expected when considered in relation to the methods of construction used for housing in England and Wales

Timber frame construction had a high level of past usage, 73% said their company had used it for housing, 13% for other construction. As this is the second most frequently used construction method for housing in England and Wales a high level was expected.

All methods of construction had a higher than expected level of past usage. Methods other than brick and block and Timber frame accounted for only 5% of housing construction in England and Wales between 1990 and March 2009 (DCLG, 2010) so past experience of other methods was expected to be low. This past usage indicates that there is some experience of using alternative construction methods in the building industry and potentially acceptability for the methods.

The relatively high past usage of alternative construction methods shown by respondents in this question was felt to be beneficial when considering responses to the following questions about acceptability. Having past experience with a method may have given respondents insight into benefits and issues and influenced their decision on each method's acceptability.

6.2.6. Acceptability of alternative construction methods

To determine the acceptability of the alternative construction methods being considered the respondents were shown a labelled axonometric diagram of the method and given a brief description. Respondents were asked if they felt their company would use this method in construction with answer options of “yes”, “no” and “maybe”. An optional open ended question allowed respondents to add any further comments they had about the method. This question was similar to the one used for the public opinions survey, however the method description was slightly more technically worded.

Respondents were asked to give the views of the company they worked for rather than their individual views which may have affected the acceptability. For example a timber frame construction company is unlikely to find brick and block construction acceptable. Responses to this section were considered in conjunction with the data on past usage to see if a company with past experience of a particular method would be prepared to reuse it and if not why. Percentage responses to this question are shown graphically in Figure 6.3.

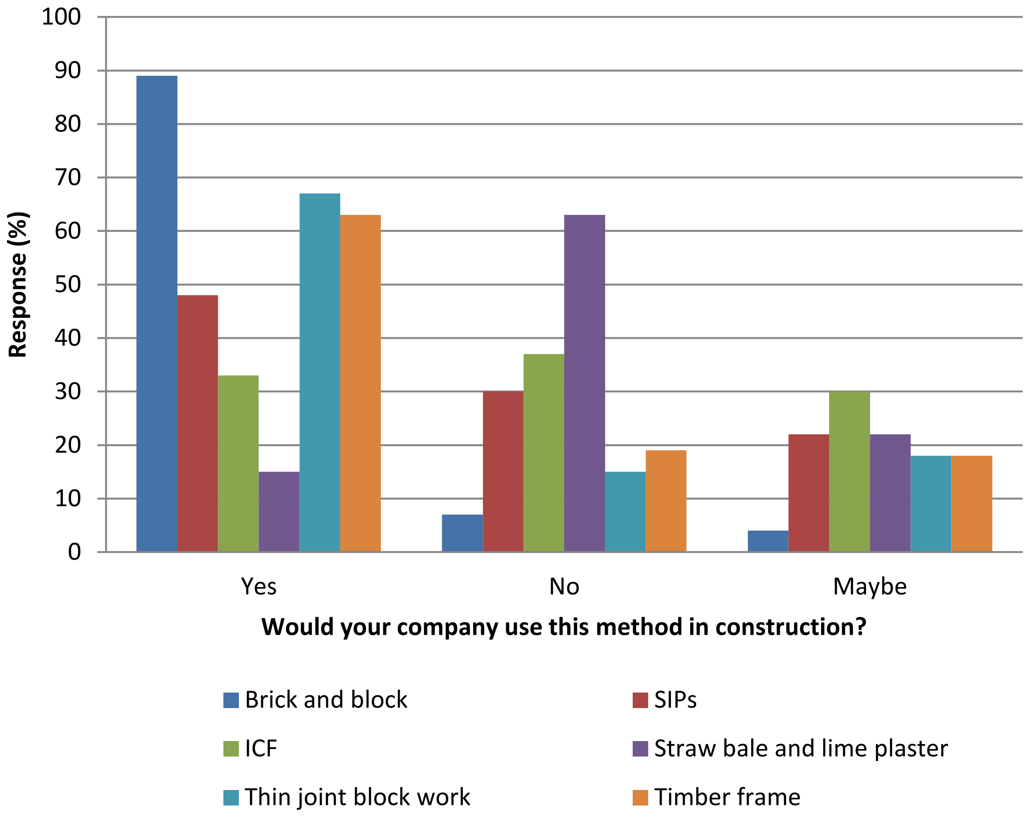

Figure 6.3- Percentage responses to the question “Would your company use this method?” for each option

A high level of acceptability was expected with brick and block construction as it is the most frequently used method for UK housing, this was seen with 89% of respondents saying they would use this method. Of those who would not use the method, one respondent stated they work only in the timber construction sector so their acceptability of other methods was expected to be low. A dislike of the insulation used was given as the reason for not using the method by the other respondent to say they would not use it, if an alternative was offered they may find the construction method acceptable.

Positive views expressed in the open ended question included that the method was the traditional method of house construction, it is proven and affordable. The acceptability and familiarity of this method for both tradesmen and purchasers was noted. The ability to meet Building Regulations using it was also listed as a positive.

Only one respondent stated a negative comment. It was noted that the construction method is “not carbon friendly”. However, this respondent indicated they would still use the method. Several respondents commented that a brick and block construction is used because it is specified, indicating there may be scope for other methods if the designers specify their use.

A lower level of acceptability was expected with SIPs than for brick and block as it is a non typical form of construction. Figure 6.3 shows that the acceptability is significantly lower at 48%. If the “yes” and “maybe” responses are considered together it shows there is the potential for use if the issues causing “maybe” responses can be addressed. Respondents who would not use the method accounted for 30% responses. Two respondents who had past experience of the method, either for housing or other construction indicated they would not use it again; however they made no further comment to indicate why.

The speed of construction was commented on by several respondents. Having a faster construction time has the potential to reduce costs by reducing labour requirements and reaching completion faster, allowing a quicker recovery of investment. The structural performance, air tightness and thermal efficiency achievable using this method were noted by respondents who indicated they would use it in construction.

The fact it was not the typical construction method was noted, along with the fact that this may make it unpopular. One respondent commented that “Developers are terrified of systems they haven't used before”. Addressing this issue is likely to be one of the major challenges of encouraging alternative construction techniques.

Opinion was divided on the potential for financial savings, some respondents felt there was currently no potential for savings, others felt it was a cheaper option. It was indicated that changes to legislation may increase the appeal of this method as it could become a cheaper solution for meeting more stringent regulations. Another financial issue noted was the mortgagability of houses constructed using the method. This is another challenge to overcome to gain the benefits of alternative methods of construction. Financial providers would need to be encouraged to accept the alternative methods to enable purchasers to afford houses. This may require proof of performance, either from anecdotal evidence or laboratory testing.

It can be seen from Figure 6.3 that ICF has a lower level of acceptability than SIPs, with 33% “yes”, 37% “no” and 30% “maybe”. When ”yes” and “maybe” are considered in combination ICF shows a medium level of acceptability with the construction industry. Those respondents who had past experience of the method said either “yes” or “maybe” they would use the method again.

Positive comments for this type of construction included greater construction speed, structural performance and the thermal performance achievable. These were mostly noted by those who had past experience of using the method.

ICF had a greater number of negative comments, including some expressed by those who had used the method in the past. The most frequently expressed negative was related to the higher cost of construction. ICF is considered to be more expensive (Denzer and Hedges 2007, Al-Homoud 2005); however, the better thermal performance as noted by the respondents may offset this higher cost over time. Limitations on the construction as a result of using this method were noted by some respondents. These included limited future adaptability, wall thickness and restrictions on service penetration of the wall. Although these exist as issues with the method, careful design at the initial stages should limit their negative effects.

Straw bale construction was expected to have a low acceptability due to its unusual nature. This was seen in the responses, with 15% saying “yes” they would use it; 63% “no” and 22% “maybe”. Although this is a low acceptability, it is higher than expected, particularly if “yes” and “maybe” responses are considered in combination. Of those who had past experience of the method, one would use it in housing, the other would not.

Several respondents noted positives of this construction type; including the sustainable nature; good thermal performance; availability and affordability of the materials used.

The respondent with past experience of the method who would consider it for future use listed sustainability, BREAAM score, availability and cheap materials as reasons.

Perceived financial issues associated with this construction method focused on difficulties selling the end product and the lack of financial products to assist this (mortgages etc). As with other alternative methods this is likely to be an issue that would need to be resolved to take advantage of the method. The public survey results (Chapter 5.2.8) show there is some acceptability for this method with purchasers, so there would be a market for the finished houses; however, it is lower than for other options.

The respondent with past experience who would not consider using the method again gave wall thickness and its impact on reducing the number of units that can be built in a given space as the reason why. This was also noted by other respondents. Wall thickness is an issue with this type of construction. Although it has a negative impact on the density of housing units it can be used to incorporate design features (Lacinski and Bergeron, 2000). It should also be noted that as thermal performance requirements increase, other methods of wall construction will also increase in thickness, reducing the difference.

The method was viewed by respondents as unproven, with durability and fire performance of particular concern. Examples exist in the USA that are up to one hundred years old (Seyfang 2010, Smith 2007, Yates 2006) and in the UK from 1994 (Jones 2007). These examples can be used to provide anecdotal evidence for the construction method. In addition laboratory and field research has been carried out into some of the areas of highest concern such as durability (Carfrae et al. 2009, Lawrence et al. 2009, Goodhew et al. 2007, Summers 2006, Goodhew et al. 2004, CMHC 2000) and fire performance (Apte et al. 2008, Jones 2007).

Acceptability of thin joint block work was expected to be high as a result of its similarity to standard brick and block construction. Figure 6.3 shows this is the case, with 67% saying “yes” they would use this construction method. This is the second highest “yes” rate. “No” was selected by 15% of respondents and 18% said “maybe”. One respondent who had past experience said they would not use it again, but gave no further reason, all other respondents who had past experience of the method would consider using it again.

The similarity to standard construction was the most frequently expressed positive. The increased speed of construction and the reduced costs of the build method were also noted. Additional comments made included: good thermal efficiency, reduced wastage of mortar, and the possibility of improved airtightness if well constructed.

Negative comments for this type of construction focused on the issues of workmanship. In particular the issues associated with the gauge differences between the inner and outer leaf and the need to deal with this when building. Appropriate training in the construction method should avoid these issues. One respondent expressed a concern that larger blocks can result in health and safety issues on site; although this is a possibility good site practices should reduce this to a minor risk.

A high level of acceptability was expected for timber frame construction as it is a well known technique and the second most frequently used method in England and Wales, this was seen with 63% of respondents saying “yes” they would construct housing using timber frame; 19% said “no” and 18% said “maybe”.

Reduced construction speed was noted as a benefit by a number of the respondents, as with SIPs this can result in reduced costs for the project. Another comment was that it is a fairly traditional method of construction, and as such is accepted by the construction industry. The presence of insulation and the potential for achieving airtightness were seen as benefits by some respondents.

One respondent commented that the method is best for large number of repeated units, such as seen on large speculative housing estates. This is both an advantage, as the repeated nature allows the mass production of components, and a disadvantage as it can limit flexibility and reduce the appeal of the method for smaller developments or those with many styles of construction.

The more expensive nature of this type of construction was given as a disadvantage by several respondents. Although one respondent stated that this can be balanced by savings associated with the speed of construction, increased speed cannot be guaranteed as external factors such as weather can affect it. If high thermal performance is achieved the savings resulting from this may offset the higher construction costs over time.

Other negative views expressed included that the method is not popular with clients, a view which is supported to some extent by findings from the householder survey in this work (Chapter 5.2.10). The durability of the construction method was also given as a concern. However, as discussed by Hutton (1992), with high quality workmanship to avoid the condition which allow rotting to occur this should not be an issue.

6.2.7. Methods of increasing interest in alternative construction methods

Respondents were asked what would increase their interest in alternative options. If a method has high potential for improving environmental standards but low industry support it would be necessary to encourage its use. This question aimed to identify ways this could be achieved.

The factor with the greatest impact was low cost, with 96% saying this would increase interest. Reducing the cost of the construction can result in a greater profit or the ability to sell at a lower price, increasing saleability and leading to a faster return on investment.

A response of 81% yes to "market desirability" indicated that support from customers would increase the interest in alternative methods. The householder survey has shown that customers would be interested in some of the alternative options, particularly SIPs and ICF. If this information were communicated to the industry to demonstrate that a market exists for houses constructed using alternative methods the level of interest may increase. Low running costs can be linked to market desirability as the ability to sell a home as "green" and "cheap to run" both have the potential to increase the attractiveness of the property. Although this may not have a direct benefit to the builder it increases saleability resulting in faster and potentially higher returns, 87.5% of respondents said this would increase their interest. Similarly, "if they were environmentally friendly" was indicted to increase interest (87.5% "yes"). Again the direct benefits to the builder may be low, but the increased saleability and the option of marketing their product as "green" can have financial and reputational benefits.

As seen with the public questionnaire responses, more information scored highly (87% "yes"). Although the industry respondents had heard of the options, and some had past experience, those who did not may not know a great deal about the methods and their advantages. By highlighting the benefits of alternative methods their use could be greatly increased. This would discourage the attitude of sticking with what you know and encourage the use of a wider range of options.

6.2.8. Comparison of survey results

The acceptability of each construction method was compared for the public and industry questionnaire results. It was seen that there is some similarity between the acceptability, with brick and block scoring highly. Both groups show some acceptability for SIP and ICF construction, although this is lower in the construction industry responses. This lower score supports comments made in the literature review that the construction industry is reluctant to adopt new methods. Prefabricated straw bale construction had a low acceptability with both groups; however there was some degree of acceptability indicating it may have potential for use in some cases. Timber framed construction appears more acceptable to the construction industry than to the public, which agrees with responses to the industry questionnaire, which note it is not popular with the public. As a result of this it is somewhat surprising that this is the second most common method of housing construction in England and Wales.

6.3. Summary

- The three most important factors when selecting a construction method were thermal efficiency, cost and speed of construction.
- There is a high level of awareness of alternative construction methods in the industry.
- Respondents had past experience of all methods examined in this work.
- Brick and block construction has the highest level of acceptability.
- There is a good acceptability of timber frame and thin joint block work.
- The potential exists for a high acceptability of SIPs and ICF if concerns are addressed.
- Straw bale had a low acceptability, although some respondents would consider its use.
- A number of concerns were identified for each construction method; many of these can be disproven by existing evidence.
- Financial benefits and more information would increase industry interest in alternative methods of construction.
- Saleability would have some effect on industry interest in alternatives, therefore support from the public (the buyers) may encourage support within the construction industry.
- Similarities are seen between the public and industry survey results. Both groups support brick and block strongly, SIP and ICF to a moderate degree and show little support for prefabricated straw bale.
- Timber framed construction is noticeably more popular with the construction industry than with the public.

7. Development of the optimisation based methodology

To aid the design process, by simplifying the selection of wall construction method, a design methodology was created. This design methodology uses optimisation to allow the user to identify the best, or optimal, solution to the design problem; in this case, the problem of selecting the best wall construction method to use. This chapter describes the process for developing the fitness function containing the single output equation and the optimisation based design methodology.

7.1. Design of the fitness function

7.1.1. Input variables

The floor plan of the house was taken to be a rectangle with the dimension designations shown in Figure 7.1.

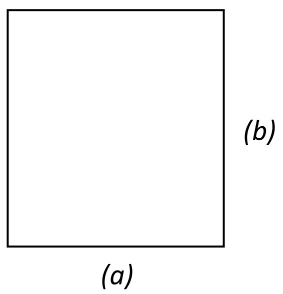

Figure 7.1- Dimension designations for single objective calculation

User inputs for the generation of the single objective variable were total internal floor area, number of storeys, height of each storey, number of doors, region, type of building, construction method, maximum window percentage, door size and the front dimension of the building *(a).* In order to maintain integer values, dimensions were set in millimetres for *(a)* during the optimisation. The value of *(a)* is then converted to metres during the calculation process. Default values were set for all except floor area. These can be seen in Table 7.1.

Table 7.1- Default values for variables in the single objective equation

Factor	Value
Total building area	No default set, input required
Number of storeys	2
Height of storeys	3.0m
Number of doors	1
Region	3 (London)
Building type	2 (Semi detached)
Construction method	1 (Brick and block)
Maximum window percentage	25
Door size	2.42m^2
Dimension *(a)*	3.6m

7.1.2. Constraints

Constraints represent a limitation on the optimisation programme. The equation must be solved but according to these limitations, for example a maximum or minimum value for some aspect of the equation.

It was considered desirable to maintain the optimisation as unconstrained as constraints can cause complications with the optimisation. Goldberg (1989) explains that genetic algorithms are naturally unconstrained. The only constraint on the single objective equation is the need to have a minimum window area of 20% of the building floor area as recommended by Part L of the Building Regulations (HM Government, 2010). This allows a sufficient amount of natural light and hence avoids excessive use of artificial lighting. By satisfying this constraint the operational energy is not negatively affected by the window area. Although operational energy resulting from heat loss through windows and doors is not included in the operational energy calculation used in this work, the area of wall removed to accommodate windows and doors must be removed for the assessment of embodied and operational energy demands resulting from the wall materials. This provides a more representative value of the energy requirements relating to the wall construction method.

The window area must also be of a size that it does not eliminate too much of the wall area. If too much wall area is discounted due to being glazed, then the value achieved from the single objective equation will be unrealistically low for large floor areas with low values of *(a)*. A maximum value of wall area that can be removed was set. The default value of this is 25%.

In order to satisfy the need for a constraint on the window and wall areas a simplified version of the penalty method discussed by Goldberg (1989) and Bunday (1984) was used. If a value of dimension *(a)* caused 20% of the floor area to be greater than 25% of the wall area (i.e. an unfeasible glazed area) the single objective value was set to 10. This value was selected as it is considerably greater than any values calculated by the programme. The result of this was a high value of the single objective equation which was discounted by the optimisation process as it was significantly higher than the optimal value.

A further constraint is applied to the optimisation by setting upper and lower bound values for the variables. This indicates limits to the variables that the optimisation process will examine. The method for applying bounds is contained within the optimisation programme; it is not part of the single variable equation. It is not desirable to apply the window area constraint by adjusting the lower bound as this would require calculations to be carried out before the optimisation methodology can be used. The method adopted in this work eliminates this step while still allowing the constraint to be incorporated.

7.1.3. Wall dimensions

For terraced and semi-detached buildings dimension *b* was always the length of the party wall.

The value for dimension *(a)* was a user input, or adopted the default setting from Table 2. During the optimisation process this value was input by the optimisation programme.

To convert the value of dimension *(a)* from millimetres to metres it was divided by 1000. This allowed the optimisation programme to use millimetres but the single objective calculation to be carried out using metres. Dimension *(b)* was calculated using Equation 7.1.

(Eqn. 7.1)

$$b = (area\ total/number\ of\ storeys)/a$$

Aspect ratio was calculated using Equation 7.2.

(Eqn. 7.2)

$$Aspect\ ratio = b/a$$

The value of total external wall area was dependent on the type of building. To incorporate this a switch function was used allowing the correct equation for the specified building type. Equations 7.3, 7.4 and 7.5 were used for detached, semi detached (s/detached) and terraced houses respectively.

(Eqn. 7.3)

$$Detached\ total\ external\ wall\ area = 2 * (a * storey\ height * number\ of\ storeys) + 2 * (b * storey\ height * number\ of\ storeys)$$

(Eqn. 7.4)

$$S/detached\ total\ external\ wall\ area = 2 * (a * storey\ height * number\ of\ storeys) + (b * storey\ height * number\ of\ storeys)$$

(Eqn. 7.5)

$$Terraced\ total\ external\ wall\ area = 2 * (a * storey\ height * number\ of\ storeys)$$

Window and door areas have a significant impact on the total embodied and operational energy requirements of the house resulting from the wall construction method. Windows and doors reduce the area constructed from the wall materials and hence the volume of materials used. Therefore, the area occupied by windows and doors must be removed from the total external wall area. Door area was based on user inputs or default values for number of doors and area of doors. Window area was set at a minimum of 20% of the floor area as suggested by part L of the Building Regulations (HM Government, 2010). This allows sufficient natural lighting to limit the use of artificial lighting and hence reduces operational energy requirements. The window area was therefore calculated using Equation 7.6.

(Eqn. 7.6)

$$Window\ area = total\ floor\ area * 0.2$$

The net wall area was then calculated using Equation 7.7.

(Eqn. 7.7)

$$Net\ external\ wall\ area = total\ external\ wall\ area - window\ area - door\ area$$

It was desirable to keep the window area below 25% of the wall area to avoid a high glazed area artificially reducing the embodied and operational energy. This limitation was accommodated by including a constraint in the single objective equation (see 7.1.2 Constraints).

For those building types with party walls, the party wall area was calculated using the Equation 7.8 and 7.9 for semi detached and terraced houses respectively.

(Eqn. 7.8)

$$Semi\ detached\ party\ wall\ area = (b * \ storey\ height * number\ of\ storeys)$$

(Eqn. 7.9)

$$Terraced\ party\ wall\ area = 2 * (b * storey\ height * number\ of\ storeys)$$

7.1.4. Embodied energy

Using the generated wall areas from Chapter 7.1.3, embodied energy could then be calculated using the embodied energy data from Chapter 4. For party walls, half the embodied energy was assigned to the house in question as the value was considered to be divided between the two adjoining properties. This calculation is shown in Equation 7.10.

(Eqn. 7.10)

$$\begin{aligned} Embodied\ energy \\ &= (net\ external\ wall\ area \\ &* embodied\ energy\ for\ 1m^2 of\ external\ wall) + \ 0.5 \\ &* (party\ wall\ area * \ embodied\ energy\ for\ 1m^2 of\ party\ wall) \end{aligned}$$

Embodied energy of the whole house was considered in relation to the floor area. To generate the embodied energy per square metre Equation 7.11 was used.

(Eqn. 7.11)

$$Embodied\ energy\ per\ m^2 floor\ area = \frac{Embodied\ energy}{Total\ floor\ area}$$

7.1.5. Operational energy

The wall construction method was considered to only impact on the operational energy requirement relating to heating as a result of heat loss through the wall fabric. Therefore, only this operational energy is considered. Operational energy associated with lighting, hot water, appliance use and heat loss resulting from ventilation systems are not considered as they are not impacted by the external fabric of the building resulting from the wall construction method. Operational energy requirements resulting from heat loss through the walls were calculated using the degree day method. Degree days are the sum of the difference between external temperature and the desired internal base temperature, in this case 18°C, over the course of a given time period. Measurements are taken at intervals, for example, daily or hourly, as the intervals decrease the accuracy improves (CIBSE 2006).

To generate values for heating energy requirements using degree day values they must be combined with the building's specific heat loss rate, calculated by multiplying the U value of the wall and the total wall area built using the wall construction method in m^2. Multiplying by 24 converts the value to days, dividing by 1000 converts the value to kWh. This calculation is shown in Equation 7.12 (based on CIBSE 2006).

(Eqn. 7.12)

$$\begin{aligned} &Operational\ energy\ resulting\ from\ heat\ loss\ via\ walls \\ &\qquad = (U\ value\ of\ material * Net\ external\ wall\ area * 24 \\ &\qquad * Degree\ days\ for\ region)/1000 \end{aligned}$$

Degree day based calculations are considered to give a less accurate, although widely accepted, value than a full thermal simulation. In addition the use of annual values for degree days allows the operational energy to be calculated for a full year, thermal simulations often calculate the energy requirement for a short time period, such as twenty four hours. The degree day method has significantly lower calculation times than a full thermal simulation. For optimisation work such as this, where it is necessary to run the calculation many times, this is considered to be a benefit and the reduced accuracy considered to be acceptable.

An internal base temperature of 18°C was selected using the World Health Organisation (WHO) recommendation that this is an acceptable temperature for healthy, appropriately dressed adults (WHO, 1979). This was considered to be an acceptable value as 15.5°C is traditionally used in the UK (CIBSE 2006). The higher value used in this work is considered to be more representative of housing situations. Higher or lower values could be substituted in future work. The locations for degree day values were based on the city in each region with the highest population, as this was considered to be the most likely location for new housing (Office for National Statistics 2011). Additional gains, for example from occupants and equipment are ignored for this work as they would be equal across the construction types.

Values of heating degree-days for investigated locations or regions were calculated by M. Mourshed using the methods described in Mourshed (2012). Interpolated weather data for the key cities within the selected region were obtained from Meteonorm software (Meteonorm 2011). Degree-days values used in this research are given in full in Appendix C.

All windows and doors were assumed to be identical across the construction methods having equal contribution in the calculation of heating related operational energy demands. Therefore, these are omitted from the equation. Party wall construction is taken to be solid or fully filled and sealed, therefore the heat loss through these is considered to be zero (see Chapter 4).

Operational energy (OE) is considered in terms of the energy per square metre of floor area, to generate this value Equation 7.13 was used.

(Eqn. 7.13)

$$OE\ resulting\ from\ heat\ loss\ via\ walls\ per\ m^2 floor\ area = \frac{Operational\ energy}{Total\ floor\ area}$$

7.1.6. The single objective calculation

Data generated in 7.1.2 to 7.1.4 was used in the calculation of the single objective. The data was combined with values for airtightness, wall thickness, fire performance and acceptability. These were taken from Chapters 4, 5 and 6 (Table 4.23, Figures 5.4-5.10, Figure 6.3). Switch functions allowed the selection of the correct value depending on the input for construction method and region.

To allow the combination of factors with different scales it was necessary to apply normalisation to the values. This was achieved by dividing the values for each construction method by a set of benchmark values. Benchmark values for each factor were calculated from the mean of the values for all methods of construction under consideration.

Published values for embodied energy per square metre of floor area and operational energy per square metre of floor area were considered as benchmark values. However, they include other elements of the construction, such as roofing; and operational energy uses such as lighting. To generate a benchmark value the details of a "typical" house were determined (see Appendix F). The embodied and operational energy per square metre were calculated using the typical house dimensions for detached, semi-detached and terraced house types. Average values of embodied energy per square metre and U value were used in these calculations. Values of embodied energy did not change with location, however, operational energy did as the result of differing degree days for each region. Operational energy values were calculated for each region. Benchmark values calculated for embodied and operational energy can be seen in Tables 7.2 and 7.3 respectively. Benchmark values used for performance factors shown in Table 7.4.

Table 7.2- Benchmark values for embodied energy, divided by house type.

House type	Benchmark Embodied energy
Detached	1532.4
Semi-detached	1169.2
Terraced	805.9

Table 7.3- Benchmark values for operational energy, divided by region and type of house.

Region	Detached	Semi-detached	Terraced
1	27.0031	16.5898	6.1765
2	27.2418	16.7364	6.2311
3	23.8927	14.6789	5.465
4	27.8301	17.0979	6.3656
5	25.2658	15.5225	5.7791
6	24.7854	15.2273	5.6692
7	25.1047	15.4235	5.7423
8	28.2463	17.3536	6.4608
9	28.3126	17.3943	6.476
10	25.7935	15.8466	5.8998

Table 7.4- Benchmark values for performance factors

Variable	Benchmark value
Air tightness	$2.73m^3/hr.m^2$ at 50Pa
Wall thickness	0.374m
Fire performance	130 minutes

Normalisation of the acceptability scores was achieved by dividing the value achieved by one hundred as this was the maximum achievable score.

User input weightings enabled the importance of the different factors to be adjusted and these to affect the single value output. These have a default setting of 1 for all variables, giving them equal importance.

To accommodate the constraint of a maximum wall area being taken by windows a switch function was included in the programme at this point (see Chapter 7.1.2).

If the value of window area required was greater than the maximum allowable, the single objective value takes a fixed value. This value is considerably larger than the values of single objective that were generated by the programme for the construction options. Having a high value of single objective means the optimisation programme will not select the variables which produce this value. In this situation the single objective was calculated using 7.14.

(Eqn. 7.14)

$$single\ objective = 10$$

If the window area was below the set value for maximum window area, and hence did not violate the constraint, Equation 7.15 was used for calculating the single objective.

(Eqn. 7.15)

$$single\ objective = (weighting\ EE * ((EE\ )/benchmark\ EE) + (weighting\ OE * ((OE\ )/benchmark\ OE) - weighting\ public\ acceptability * (public\ acceptability/100) - weighting\ industry\ acceptability * (industry\ acceptability/100) + weighting\ airtightness * (airtightness/benchmark\ airtightness) + weighting\ wall\ thickness * (wallthickness/benchmark\ wall\ thickness) - weighting\ fire\ performance * (fire\ performance/\ benchmark\ fire\ performance)$$

The lowest value of single objective indicates the best compromise between the variables.

The Matlab programming code for the fitness function based on the above process can be seen in Appendix G.

7.2. Optimisation procedure

Two input variables were selected for the optimisation process; these were building front dimension (*a*) and wall construction method. During the optimisation process, the input values are varied using a genetic algorithm until the optimal solution is identified. The programme identifies the input values which obtain the lowest score for the single objective calculation.

7.2.1. Optimisation variables

To reduce the number of variables for the optimisation procedure, those variables which were to remain fixed throughout were given a set value. Fixed variables were included in the programme with a single value, rather than being an input during the optimisation process. This simplifies the process and reduces calculation time. These values can be altered, and the programme re-run, as required to evaluate different scenarios. Values selected to be set were total building area, number of storeys, height of storeys, number of doors, region, building type, maximum window percentage and door size. The value of fixed variables is set by the user before the optimisation procedure is run; alternatively, default values will be used. Weightings for each element in the single objective equation can also be altered at this point.

Values which were to be varied during the optimisation procedure were: front building dimension *(a)* and wall construction method. This allowed the exploration of varying aspect ratios and construction method combinations. As the optimisation was to be carried out with two variables they take the form of a two dimensional vector as discussed by McKeown et al. (1990).

Although the example given here, and used in the case study presented in Chapter 8, considers two variables it is possible to use the method created to evaluate a greater number of variables. Any of the fixed values could be converted to a variable for the optimisation process. However, in this work, it was intended to demonstrate the method, so a simplified version with only two variables was used. The output of the method with two variables can be used to identify the optimal combination of dimension *(a)* and construction method.

7.3. Use of the decision making methodology

The design methodology has been created to aid house construction decision making. The main focus of this work was on the environmental impact of house wall construction method, in particular achieving the best compromise of embodied and operational energy use, with consideration given to acceptability and performance. By altering the factors used in the single objective equation, the method demonstrated could also be used to consider a wide range of construction aspects, for example roof construction, foundations, and building services. The potential exists to expand the methodology. Additional methods of construction can be incorporated, along with different specifications of the same methods, for example thicker SIP panels. The number of criteria could also be increased; the same method could be used to assess cost or other aspects of performance such as lifespan, speed of construction etc. The factors chosen for this work were intended to demonstrate the range of criteria that can be included.

The case study presented in Chapter 8 demonstrates the use of the optimisation methodology to solve the question of the best compromise between method of construction and size of dimension *(a)* when consideration is given to energy use, public and industry acceptability of the method, air tightness, wall thickness and fire performance. This is an example of how it could be used in a design situation where the best compromise of these elements is required.

The methodology could be used in any situation where construction method selection is necessary. This is most likely to occur at the design stage of housing construction, so it will be of most use to designers. The use of optimisation aids the difficult decision between choices that have no clear single best solution. A compromise is achieved but it is one that can be justified. Identification of sub-optimal, but good scoring, variables can also assist with decision making; these may ultimately be the best options when other criteria are considered. The ability to demonstrate why a particular method is the best compromise, for example by the use of fairly easy to understand graphical images such as three dimensional plots and phi arrays, could support the case for a particular construction method. This could be useful to financial backers, planners, Building Regulation officers as well as to the end user. Phi arrays are of particular benefit here as a visual representation is often easier to understand for non specialists. This agrees with comments made by Li and Shen (2002) regarding the way in which decision tools can increase the transparency of the decision making process with all parties understanding the reasons for an option being selected.

The ability to demonstrate the reasoning behind a construction method selection could be used to encourage Government support. Government backing of alternative construction methods could increase their use. This may be by financing research into methods or by promoting methods to increase awareness and acceptability. This would allow the benefits demonstrated by the alternative methods used in this work, such as better U values, lower embodied energy and good airtightness to be accessed.

7.4. Summary

- To allow the use of optimisation in aiding construction method selection, a fitness function was designed.
- The fitness function combines data generated and collected in Chapters 4, 5 and 6 to create a single value that incorporates embodied energy, operational energy, performance, acceptability and weightings.
- The single value equation can be used to assess a particular design combination. It is also used as the basis for the optimisation design methodology.

- An unconstrained problem was preferred due to its simpler nature. To achieve this, but to accommodate the need for a minimum window area and associated external wall area, a simplified version of the penalty method was used. Values of *(a)* which do not allow sufficient window area will result in a high value of the fitness function. This will not be the optimal value and therefore will not be selected.
- To simplify the optimisation process, two variables were selected for consideration; these were construction method and dimension (*a)*, the front dimension of the house.
- All other variables were set prior to the optimisation.
- An alternative combination of fixed and non fixed variables can be used if desired.
- Potential uses for the optimisation based methodology were identified as material selection when designing buildings.
- Phi arrays and graphs produced from optimisation data can be used to demonstrate the reasoning behind a construction method selection.
- Use of the methodology to demonstrate the best construction option for England and Wales could provide justification for Government support of a particular construction method, resulting in increased use and accessing the environmental benefits it offers.

8. Case study

8.1. Introduction

To demonstrate the potential implications of this work, the optimisation based design methodology developed in Chapter 7 was run for a given scenario. The scenario was based on housing figures for England and Wales, with the most frequently-constructed type and size of housing examined. The design methodology was run for the case study with three sets of weightings for the factors in the single objective equation: energy use, acceptability and performance. These weightings were: all factors equal, weightings based on the public survey and weightings based on the construction industry survey. The use of varied weightings demonstrates the impact weightings can have on the output of the design methodology. The initial run of the design methodology used equal weightings to demonstrate the functionality of the methodology and ways in which the solution space can be examined. Using weightings based on the results of the questionnaires in chapters 5 and 6 was considered to provide a more realistic view than equal weightings; therefore this was carried out to determine which method of construction would be the optimal for the case study situation. Where an alternative method of construction was identified as optimal, energy consumption values were generated for constructing the case study house from the alternative method of construction and from brick and block construction. A comparison of these allows a demonstration of the effect of using the most suitable alternative material as identified by the optimisation.

8.2. Case study optimisation results

8.2.1. Solution metrics for equal weighting case study

The solution metrics achieved by running the optimisation programme for the case study detailed above, when equal weightings for all factors, are given in Table 8.1.

Table 8.1- Solution metrics for the optimisation of the case study

Variable	Optimal solution
Construction method	1- Brick and block
Dimension a (mm)	6377

For the case study values discussed above, the optimisation programme identified option 1- Brick and block as the best option for construction method. Brick and block has a number of factors which result in a good score for the single objective value. A low embodied energy, combined with high acceptability and fire performance result in the “typical” construction method being selected as the best option when all factors are equally weighted.

The best dimension of *(a)* was identified as 6377mm. This is very close to the minimum value at which the constraint applied by window area is not violated. The minimum value of *(a)* which will give an acceptable external wall area, allowing sufficient window area to satisfy the Building Regulations, is 6373mm. Increasing values of *(a)* require more materials and allow greater heat loss due to increased external wall area. This will increase their embodied and operational energy values and hence their fitness function value, making them less desirable. It can be seen that satisfying the requirement for window area to be equivalent to twenty per cent of the floor area is a challenge when constructing terraced properties. The reduced external wall resulting from terraced construction leads to a limited area for window placement. Possible solutions to this could be to allow a glazed area greater than twenty five percent of the wall, or to use methods such as sun tunnels which transport light from roof windows into the living areas of the building. Constraint violation could be permitted, meaning that the window area is less than twenty percent of floor area, if it is shown that the housing design is capable of generating sufficient energy to compensate for the increased operational energy requirements. However, this is undesirable as it places greater requirements on energy generation and natural lighting is considered to be better for health reasons.

8.2.2. Fitness landscapes

The fitness landscape is the score of single objective achieved for each combination of options. To display this values were calculated for the case study using a spreadsheet. Calculating all possible combinations would be a large and time-consuming task as for the case study values discussed above there were 5.8×10^4 possible combinations of dimension *(a)* and construction method. Therefore, dimension *(a)* was increased in intervals of 0.250m for each construction method; the single objective value was calculated for each combination. Whilst this allows a graphical representation of the results, which can be useful for gaining a better understanding of the solution space and high and low scoring regions, it would not be sufficiently accurate for use in design. The use of optimisation in determining the best value of *(a)* greatly simplifies this in comparison with the use of a spreadsheet. Fitness landscapes can be portrayed three dimensionally as shown in Figure 8.1.

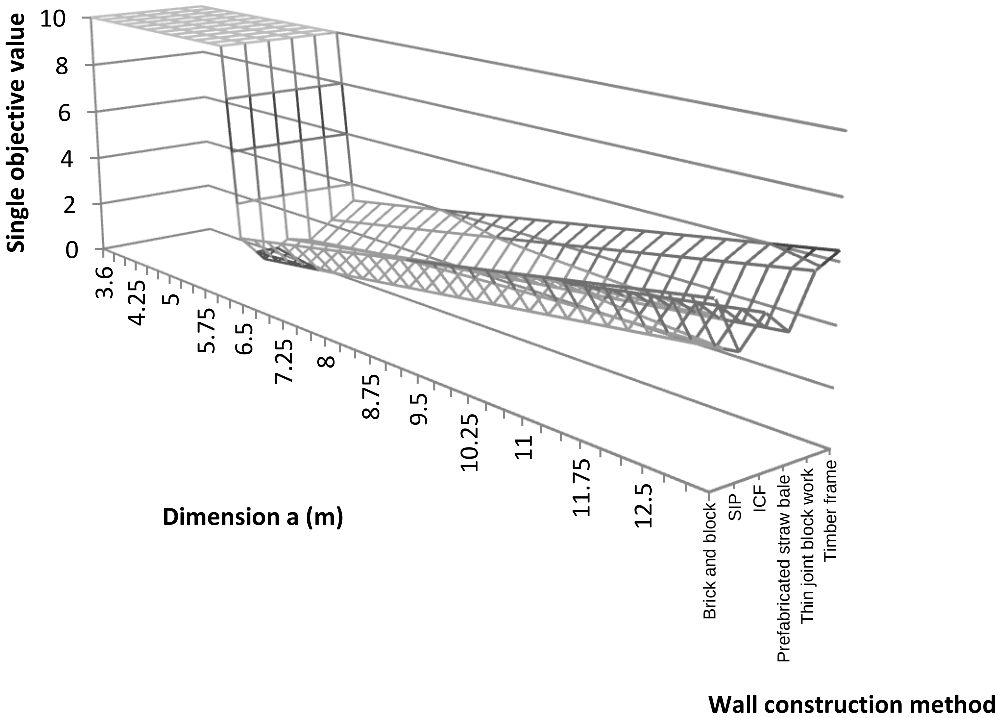

Figure 8.1- Three dimensional representation of the fitness landscape

The region which violates the window area constraint can clearly be seen as the high section at low values of *(a)*. However, when considering viable values of *(a),* which do not violate the constraint, the three dimensional nature causes low values to be obscured by the higher values surrounding them. For example, low values achieved by prefabricated straw bale are obscured by the higher scores for ICF. As the variable wall construction method has a low range of values, the results can also be displayed on a two dimensional graph with a line for each construction method option. This allows low values to be seen more easily and the optimal method of construction to be identified. The optimal method is the one which has the lowest score for single objective value. It appears on the graph as the lowest point of all the lines. The two dimensional display of the fitness landscape values for the case study with equal weightings is shown in Figure 8.2.

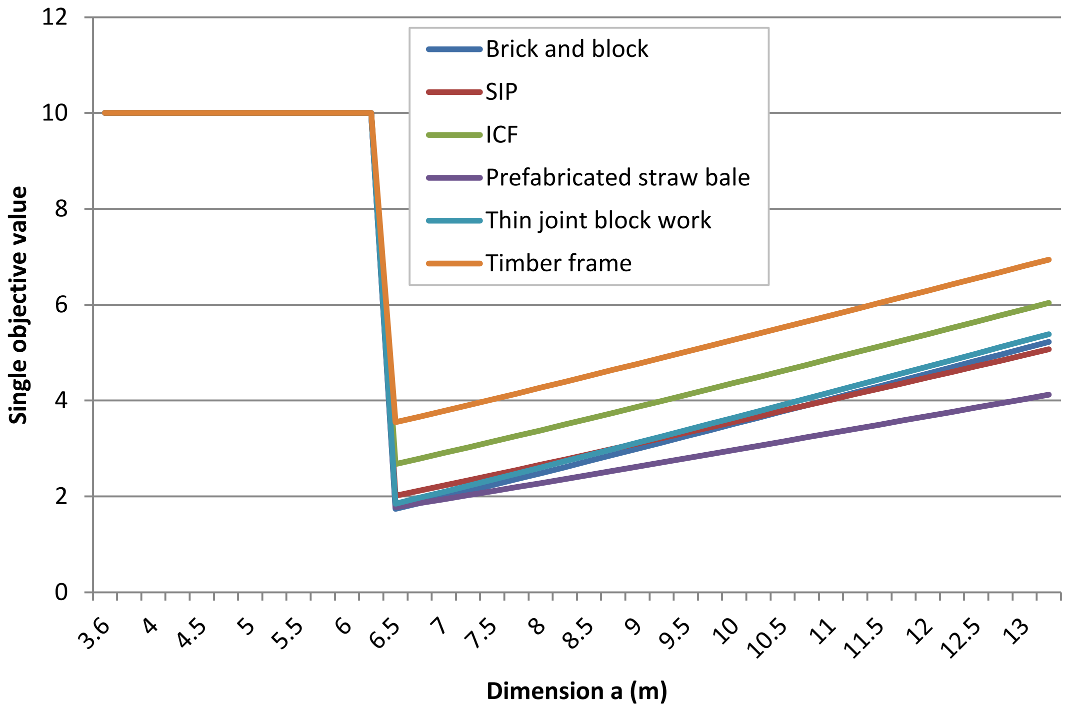

Figure 8.2- Two dimensional graphical display of the fitness landscape for case study optimisation with equal weighting

The region which violates the window area constraint can be seen as the high scoring region from *(a)*=3600mm to *(a)*=6500mm. Houses built using dimensions of *(a)* in this range would have a low window area, below the 20% of floor area recommended by Part L1A of the Building Regulations. This would result in higher operational energy requirements for lighting and so presents an unsatisfactory solution. Although reducing the value of *(a)* results in lower values for embodied energy as material requirements decrease, it is not acceptable for this to lead to increased lighting requirements and hence greater operational energy.

The optimal solution of brick and block as the construction method can be identified from the graph, the optimal value of *(a)* can be seen to occur in the region of 6500. It is logical that the single objective value increases as dimension *(a)* moves away from the optimal value. The external wall area is increasing, which will result in increasing values for operational and embodied energy. Use of the graph allows sub-optimal solutions that have low single objective values to be identified. It is noted that, although brick and block is identified as optimal, thin joint block work and prefabricated straw bale panels are sub-optimal, but are nevertheless low scoring options in the optimal region of *(a)*. These may be more suitable if other criteria are considered, for example, the dimensions achieved by multiple standard brick units.

As the value of dimension *(a)* increases, the single objective value does not increase at the same rate for all materials. At higher values of *(a),* different construction methods may prove to be optimal, for example, at a = 8m the optimal method of construction would be prefabricated straw bale construction.

Figure 8.2 shows Timber frame and ICF wall construction methods to have particularly poor performance compared to the other construction methods examined; this indicates that they may be unsuitable for use. This is of particular interest, as timber frame is currently the most widely used alternative construction method for the area of study.

It should be noted that the use of a two-dimensional graph as shown in Figure 3 would not be feasible if the second variable had a high range of values, for example, floor area. The number of lines on the graph would cause a low level of clarity and obscure information. For consideration of this situation, the fitness would need to be displayed on a three dimensional graph, or by use of a Phi array.

8.2.3. Phi array visualisation

The use of Phi arrays allows a visual representation of the solution space (Mourshed et al. 2011). For visual clarity when designing the phi array, the single objective value for each point was subtracted from ten, making the optimal solution have the highest value. As a result of this, the optimal combinations of material and dimension *(a)* appear as large red circles. As the suitability decreases, the circles become smaller and the colours descend the scale until the small blue circles (representing constraint violation) are reached. Phi array generation programming created by M. Mourshed, following methods in Mourshed et al. (2011) was used to create a Phi array for the case study; this is shown in Figure 8.3.

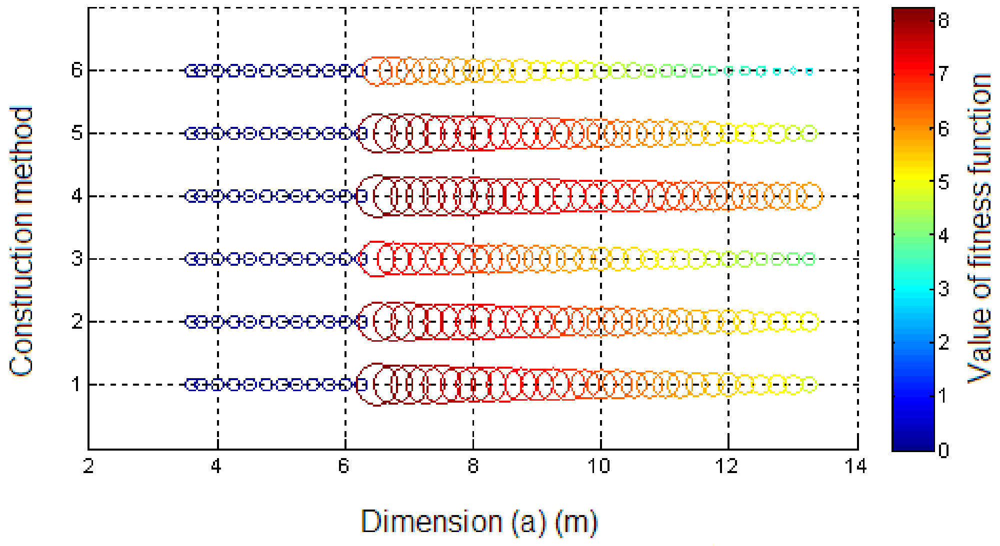

Figure 8.3: Phi array for single objective function for case study, equal weightings.

The results seen from the phi array correspond to those discussed for Figures 8.1 and 8.2. It can be seen that there is a low level of fitness at low values of *(a)*, indicated on the Phi array by small, dark blue circles. This corresponds to the region where the external wall area is too small to allow sufficient glazed area to avoid additional artificial lighting. The region following this demonstrates the best fitness, corresponding to the values of *(a)* where the window area is acceptable but *(a)* is the lowest it can be. This scores highly as it leads to the lowest levels of embodied and operational energy. As the value of *(a)* increases, the fitness decreases- these values are less suitable.

The phi array also demonstrates the difference in single objective value achieved by changing the construction method. It can be seen that brick and block, prefabricated straw bale, SIP and thin joint block work are the better options, with large circles in the red-yellow range throughout. Prefabricated straw bale shows the best score at higher values of *(a),* indicated by the larger circles which do not drop below orange on the colour spectrum. Scores for timber frame and ICF are noticeably worse, as shown by the smaller circles which reach the lower end of the colour scale.

8.2.4. Non equal weightings

Further experiments were carried out using the case study to determine the effect of altering the weightings on the results achieved and to evaluate the case study on realistic terms to identify the best construction method for the situation examined. An equal importance for all factors as used above is unlikely to occur in a real design situation. The use of equal weightings in the previous sections of this chapter served to demonstrate the use of the optimisation based methodology, however, equal weightings is unrealistic. Evidence for this comes from the questionnaires, where different factors received different scores for importance. This occurred even though the factors were scored out of five for importance, rather than ranked, in the questionnaire which would have allowed all factors to demonstrate equal importance if this were the case. Two scenarios were examined, with focus on different aspects, to determine the effect this would have on the result of the optimisation process.

Considering the results from the public survey in Chapter 4, the ranking of importance factors and the results of the principal component analysis, a public importance weighting was devised, this is shown in Table 8.2.

Table 8.2: Weighting focusing on the views of the public

Factor	Weighting	Justification
Embodied energy	1.00	Environmental impacts area of concern
Operational energy	1.00	Environment and running cost considered important
Public acceptability	1.00	Ability to sell property on indicated as important
Industry acceptability	0.50	Little concern displayed over this, provide customer with what they want
Airtightness	0.75	Affects cost and environmental performance
Wall thickness	0.75	Connected to cost as thick walls mean larger area per housing unit
Fire performance	0.25	Relates to risk but scores low as a concern

It should be noted, that although fire performance is given a low weighting, all the construction methods examined meet the requirements for the Building Regulations fire performance as a minimum. This is shown in Table 4.24. Any method which is incapable of meeting the required fire standard should not be considered as a possible construction method on safety grounds.

Re-running the case study optimisation methodology, but with these weighting substituted for the original equal values, produced an optimal result of prefabricated straw bale panels for construction method, and 6376mm for dimension *(a)*. A two dimensional representation of the fitness landscape is shown in Figure 8.4.

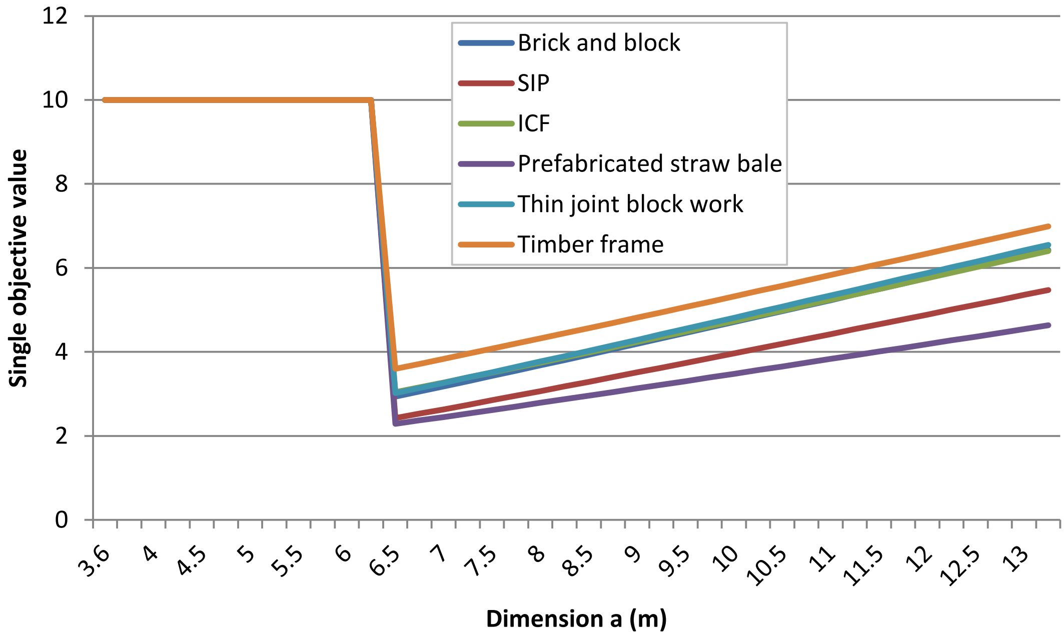

Figure 8.4- Two dimensional graphical display of the fitness landscape for case study optimisation with public-focused weightings

Examination of Figure 8.4 shows that straw bale construction achieves the best single object score at all values of dimension *(a)*. Straw bale construction shows excellent values of embodied energy, and good values of operational energy, airtightness and fire performance. Although the scores achieved for acceptability and wall thickness were low, the benefits outweighed these when examined with the public-focused weightings. At values of *(a)* near the optimal, SIPs achieve sub optimal, but good scores, this may be a result of the high embodied energy associated with SIPs. If this were addressed, SIPs may prove to be the optimal construction method. Altering the weighting has noticeably reduced the suitability of thin joint block work and brick and block construction. The reduction in importance of fire performance will have affected these materials. They score very well in terms of fire performance, so reducing the impact of this will lower their score. The score of timber frame and ICF were largely unaffected by the alteration in weightings, this indicates they are far from the optimal solution.

A second set of weightings was generated based on the importance of factors found from the construction industry survey. These are shown in Table 8.3.

Table 8.3: Weighting focusing on construction industry views

Factor	Weighting	Justification
Embodied energy	0.50	Environmental impacts area of some concern
Operational energy	1.00	Thermal efficiency given as most important concern
Public acceptability	0.75	Saleability of some concern
Industry acceptability	1.00	Method must be acceptable to themselves and employees
Airtightness	1.00	Affects thermal efficiency
Wall thickness	0.75	Connected to cost as thick walls mean larger area per housing unit
Fire performance	0.25	Of little concern to industry provided Building Regulations requirements are met

The results of the case study optimisation when these weightings are substituted were that the optimal material is SIPs with a value of 6377mm for dimension *(a).* Figure 8.5 shows the fitness landscape for the optimisation with construction industry weightings.

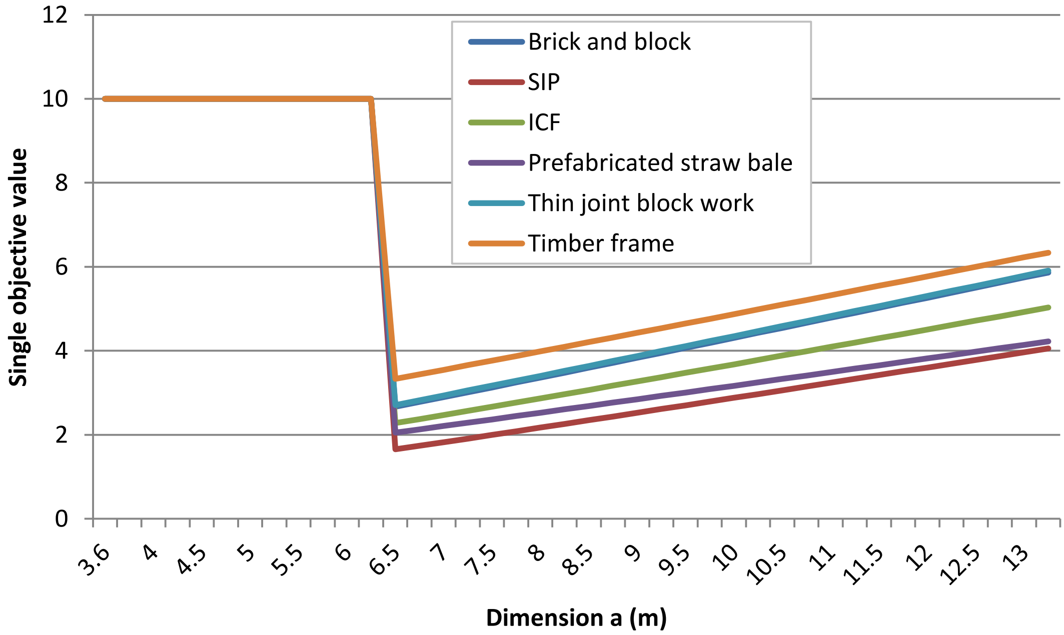

Figure 8.5- Two dimensional graphical display of the fitness landscape for case study optimisation with construction industry-focused weightings

Examination of Figure 8.5 shows that SIPs are the optimal solution at all examined dimensions of *(a)* with these weightings. SIPs achieve good values of operational energy use, wall thickness, acceptability and airtightness, the combination of these factors result in a good score for single objective value when these are highly ranked by the weightings set. Prefabricated straw bale also achieved a good score; however its low acceptability is likely to have reduced its suitability here. While ICF showed a small improvement in score as a result of the weightings being based on the construction industry's interests, it is still outperformed by SIPs and prefabricated straw bale. Timber frame showed little improvement as a result of the weightings change. Although it is the most frequently used alternative method of construction in the area of study these results indicate better alternatives exist in terms of selecting the construction method based on energy use, acceptability and performance.

It can be seen that the weightings chosen can have a significant impact on the output of the optimisation. The value of dimension *(a)* is dictated by the window area constraint; however the material identified as optimal varies as weightings are adjusted.

The two sets of weightings examined here were intended to show the impact of altering the weightings and to highlight the importance of selecting suitable values. There are many other parties who may suggest different weightings, for example, health and safety, financial parties, and planners. Comparing the results of the optimisation run with each of these different points of view has the potential to find the best compromise in terms of interested parties, in addition to in terms of the factors included in the optimisation. It is unlikely the optimal construction method for all interested parties would be the same, due to different areas of concern. However, the selection of sub-optimal but good options can allow the best compromise to be identified. Identifying weightings which would represent the views of these parties is identified as an area for further work in the development of the design methodology.

8.3. Comparison of case study results with brick and block construction

8.3.1. Equal weighting case study

No comparison was carried out for the results of the equal weighting case study as brick and block construction was identified as the optimal method of construction. In addition, as the equal weighting was considered unrealistic any comparison would not have represented a realistic situation had an alternative method of construction been identified.

8.3.2. Public weighting case study

Values were calculated for embodied and operational energy for both brick and block and the recommended prefabricated straw bale panel versions of the case study. The results of this are shown in Table 8.4. Performance and acceptability data for each are also shown in Table 8.4, values taken from table 4.24.

Table 8.4- A comparison of prefabricated straw bale construction with the "typical" method used in England and Wales for the case study house

Construction method	Embodied energy (MJ/m^2)	Operational energy ($kWh/m^2/year$)	Air tightness ($m^3/(h.m^2)$ at 50Pa)	Wall thickness (m)	Fire performance (minutes)	Public acceptability	Industry acceptability
Brick and block	744.88	11.77	4.50	0.346	240	95	91
Prefab. Bale panels	467.91	8.0756	0.86	0.480	135	44	26
Building Regulations	N/A	N/A	10.00	N/A	60	N/A	N/A

It can be seen from Table 8.4 that straw bale construction shows many benefits over traditional brick and block construction. Values for embodied energy, operational energy and airtightness all outperform those seen for traditional construction. The fire performance is significantly less that that seen for brick and block construction, although it outperforms that required by the Building Regulations, with almost double the required time. This high level of performance was considered to be acceptable. Wall thickness is greater than for brick and block; this can have impacts on the cost of construction as fewer houses could be built in a given area. However, if the insulation in the brick and block were increased to achieve comparable operational energy values, the greater depth required would reduce the advantage of brick and block in terms of wall thickness. The low acceptability of straw bale construction, both public and industry, is the main challenge for this form of construction. Increasing awareness of the benefits and proving that commonly held beliefs are incorrect could raise the acceptability and improve the viability of this method of construction. For example, the belief that straw bale construction burns easily when, in fact, the fire performance value for prefabricated straw bale construction in Table 8.4 demonstrates this is not the case (see Chapter 5 for further examples). Achieving this would allow the embodied energy and operational benefits to be achieved, resulting in reduced energy use and associated emissions. This could then help to achieve the emissions reduction targets set out in the Climate Change Act (2006).

8.3.3. Construction industry weighting case study

Consideration was also given to the effect of using SIPs as suggested by the construction industry focused case study run. Table 8.5 presents a comparison of SIP construction with brick and block construction for the case study building, values taken from Table 4.24.

Table 8.5- A comparison of the SIP construction method with the “typical” method used in England and Wales for the case study house.

Construction method	Embodied energy (MJ/m^2)	Operational energy ($kWh/m^2/year$)	Air tightness ($m^3/(h.m^2)$ at 50Pa)	Wall thickness (m)	Fire performance (minutes)	Public acceptability	Industry acceptability
Brick and block	744.88	11.77	4.50	0.346	240	95	91
SIP	1197.7	7.10	1.00	0.326	73	74.5	59
Building Regulations	N/A	N/A	10.00	N/A	60	N/A	N/A

It can be seen that brick and block performs much better than SIP construction in terms of embodied energy and fire performance. As the importance of the fire performance falls due to the adjusted weightings, the other aspects in which SIP construction performs well become more important. As a result of this, the single objective score is lower and SIP construction becomes optimal. The high embodied energy of SIP construction is undesirable; however, it may be that alternative cladding methods, such as the use of brick slips could reduce this to a more comparable, or lower, level.

The SIP version of the case study had a much lower annual operational energy per square metre of floor area, a saving of 4.67MJ/m^2/year is seen. This would be desirable for members of the construction industry who are looking towards the requirement for building zero carbon homes from 2016. Airtightness achieved by SIPs is much better, again something that would appeal to the construction industry who must meet targets, Building Regulations as a requirement, but ideally lower ones set by best practise guidelines. Wall thickness is somewhat improved when SIPs are compared with brick and block. This would appeal to the construction industry as it allows more units to be built in a given area; alternatively it could result in larger homes which are more desirable and more appealing to the purchaser. SIPs show a fairly high level of acceptability, both with the public and the construction industry. Although this is lower than brick and block construction, education could improve this value by publicising the benefits and dispelling those concerns stated in the survey responses (see Chapter 5). For example, SIP construction was considered by some survey respondents to be insufficiently strong for housing, in fact the strength of SIPs has been tested and found to be acceptable by authors such as Mosey et al. (2009), Hairstans and Kermani (2007) and Morley (2000).

8.4. Case study recommendations

The method considered to be most suitable for constructing the case study building is SIPs. This is the optimal method when the construction industry weightings are used, and sub-optimal, but good scoring when the public weightings are used. This was considered to be the best compromise between the two interested parties. The main disadvantage to SIP construction as examined in this work is the relatively high value of embodied energy when compared with brick and block construction. The use of alternative cladding, such as brick slips, may improve this situation by reducing the embodied energy. The impact of this change on the acceptability of the method would need to be examined as based on comments, in the public questionnaire the use of alternative cladding is likely to negatively impact the acceptability, a brick external appearance was desirable. In addition, some questionnaire respondents felt SIPs did not appear to be sufficiently strong. Removing the brick outer skin may be perceived to lower the strength of the system to a level the public would not trust, despite evidence that SIP construction is able to perform sufficiently (Mosey et al. 2009, Hairstans and Kermani 2007, Morley 2000).

As the data used in the design methodology was based on realistic values and the case study was based on construction figures for England and Wales it is considered that SIP construction may have the potential for use in speculative housing on a large scale. As a result of increased use, savings would be seen in terms of operational energy, and if alternative cladding were used in terms of embodied energy, contributing to reduced emissions.

8.5. Summary

- A case study was designed based on housing figures for England and Wales.
- The optimisation based design methodology was used to identify the best solution to the case study problem presented.
- The case study allowed the exploration of population size, number of generations and crossover, and hence mutation, probabilities. These were set at Population = 100, Number of generations = 200, P_C= 0.4 and P_M= 0.6.
- The solution identified by the methodology as optimal for the case study scenario with equal weighting for all factors was brick and block with dimension *(a)*= 6374mm.
- Fitness landscapes were examined both in three and two dimensional graphical form. These can allow sub-optimal, but good, solutions to be identified and allow for additional criteria to be considered.
- A phi array was also used to demonstrate the fitness landscape. This presents a method for visualising the results. Sub optimal solutions can also be identified from the phi array.
- Both fitness landscapes and Phi arrays identify the variable values which violate the constraint applied by window area. These occur at low values of *(a)* (below 6.5m). These values of *(a)* are undesirable as they would result in low natural lighting and increased use of artificial light.
- The importance of weighting was demonstrated by running the case study optimisation with different weightings.
- There was no impact on the optimal value of dimension *(a)* as weightings were altered.

- A public focused weighting indicated that prefabricated straw bale construction was optimal. SIP construction was sub-optimal but scored well.
- Industry focused weightings suggested the use of SIPs would be the most effective compromise.
- A comparison of the embodied energy, operational energy and performance of the suggested solution with traditional methods was carried out.
- Prefabricated straw bale panels outperformed brick and block construction in terms of embodied and operational energy and airtightness. Wall thickness and fire performance was lower than the traditional method, but still good. The very low acceptability of this method is the major challenge it presents.
- SIP construction requires a greater amount of embodied energy for its manufacture, it is suggested that alternative methods of cladding may solve this. Areas that concern the construction industry such as operational energy use and airtightness outperform the traditional method making it a good choice. A reasonable level of acceptability is seen, this could be further improved with education about the benefits of SIP construction.
- The combination of SIP construction as optimal for the industry weightings and sub-optimal but good based on the public weightings supports its use in housing construction in England and Wales.

9. Conclusions

9.1. Findings from the work

To examine the potential of alternative methods of wall construction to reduce energy requirements associated with housing, six methods of construction were investigated in detail. These included the "typical" method of brick and block construction, and a range of alternative methods. A design methodology was created, using optimisation based techniques to help identify the construction method and building size which give the best compromise between energy use, acceptability and performance.

9.1.1. Embodied energy of construction methods

It was initially expected that alternative methods of construction may have lower values of embodied energy, due to the presence of timber and reduced quantities of concrete. However, it was found that materials such as foam insulation require large amounts of energy to manufacture. The high performance achieved using these materials may ultimately pay the high energy cost of production back. However, the opportunity to save energy and the associated emissions at the manufacturing stage is lost if higher embodied energy materials are used. Prefabricated straw bale panels were the only method studied to demonstrate a lower embodied energy than brick and block construction.

The high embodied energy of brick contributed significantly to the total embodied energy of all those methods that included it as a material. Bricks accounted for 58% of the embodied energy of brick and block, 30% for SIPs and ICF, 51% for thin joint block work and 46% for timber frame. Using alternative methods of cladding, such as timber, has the potential to reduce the embodied energy of new build housing. However, comments from the public questionnaire strongly support a brick appearance. Satisfying both the need for lower embodied energy and the desire for a "traditional" appearance is a significant challenge. Materials such as brick slips may provide a middle ground. They are most suitable for methods of construction such as ICF and SIPs. Although they can be used with other methods of construction, such as timber frame, extra materials required to apply the slips onto may negate the embodied energy savings achieved by eliminating brickwork.

9.1.2. Acceptability of alternative methods of construction

The acceptability of the six methods of construction was examined to determine their potential for use. Both public and construction industry opinions were examined via questionnaires. Both groups showed a preference for the traditional method of construction (brick and block) but some acceptability was seen for alternative methods.

The level of acceptability varied significantly across the methods. Thin joint block work, SIPs and ICF showed a similar, fairly high, level of acceptability. Methods with high acceptability are most likely to be successful in speculative construction as they have greater appeal to the house buying market as a whole.

Timber frame and straw bale construction showed low acceptability. That there is some acceptability indicates they do have the potential to be used in housing construction. However, they may be more suited to individual houses, constructed to order with the client who will live in the house being part of the consultation process.

A noticeable variation in acceptability was seen with geographical location. For example, the acceptability of prefabricated straw bale panels was significantly lower in Wales and London, it was higher than average in the South West, it was considered that the rural nature of the South West may be responsible for this trend. The potential for regional variation in acceptability should be considered when selecting a construction method to use.

9.1.3. Areas of concern relating to housing

Concerns held by the public when considering a house to buy were examined in the questionnaire. These areas were categorised as environmental factors, financial factors and risk management. The highest scoring individual concerns were price, need for maintenance and mortgage availability. For the construction industry the factors with the greatest influence on construction method choice were identified as thermal efficiency, cost and speed of construction. These factors should be considered when making decisions related to the construction of housing, they are relevant to all areas of the process, not just to wall construction methods.

9.1.4. Increasing acceptability

Questionnaire responses indicated that alternative methods which emulate the properties of “traditional” construction they are more likely to be acceptable. Desirable characteristics were identified as a traditional appearance i.e. brickwork outer, good levels of insulation, high strength, good durability and proof of performance.

Education is key to increasing the use of alternative methods of construction. Many of the concerns listed in the survey responses have already been disproven by existing research and anecdotal evidence, as shown in Chapter 4. The desirable characteristics listed above can also be achieved by alternative methods of construction. This information needs to be demonstrated to purchasers and the construction industry. Increasing awareness of the benefits of alternative methods could increase their acceptability.

Financial benefits scored highly as a way of increasing interest in alternative methods of construction. This may be from reduced construction costs or lower heating bills due to better thermal performance. Low materials cost was identified as attractive to the construction industry. If this can be achieved by alternative methods, they have a higher likelihood of being adopted.

Guarantees were identified by survey respondents as something that would increase their interest in alternative methods of construction. In addition to reducing concerns relating to the construction method this provides a guarantee of the workmanship and ensures houses are built to an acceptable standard. This was identified as an area where the Government could show support for alternative methods of construction, by backing guarantees for houses built using the alternative methods.

9.1.5. The optimisation based design methodology

It was noted that no single construction method examined presented a clear best option; all methods had benefits and disadvantages. The key to identifying the optimal solution is identifying the best compromise.

A fitness function, which combines values for embodied energy, operational energy, acceptability and performance with weightings, was created to assess combinations of construction method and building front dimension *(a)*. Optimisation using genetic algorithms was applied to the fitness function to allow a wide range of options to be examined and the optimal solution to be identified. This represents the best compromise, and the most suitable choice for the design. Sub-optimal solutions may be better than the optimal solution in some cases, visual representations of the solution space, such as Phi-arrays, help to identify these.

Possible uses for the methodology were identified as building design, where construction method and building layout selection is necessary. Outputs from the methodology can be used to explain the reasoning behind a construction method selection. The methodology was designed to demonstrate the potential of the method, there is wide opportunity for expansion, allowing more criteria to be examined. Identifying the optimal solution and clearly demonstrating the reasons why it is optimal can help to encourage support for the chosen solution. This may be from financial parties, the Government or end users.

9.1.6. Case study solution

The use of the optimisation based design methodology was demonstrated with a case study based on the most frequently constructed house type and size for England and Wales. Case study values were used to determine the best values to use for crossover, and hence mutation, fraction; for number of generations and size of population.

From the optimisation of the case study it was seen that the solution which uses the minimum amount of material will always be selected as favourable using the current programme design. A small value of dimension *(a)* minimises the materials used, and hence the embodied energy. The area which allows heat loss is also minimised, reducing the operational energy requirements.

The minimum value of dimension *(a)* must allow a suitable amount of natural lighting. This was achieved by the use of a simplified penalty constraint in the optimisation calculation. From the case study results it can be seen that for terraced houses meeting this constraint requires fairly large values of dimension *(a)*, in excess of 6m. The reduced wall area available for windows at small values of *a* makes it impossible to satisfy both the 20% of floor area requirement and the 25% of wall area restriction. Larger window areas could be used if they are thermally efficient. Alternatively, some natural lighting could be provided by other measures, such as sun tunnels. Constraint violation may be allowed if the housing design provides sufficient energy generation to compensate for the increased artificial lighting, however, this is undesirable.

The case study examined indicates that if the aspects considered have equal weighting, brick and block construction is optimal. Equal weighting for all factors was used to demonstrate the functionality of the methodology and the ways in which the solution landscape can be examined. However, equal weightings are not considered to be realistic. Two sets of realistic weightings were created based on the questionnaire findings.

The results from the case study with realistic weightings suggest that prefabricated straw bale construction was optimal for the public viewpoint, with SIP construction sub-optimal but achieving a good score. SIPs were optimal for the industry focused weightings. That altering the weightings produced a different optimal construction method for each set of values shows the importance of weightings and that they must be carefully considered.

A major disadvantage of straw bale construction is the low acceptability seen in the survey responses; this would need to be improved for straw bale construction to be viable on a large scale. If this could be addressed the potential for low embodied energy, thermally efficient houses this method offers could be accessed.

The fact that SIP construction was optimal for the construction industry weighting and sub-optimal, but good scoring, for the public based weighting indicates it may be the best option for speculative construction in England and Wales. It is the solution which best meets the requirements of both parties. Energy use, performance and acceptability are all good. The major disadvantage to this method is its high embodied energy. It has been noted that the use of bricks as an outer skin contributes significantly to the embodied energy of this method. If the bricks were replaced with an alternative cladding, SIP construction may equal or outperform brick and block construction in terms of embodied energy. The impact on acceptability, both due to appearance and perceived strength must be carefully considered if this approach is taken.

The operational energy saving achievable by SIPs, compared to brick and block construction has been examined using the case study dimensions. An operational energy saving of 4.67MJ/m^2/year was calculated. If this was achieved across all new build houses constructed in England and Wales the savings in energy use and the associated emissions would play a significant part in achieving emissions reduction targets.

9.2. Conclusions and recommendations

The following recommendations are made based on the findings of this work.

- Brick work has been identified as a major contributor to the embodied energy of construction. Replacing this with a less energy intensive material could reduce the embodied energy of construction and result in significant energy savings and the reduced emissions associated with them. However, a brick finish has been identified as strongly desirable to house purchasers. These two factors must be balanced to achieve the best combination of saleability and embodied energy. Brick slips may present a solution in some cases.
- Education to improve the understanding of alternative construction methods is a key step in raising their acceptability and accessing the benefits they present. Awareness of the existence of alternative methods of construction and the benefits they offer should be encouraged. This could be by the use of media, as seen with straw bale construction becoming better known due to the television programme “Grand Designs”. Greater education would also help to dispel fears, such as fire performance being poor for straw bale construction.
- Government support for housing developments made using alternative methods of construction would allow them to become examples which can then demonstrate the benefits of the alternative methods. For example, actual use figures for energy requirements, durability and maintenance requirements.
- Guarantees were identified as a method of increasing the level of interest in alternative methods of construction. These could be offered by construction firms; however this relies on support from the construction industry for the alternative method. This is also an area where Government support could play a role.
- Areas to consider when making decisions related to housing construction include environmental factors, financial factors and risk management. Price was of particular importance to the public. Although this was not covered in the optimisation based design methodology it could be assessed using a similar method to that demonstrated for embodied energy.

- An optimisation based design methodology has been devised which can be used to aid decision making. Opportunities exist for it to be expanded and modified to suit a range of purposes. Using phi arrays to identify sub optimal but high scoring solutions allows other factors to be included in the decision making process. Phi arrays present a way of showing the solution space that is easy to understand without specialist knowledge. This would be useful at the design phase when options are being discussed by a wide range of interested parties. Potential areas for expansion of the methodology are discussed in Chapter 10.
- Potential users of the methodology include designers. However it also has applications as a result of increasing the transparency of the decision making process. Low environmental impact construction methods can be identified; these could be used as the basis for Government backing of a particular construction method.
- SIP construction has been identified as a good choice for achieving lower operational energy, higher performance, housing construction in England and Wales. To support this, further research into the method would be beneficial, accompanied by dissemination of the findings to a wide audience. Making the public and industry aware of the benefits and disadvantages is key to increasing the acceptability of this method and hence it's economic viability. Government support for the method, for example, by funding research or backing guarantees could also help the method be used on a wider scale, and the reduced operational energy requirements it offers to be accessed.

9.3. Contribution to knowledge

The contribution to knowledge provided by the work included in this thesis is:

- The performance and energy associated with the construction methods studied has been reviewed. In particular brick has been identified as a high embodied energy material, finding alternatives to this, such as brick slips, has been discussed.
- The public and industry acceptability of the six construction methods studied has been examined. Alternative methods of construction with high acceptability are Structural Insulated Panels, Insulating Concrete Formwork and Thin joint block work. Prefabricated straw bale panels and timber framed construction

have low acceptability with the public. Timber framed construction has moderate acceptability with the construction industry.

- Desirable characteristics for wall construction methods were identified as a traditional appearance i.e. brickwork outer, good levels of insulation, high strength, good durability and proof of performance.
- Education was identified as the key to improving the acceptability of alternative methods of construction. Many of the issues identified with them have been disproven by testing or anecdotal evidence, by disseminating this information the acceptability of alternative methods may increase.
- An optimisation based design methodology for the selection of construction methods that considers energy use, acceptability and performance to identify the best compromise for a given situation has been created. The use of this was demonstrated with a case study. Areas have been identified for further work to expand this into a tool which can be used in a design environment

The case study examined identified SIP construction as the most suitable construction material, balancing the points of view of the public and industry. This construction method is considered to have the greatest potential for reducing the energy requirements of housing construction whilst maintaining performance and economic viability. Further investigation into this is recommended as the case study used in this work was limited by the number of performance indicators used.

9.4. Further work

There is enormous potential for the expansion of the optimisation based methodology developed in this thesis. This work intended to demonstrate the potential of optimisation in this situation and some of the methods that could be used to generate data. Suggestions for expanding the methodology include:

- The inclusion of other construction methods, for example those discarded during the method selection (see Chapter 4.3).
- Altering specification of construction methods. For example, thicker SIP panels, greater depth of insulation in thin joint block work. This would not require additional acceptability information; energy values and performance would be affected.
- Altering the cladding material has the potential to affect all aspects considered. To include different cladding options a further survey would have to be carried out to determine acceptability.
- Further aspects of the construction methods' performance could be considered in the design methodology. Examples include, cost, durability, maintenance requirements, time to construct and construction waste. The methods demonstrated can be adapted to these factors.
- Embodied energy assessment could be expanded to include transportation and site activities.
- Alteration of the degree day values used. This may be to focus the methodology on a particular location or to use a different degree day base temperature.
- Cooling degree days could be considered if the methodology was to be used in a country or region which experiences high temperatures during part of the year.
- The development of weightings for additional parties with an interest in construction so their views can be incorporated into the decision making process, for example, health and safety and planners.

It was noted that the use of brick has a significant impact on the embodied energy of the construction methods. It would be useful to consider the effect of different types of cladding on the total embodied energy of construction methods. This could be independent of the optimisation methodology; however the results would apply to the methodology. The acceptability of alternative cladding methods would need to be examined as many survey comments indicated a preference for a brick appearance externally.

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Hamilton-MacLaren, F., Loveday, D.L.L & Mourshed, M., 2012. Public opinions on alternative lower carbon wall construction techniques for UK housing. *Habitat International*, 37, pp.163–169

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Appendix A- Sample survey, house holder

House holder survey

Alternative wall construction materials for UK housing

This study is being carried out as part of a PhD investigation into the use of alternative materials to build house walls.

I would be grateful for your opinions on this topic. Information received will be used as part of the PhD project and published in the thesis.

All surveys are anonymous and data collected will be stored in accordance with the Data Protection Act.

If you have any further questions please refer to the Survey FAQs at http://cvfh2010.moonfruit.com/#/survey-faqs/4542996141 or contact me via the website contact page.

1. Please tick this box to confirm you are happy to answer the survey questions and have your answers used as part of the PhD project. If you are not happy to continue please close the browser window.

○ Yes

House holder survey

2. In what region do you currently live?

- East Anglia
- East Midlands
- London
- North East
- North West
- South East
- South West
- West Midlands
- Yorkshire and Humberside
- Scotland
- Wales
- Northern Ireland

3. Please indicate your gender

- Male
- Female

4. Please indicate which age range you are in

- 18-29
- 30-44
- 45-59
- 60-74
- 75 and over

5. Is your main residence currently:

- Rented
- Owner occupied
- Other

(please specify)

6. When considering a house for purchase how important are the following factors to you? (Please rate from 1 to 5)

	1- Not at all	2- A little	3- Some	4- Quite a bit	5- Very much
Fire risk	○	○	○	○	○
Price	○	○	○	○	○
Low energy use	○	○	○	○	○
Need for maintenance	○	○	○	○	○
Price of insurance	○	○	○	○	○
Mortgage availability	○	○	○	○	○
Environmental impacts of construction	○	○	○	○	○

House holder survey

7. What is your main residence constructed from?

- ◯ Brick and block
- ◯ Timber frame with brick covering
- ◯ Don't know
- ◯ Other

(please specify)

8. Is the material from which your house is built of interest to you?

- ◯ Yes
- ◯ No

9. Are you only interested in living in houses with walls built from a particular material?

- ◯ No
- ◯ Yes

Please say which

House holder survey

Many newly built houses in the UK are made from bricks and concrete blocks. Alternative materials are being examined to see if they have a lower environmental impact but would still interest customers.

10. Have you heard of the following construction materials?

	Yes	No
Brick and block	○	○
Structural insulated panels (SIPs)	○	○
Insulating concrete formwork (ICF)	○	○
Straw bales with lime plaster	○	○
Brick and thin joint blockwork	○	○
Timber frame with brick covering	○	○

The following pages contain details and pictures of some house wall material options.

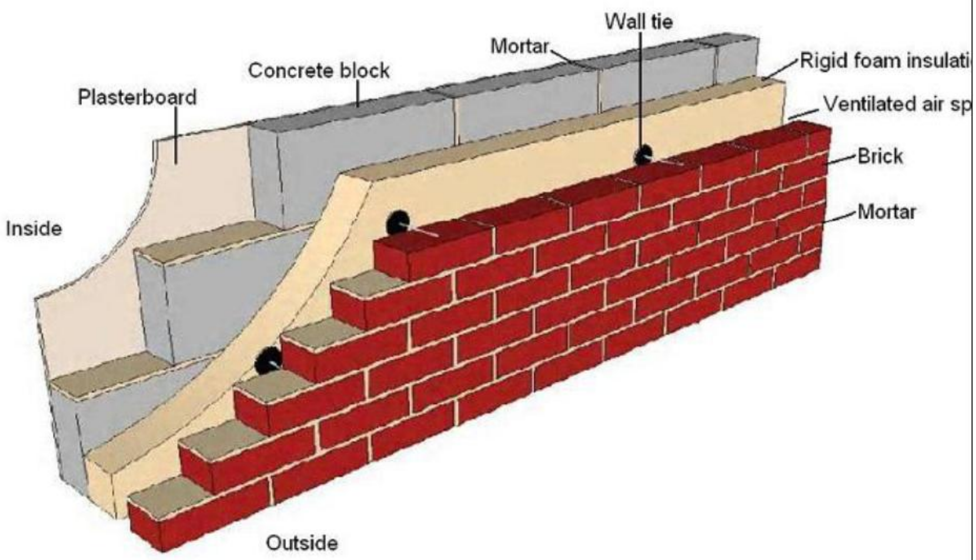
Please imagine that you are purchasing a new house and look at the information then answer the questions on each type of wall construction.

House holder survey

Brick and block

This is built from:
Outside layer- Brick
Centre space- Air space and insulation, wall ties to join layers
Inside layer- Concroto block

From the outside the wall is seen as brick, from the inside a plastered finish which can be decorated.



11. Would you consider buying a house built from this material?

◯ Yes ◯ No ◯ Maybe

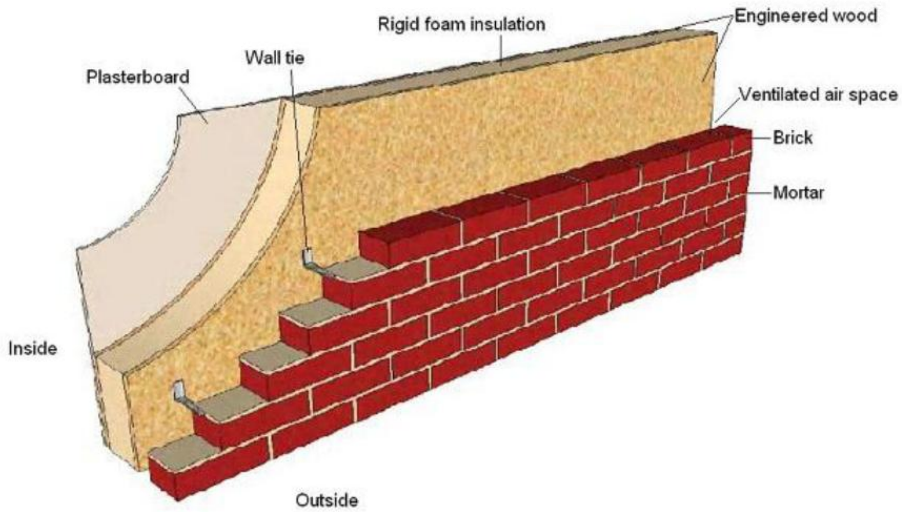
12. Are there any reasons for this?

House holder survey

Structural Insulated Panels (SIPs)

This is built from:
Outside layer- Brick
Centre space- Air space and wall ties to join layers
Inside layer- Foam insulation sandwiched between two sheets of engineered wood

From the outside the wall is seen as brick, from the inside a plastered finish which can be decorated.



13. Would you consider buying a house built from this material?

◯ Yes ◯ No ◯ Maybe

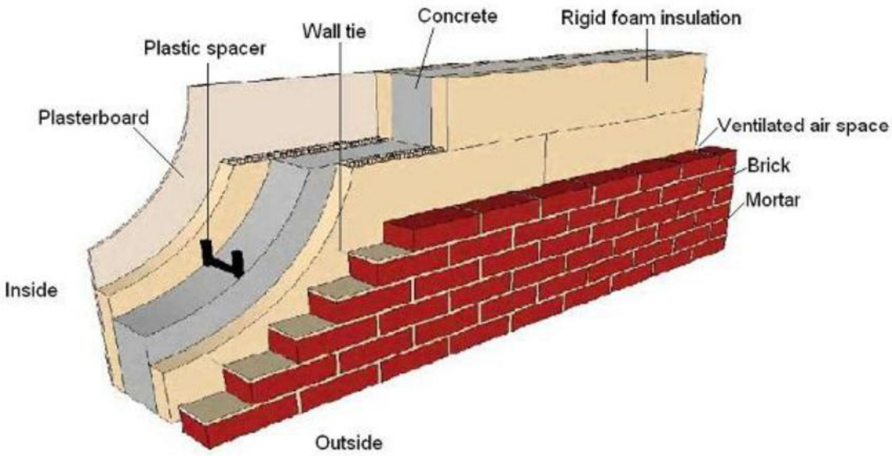
14. Are there any reasons for this?

House holder survey

Insulating Concrete Formwork (ICF)

This is built from:
Outside layer- Brick
Centre space- Air space and wall ties to join layers
Inside layer- Polystyrene foam insulation filled with concrete

From the outside the wall is seen as brick, from the inside a plastered finish which can be decorated.



15. Would you consider buying a house built from this material?

○ Yes ○ No ○ Maybe

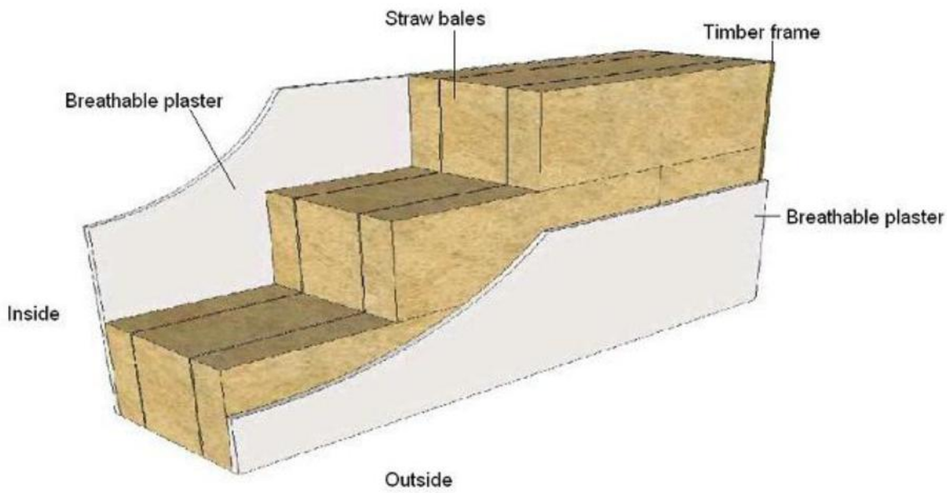
16. Are there any reasons for this?

House holder survey

Straw bales with lime plaster

This is built from:
Outside layer- Breathable plaster and paint
Centre space- Straw bales
Inside layer- Breathable plaster and paint

From outside and inside the walls have a plaster finish in the chosen colour.



17. Would you consider buying a house built from this material?

◯ Yes ◯ No ◯ Maybe

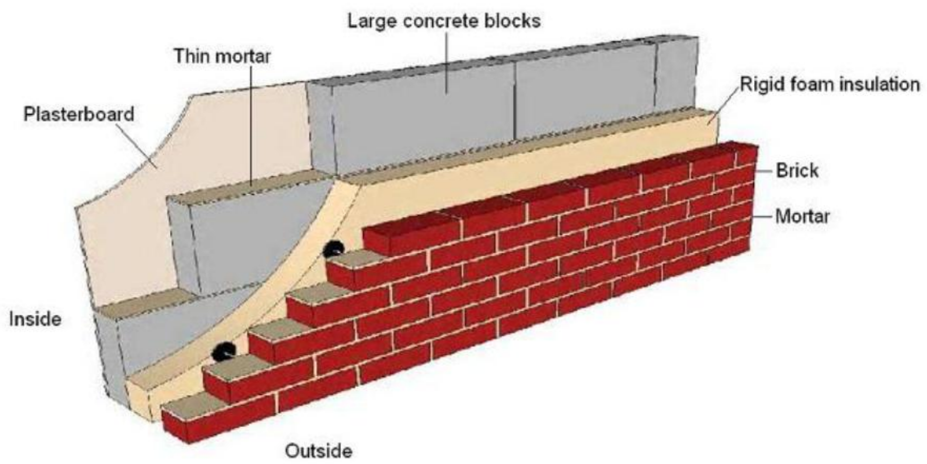
18. Are there any reasons for this?

House holder survey

Brick and thin joint blockwork

This is built from:
Outside layer- Brick
Centre space- Air space, insulation and wall ties to join layers
Inside layer- Large concrete blocks

From the outside the wall is seen as brick, from the inside a plastered finish which can be decorated.



19. Would you consider buying a house built from this material?

◯ Yes ◯ No ◯ Maybe

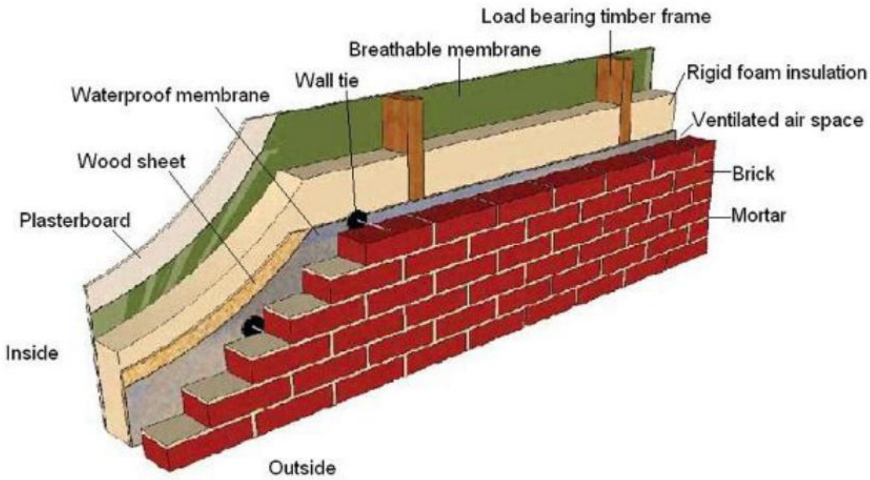
20. Are there any reasons for this?

House holder survey

Timber frame with brick covering

This is built from:
Outside layer- Brick
Centre space- Air space and wall ties to join layers. Timber "skeleton" which supports roof and floors.
Inside layer- Insulation sandwiched between a sheet of wood and a sheet of plasterboard and protected by waterproof membranes

From the outside the wall is seen as brick, from the inside a plastered finish which can be decorated.



21. Would you consider buying a house built from this material?

◯ Yes ◯ No ◯ Maybe

22. Are there any reasons for this?

House holder survey

23. Would the following increase your interest in a house built from alternative materials?

	Yes	No
Low prices	◯	◯
Low running costs	◯	◯
Low environmental impact	◯	◯
More information	◯	◯
Nothing would increase my interest	◯	◯

Other (please specify)

House holder survey

If you have any other further comments about any of the materials or topics you feel are relevant please add them to the box below or email them to me at cvfh2@lboro.ac.uk

A summary of the questionnaire results will be available on request from cvfh2@lboro.ac.uk

Many thanks for your participation
Fiona Hamilton-MacLaren

24. Please feel free to add any additional comments you feel to be relevant

Appendix B- Sample survey, house builder

House builder survey

Alternative wall construction materials for UK housing

This study is being carried out as part of a PhD investigation into the use of alternative materials in the constuction of house walls.

I would be grateful for your opinions on this topic. Information received will be used as part of the PhD project and published in the thesis.

All surveys are anonymous and data collected will be stored in accordance with the Data Protection Act.

If you have any further questions please refer to the Survey FAQs at http://cvfh2010.moonfruit.com/#/survey-faqs/4542996141 or contact me via the website contact page.

1. Please tick this box to confirm you are happy to answer the survey questions and have your answers used as part of the PhD project. If you are not happy to continue please close the browser window.

○ Yes

House builder survey

2. In what region(s) does your company currently operate? (Please tick all that apply)

- ☐ East Anglia
- ☐ East Midlands
- ☐ London
- ☐ North East
- ☐ North West
- ☐ South East
- ☐ South West
- ☐ West Midlands
- ☐ Yorkshire and Humberside
- ☐ Scotland
- ☐ Wales
- ☐ Northern Ireland

3. What aspect(s) of housing construction does your company deal with? (Please tick all that apply)

- ☐ Design
- ☐ Planning
- ☐ Construction
- ☐ Other

Please specify

4. When considering a material for housing wall construction how much do the following factors concern you? (Please rate from 1 to 5)

	1- Not at all	2- A little	3- Some	4- Quite a bit	5- Very much
Fire performance	○	○	○	○	○
Cost	○	○	○	○	○
Thermal efficiency	○	○	○	○	○
Embodied energy	○	○	○	○	○
Construction speed	○	○	○	○	○
Saleability	○	○	○	○	○
Health and safety requirements	○	○	○	○	○
Waste material disposal	○	○	○	○	○
Availability	○	○	○	○	○
Durability	○	○	○	○	○
Environmental impacts of construction	○	○	○	○	○

House builder survey

Many newly built houses in the UK are constructed with brick and block walls. Alternative materials are being examined to see if they have a lower environmental impact but would still interest the construction industry.

The following pages contain details and images of some options, please answer the questions about each of the following materials.

5. Have you heard of the following construction materials?

	Yes	No
Brick and block	◯	◯
Structural insulated panels (SIPs)	◯	◯
Insulating concrete formwork (ICF)	◯	◯
Straw bales with lime plaster	◯	◯
Brick and thin joint blockwork	◯	◯
Timber frame with brick cladding	◯	◯

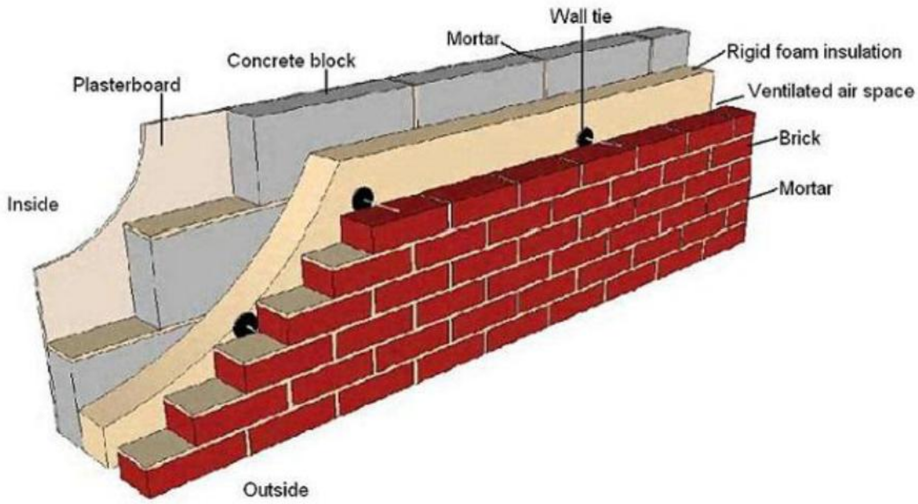
6. Has your company ever used the following materials in construction? (Please tick all that apply)

	Yes- housing	Yes- other	No	Don't know
Brick and block	☐	☐	☐	☐
Structural insulated panels (SIPs)	☐	☐	☐	☐
Insulating concrete formwork (ICF)	☐	☐	☐	☐
Straw bales with lime plaster	☐	☐	☐	☐
Brick and thin joint blockwork	☐	☐	☐	☐
Timber frame with brick cladding	☐	☐	☐	☐

House builder survey

Brick and block
This is built from:
External leaf- Bricks and mortar
Cavity- Rigid foam insulation, wall ties and ventilated air space
Internal leaf- Concrete blocks and mortar

Externally the red bricks give the finished appearance, internally the wall is plastered and painted.



7. Would your company use this material in construction?

◯ Yes ◯ No ◯ Maybe

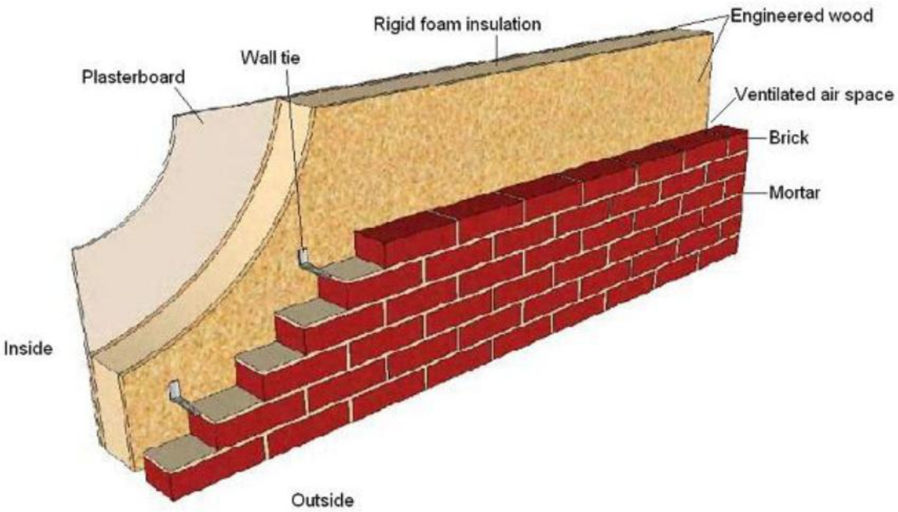
8. Are there any reasons for this?

House builder survey

Structural Insulated Panels (SIPs)

This is built from:
External leaf- Brick and mortar
Cavity- Ventilated air space and wall ties
Internal leaf- Rigid foam insulation sandwiched between two sheets of engineered timber

External appearance is of red bricks, internally plasterboard is applied directly to the SIP and finished as required.



9. Would your company use this material in construction?

◯ Yes ◯ No ◯ Maybe

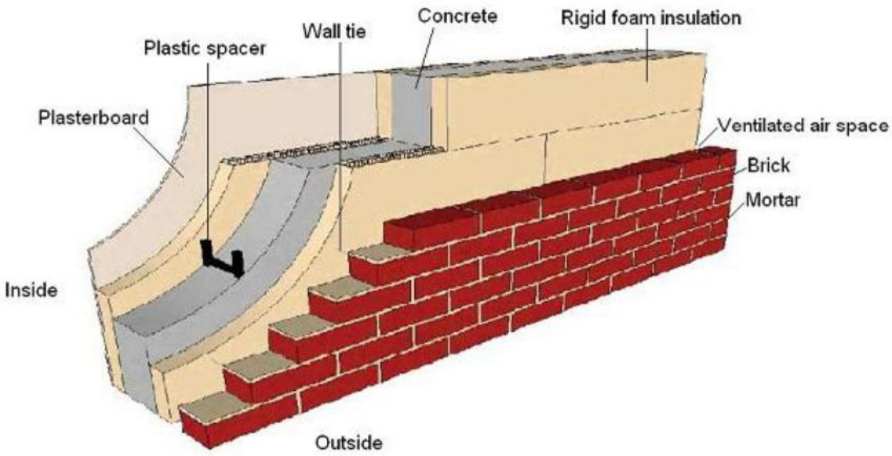
10. Are there any reasons for this?

House builder survey

Insulating Concrete Formwork (ICF)

This is built from:
External leaf- Bricks and mortar
Cavity- Ventilated air space and wall ties
Internal leaf- Rigid polystyrene foam forms filled with concrete

Externally the appearance is red brick, internally plasterboard is applied to the foam forms and finished as required.



11. Would your company use this material in construction?

◯ Yes ◯ No ◯ Maybe

12. Are there any reasons for this?

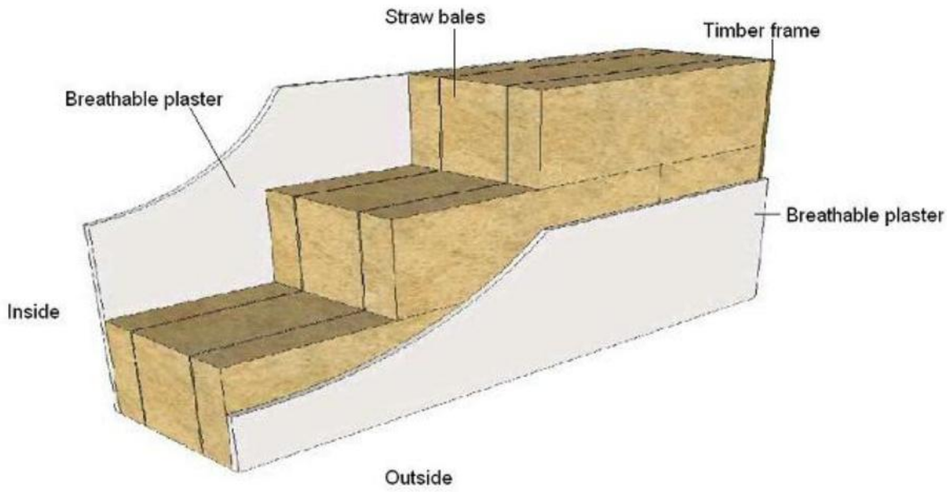
House builder survey

Straw bales with lime plaster

This is built from:
External leaf- Lime based breathable plaster
Centre of wall- Straw bales
Internal leaf- Lime based breathable plaster

A timber frame around the bales provides additional load bearing capabilities and allows offsite fabrication of bale filled panels.

Internal and external appearance is a plaster finish.



13. Would your company use this material in construction?

◯ Yes ◯ No ◯ Maybe

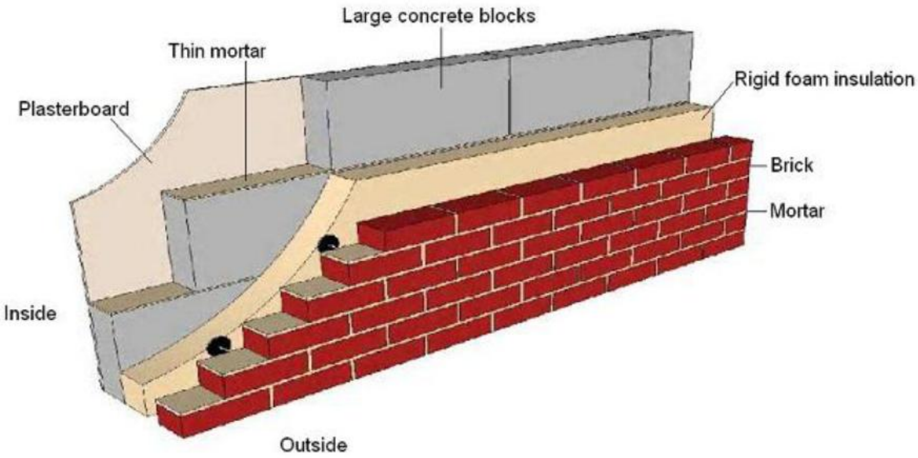
14. Are there any reasons for this?

House builder survey

Brick and thin joint blockwork

This is built from:
External leaf- Bricks and mortar
Cavity- Ventilated air space. rigid foam insulation and wall ties
Internal leaf- Large sized concrete blocks and 5mm mortar

External appearance is a brick finish, internally the wall is plasterboarded and finished as required.



15. Would your company use this material in construction?

◯ Yes ◯ No ◯ Maybe

16. Are there any reasons for this?

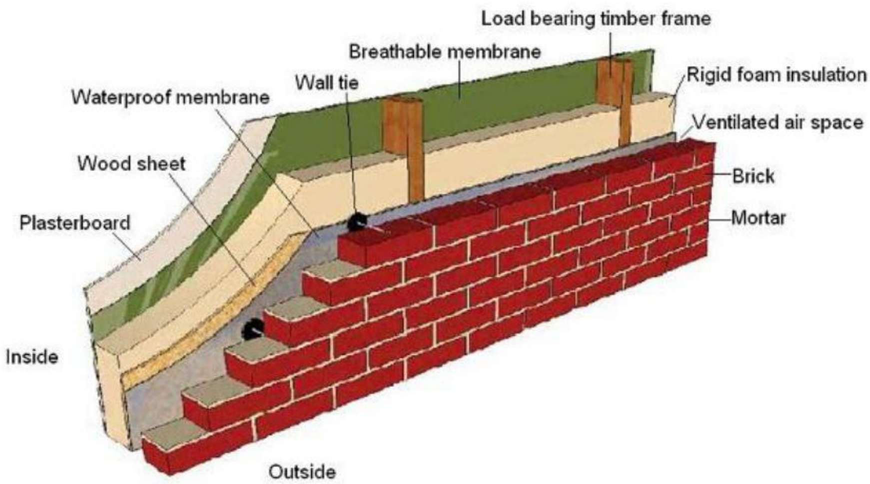
House builder survey

Timber frame with brick cladding

This is built from:
External leaf- Bricks and mortar
Cavity- Ventilated air space and wall ties
Internal leaf- Moisture control membrane, timber sheeting, insulation, water vapour control membrane and plasterboard (arranged as shown below)

A timber frame is contained within the inner leaf and supports the building loads.

External appearance is a brick finish, internally the walls are finished as required.



17. Would your company use this material in construction?

◯ Yes ◯ No ◯ Maybe

18. Are there any reasons for this?

House builder survey

19. Would any of the following increase your company's interest in alternative construction materials?

	Yes	No
Low prices	◯	◯
Low running costs	◯	◯
If they are environmentally friendly	◯	◯
Market desirability	◯	◯
More information	◯	◯
Nothing would increase my company's interest	◯	◯

Other (please specify)

House builder survey

If you have any other further comments about any of the materials or topics you feel are relevant please add them to the box below or email them to me at cvfh2@lboro.ac.uk

A summary of the questionnaire results will be available on request from cvfh2@lboro.ac.uk

Many thanks for your participation
Fiona Hamilton-MacLaren

20. Please feel free to add any additional comments you feel to be relevant

Appendix C- Acceptability of construction methods

Results from the public survey in response to the question "Would you buy a house built from this material are presented below in Table C.1- C.6. A separate table is presented for each method of construction.

Table C.1- Acceptability of brick and block construction by region

	Percentage response to the question "Would you buy a house built from this material?"		
Region	**Yes**	**No**	**Maybe**
East Anglia	88	0	12
East Midlands	92	2	6
London	86	3	11
North East	80	10	10
North West	94	2	4
South East	90	0	10
South West	90	5	5
West Midlands	98	0	2
Yorkshire and Humberside	87	5	8
Wales	78	11	11

Table C.2- Acceptability of SIP construction by region

	Percentage response to the question "Would you buy a house built from this material?"		
Region	**Yes**	**No**	**Maybe**
East Anglia	61	9	30
East Midlands	57	8	35
London	54	14	32
North East	44	11	45
North West	43	16	41
South East	53	11	36
South West	69	6	25
West Midlands	63	7	30
Yorkshire and Humberside	68	11	21
Wales	44	11	45

Table C.3- Acceptability of ICF construction by region

Region	Percentage response to the question "Would you buy a house built from this material?"		
	Yes	No	Maybe
East Anglia	46	12	42
East Midlands	63	9	28
London	60	9	31
North East	45	22	33
North West	52	6	42
South East	48	7	45
South West	65	12	23
West Midlands	72	7	21
Yorkshire and Humberside	58	11	31
Wales	44	22	34

Table C.4- Acceptability of Prefabricated straw bale construction by region

Region	Percentage response to the question "Would you buy a house built from this material?"		
	Yes	No	Maybe
East Anglia	27	46	27
East Midlands	29	41	30
London	15	41	44
North East	22	45	33
North West	27	51	22
South East	27	42	31
South West	40	28	32
West Midlands	26	35	39
Yorkshire and Humberside	30	38	32
Wales	11	56	33

Table C.5- Acceptability of thin joint block work construction by region

Region	Percentage response to the question "Would you buy a house built from this material?" Yes	No	Maybe
East Anglia	81	3	16
East Midlands	74	2	24
London	68	6	26
North East	78	22	0
North West	80	2	18
South East	72	2	26
South West	76	5	19
West Midlands	91	0	9
Yorkshire and Humberside	70	8	22
Wales	67	11	22

Table C.6- Acceptability of timber framed construction by region

Region	Percentage response to the question "Would you buy a house built from this material?" Yes	No	Maybe
East Anglia	47	9	48
East Midlands	59	13	28
London	53	6	41
North East	78	11	11
North West	43	25	32
South East	48	12	40
South West	64	10	26
West Midlands	54	14	30
Yorkshire and Humberside	59	14	27
Wales	56	22	22

Numerical results to the question “Would your company use this method in construction?” from the construction industry survey can be seen in Table D.7

Table C.7- Percentage responses to the question “Would your company use this material in construction?”

Response	Brick and block	SIPs	ICF	Prefabricated straw bale	Thin joint block work	Timber frame
Yes	89	48	33	15	67	63
No	7	30	37	63	15	19
Maybe	4	22	30	22	18	18

Appendix D- Degree day data

Degree day data

The city selected for each region and the number of heating degree days used in calculations is shown in Table D.1.

Table D.1- Number of heating degree days for city in each region of England and Wales

Region	City	Number of heating degree days, base temp 18°C
East Anglia	Peterborough	3192.70
East Midlands	Leicester	3220.92
London	London	2824.94
North East	Sunderland	3290.48
North West	Liverpool	2987.29
South East	Brighton	2930.49
South West	Bristol	2968.24
West Midlands	Birmingham	3339.69
Yorkshire and Humberside	Leeds	3347.53
Wales	Cardiff	3049.68

Using a base temperature of 25 based on information produced by the WHO (1979) the number of cooling days required for the same locations is shown in Table D.2.

Table D.2- Number of cooling degree days for city in each region of England and Wales

Region	City	Number of cooling degree days, base temp 25°C
East Anglia	Peterborough	3
East Midlands	Leicester	1
London	London	2
North East	Sunderland	0
North West	Liverpool	1
South East	Brighton	0
South West	Bristol	0
West Midlands	Birmingham	1
Yorkshire and Humberside	Leeds	0
Wales	Cardiff	0

This low number of cooling days indicates it would not be viable to install cooling systems as there is such a small cooling requirement. In addition England and Wales do not have a history of installing cooling systems into domestic housing. Therefore energy requirements associated with cooling were not included in this work.

Appendix E- The typical house

The typical house

In order to determine benchmark values for the embodied energy and operational energy relating to wall materials it was necessary to generate the details of a typical house for the area of study.

The most common method of construction for England and Wales is brick and block. This was used for 88% of dwellings in England between 1990 and March 2009 (DCLG, 2010). Therefore, the typical house was considered to be built from a double skinned brick and block system.

The average area of the typical house was based on a weighted average of mean floor area for number of bedrooms combined with the percentage of houses built with each bedroom number. This calculation can be seen in Table E.1.

Table E.1- Weighted average calculation for floor area.

Type of house	Mean area (m2)	Percentage of completions 2009-2010	Area x percentage
1 bed	64.30	1	64.30
2 bed	71.20	10	712.00
3 bed	95.60	25	2390.00
4 bed	120.60	19	2291.40
		55	5457.70

Dividing the summed values of area multiplied by percentage, by the total percentage of completions represented by the table gives the weighted average floor area. The floor area used for the typical house was $99.23m^2$.

The typical house discussed by Monahan and Powell (2011) shows an aspect ratio in the region of 1:2. The value of dimension a was therefore set at 5m, giving dimension b a value of 9.923m; an aspect ratio of 1:1.98. This also accommodates recommendations by Chown (1999) which indicate that 5.0m is the limit for narrow fronted housing, with houses below this being difficult to successfully design internally.

Bungalows are considered separately in the data used; therefore two storeys were selected as the typical number. This is stated to be the typical number by Chown (1999) and reflects that case study used by Monahan and Powell (2011).

The height of each storey is based on data provided by Chown (1999). Recommended ceiling height is 2.4m; therefore 3.0m was used as storey height to allow sufficient space for the ceiling, floor joints and flooring.

Appendix F- Fitness function

```
function [singleobjective]=fn_fitness5b(v)


material = v(1);
a = v(2);


%   Evaluates singleobjective, reduces number of variables for
optimisation
%   process

%specify values that will not change during optimisation
    areatotal = 95.6;
    nostoreys = 2;
    hgtstoreys = 3;
    nodoors = 2;
    region = 2;
    buildingtype = 3;
    maxwindowpercentage = 25;
    doorsize = 2.42;
   % material = 1
   % a = 6500


%Calculate embodied energy, operational energy, acceptability,
airtightness

 %evaluate dimensions
        %a = a;
        am = a/1000;
        disp(a)
        b = (areatotal/nostoreys)/am;
        %disp(b)
        aspectratio = b/am;
        %disp(aspectratio)

 %evaluate total external wall area
        switch buildingtype
            case 1  % Detached
                totextwall = 2*(am*hgtstoreys*nostoreys) +
2*(b*hgtstoreys*nostoreys);
            case 2  % Semi-detached
                totextwall = 2*(am*hgtstoreys*nostoreys) +
(b*hgtstoreys*nostoreys);
            case 3  % Terraced
                totextwall = 2*(am*hgtstoreys*nostoreys);
        %disp(totextwall)
        end

 %evaluate window area
       twentypercentfloor = areatotal*.2;
       maxwindow = totextwall*(maxwindowpercentage/100)

  %evaluate door area
        doorarea = doorsize * nodoors;


  %evaluate net external wall area
```

```
    % if twentypercentfloor > maxwindow

     % netextwallarea = 10000000000;

         %windowarea = maxwindow;
    %else %windowarea =< twentypercentfloor;

        netextwallarea = totextwall - twentypercentfloor - doorarea;
      %end

%evaluate party wall area
      switch buildingtype
          case 1  % Detached
              partywallarea = 0;
          case 2  % Semi-detached
              partywallarea = (b*hgtstoreys*nostoreys);
          case 3  % Terraced
              partywallarea = 2*(b*hgtstoreys*nostoreys);
      %disp(partywallarea)
      end



 %evaluate embodied energy
      switch material
          case 1  % Brick and block
              embenergy = (netextwallarea * 744.3) + (0.5 *
partywallarea * 713.46);
          case 2  % SIPs
              embenergy = (netextwallarea * 1464.12) + (0.5 *
partywallarea * 834.77);
          case 3  % ICF
              embenergy = (netextwallarea * 1448.31) + (0.5 *
partywallarea * 1060.47);
          case 4  % Lime plastered straw bale
              embenergy = (netextwallarea * 458.61) + (0.5 *
partywallarea * 458.61);
          case 5  % Thin joint blockwork
              embenergy = (netextwallarea * 847.56) + (0.5 *
partywallarea * 739.92);
          case 6  % Timber frame
              embenergy = (netextwallarea * 946.45) + (0.5 *
partywallarea * 747.12);

        %disp(embenergy)
      end

 embenergym2 = embenergy/areatotal;

 %evaluate operational energy
      switch material
          case 1  % Brick and block
              uvalue = 0.277;
          case 2  % SIPs
              uvalue = 0.167;
          case 3  % ICF
              uvalue = 0.204;
          case 4  % Lime plastered straw bale
              uvalue = 0.190;
```

```
            case 5   % Thin joint blockwork
                uvalue = 0.272;
            case 6   % Timber frame
                uvalue = 0.249;
               %disp(uvalue)
        end

        switch region
            case 1   % East Anglia
                hdd = 3192.7;
            case 2   % East Midlands
                hdd = 3220.92;
            case 3   % London
                hdd = 2824.94;
            case 4   % North East
                hdd = 3290.48;
            case 5   % North West
                hdd = 2987.29;
            case 6   % South East
                hdd = 2930.49;
            case 7   % South West
                hdd = 2968.24;
            case 8   % West Midlands
                hdd = 3339.69;
            case 9   % Yorkshire and Humberside
                hdd = 3347.53;
            case 10 % Wales
                hdd = 3049.68;
          %disp(hdd)
        end

        openergy = (uvalue * netextwallarea * 24 * hdd )/ 1000;
        %disp(openergy)

        openergym2 = openergy/areatotal;

  %evaluate acceptability
  %public
        switch region
            case 1   % East Anglia
                acceptBB = 94;
                acceptSIP = 76;
                acceptICF = 67;
                acceptSB = 40.5;
                acceptTJB = 89;
                acceptTF = 71;
            case 2   % East Midlands
                acceptBB = 95;
                acceptSIP = 74.5;
                acceptICF = 77;
                acceptSB = 44;
                acceptTJB = 86;
                acceptTF = 73;
            case 3   % London
                acceptBB = 91.5;
                acceptSIP = 70;
                acceptICF = 75.5;
                acceptSB = 37;
                acceptTJB = 81;
                acceptTF = 73.5;
            case 4   % North East
```

```
            acceptBB = 85;
            acceptSIP = 66.5;
            acceptICF = 61.5;
            acceptSB = 38.5;
            acceptTJB = 78;
            acceptTF = 83.5;
        case 5  % North West
            acceptBB = 96;
            acceptSIP = 63.5;
            acceptICF = 73;
            acceptSB = 38;
            acceptTJB = 89;
            acceptTF = 59;
        case 6  % South East
            acceptBB = 95;
            acceptSIP = 71;
            acceptICF = 70.5;
            acceptSB = 42.5;
            acceptTJB = 85;
            acceptTF = 68;
        case 7  % South West
            acceptBB = 92.5;
            acceptSIP = 81.5;
            acceptICF = 76.5;
            acceptSB = 56;
            acceptTJB = 85.5;
            acceptTF = 77;
        case 8  % West Midlands
            acceptBB = 99;
            acceptSIP = 78;
            acceptICF = 82.5;
            acceptSB = 45.5;
            acceptTJB = 95.5;
            acceptTF = 69;
        case 9  % Yorkshire and Humberside
            acceptBB = 91;
            acceptSIP = 78.5;
            acceptICF = 73.5;
            acceptSB = 46;
            acceptTJB = 81;
            acceptTF = 72.5;
        case 10  % Wales
            acceptBB = 83.5;
            acceptSIP = 66.5;
            acceptICF = 61;
            acceptSB = 27.5;
            acceptTJB = 78;
            acceptTF = 67;
    end

   switch material
        case 1  % Brick and block
            acceptpublic = acceptBB;
        case 2  % SIPs
            acceptpublic = acceptSIP;
        case 3  % ICF
            acceptpublic = acceptICF;
        case 4  % Lime plastered straw bale
            acceptpublic = acceptSB;
        case 5  % Thin joint blockwork
            acceptpublic = acceptTJB;
```

```
            case 6  % Timber frame
                acceptpublic = acceptTF;
               %disp(acceptabilitypublic)
       end

      %industry
       switch material
            case 1  % Brick and block
                acceptindustry = 91;
            case 2  % SIPs
                acceptindustry = 59;
            case 3  % ICF
                acceptindustry = 48;
            case 4  % Lime plastered straw bale
                acceptindustry = 26;
            case 5  % Thin joint blockwork
                acceptindustry = 76;
            case 6  % Timber frame
                acceptindustry = 72;
               %disp(acceptindustry)
       end

%evaluate airtightness

        switch material
            case 1  % Brick and block
                airtightness = 4.5;
            case 2  % SIPs
                airtightness = 1.0;
            case 3  % ICF
                airtightness = 1.0;
            case 4  % Lime plastered straw bale
                airtightness = 0.86;
            case 5  % Thin joint blockwork
                airtightness = 4.0;
            case 6  % Timber frame
                airtightness = 5.00;
               %disp(airtightness)
        end

%evaluate wall thickness

        switch material
            case 1  % Brick and block
                wallthickness = .346;
            case 2  % SIPs
                wallthickness = .326;
            case 3  % ICF
                wallthickness = .449;
            case 4  % Lime plastered straw bale
                wallthickness = .480;
            case 5  % Thin joint blockwork
                wallthickness = .346;
            case 6  % Timber frame
                wallthickness = .295;
               %disp(wall thickness)
        end

 %evaluate fire performance
```

```
        switch material
            case 1  % Brick and block
                fireperformance = 240;
            case 2  % SIPs
                fireperformance = 73;
            case 3  % ICF
                fireperformance = 90;
            case 4  % Lime plastered straw bale
                fireperformance = 135;
            case 5  % Thin joint blockwork
                fireperformance = 180;
            case 6  % Timber frame
                fireperformance = 60;
               %disp(fireperformance)
        end


%specify weighting for elements

    WEE = 1; % weighting for embodied energy
    WOE = 1;% weighting for operational energy
    WAP = 1; % weighting for public acceptability
    WAI = 1; % weighting for industry acceptability
    WAir = 1; % weighting for air tightness
    Wthickness = 1; % weighting for wall thickness
    Wfire = 1; % weighting for fire performance


%specify benchmark values for normalisation. Average values used,
%alternatively use British Regulation values.
%Switch functions used to apply correct value for building type

 switch buildingtype
            case 1  % Detached
                benchmarkee = 11580;
            case 2  % Semi-detached
                benchmarkee = 7328.7;
            case 3  % Terraced
                benchmarkee = 3076.9;
        %disp(benchmarkee)
 end

        switch buildingtype
            case 1  % Detached
                benchmarkoe = 33.3156;
            case 2  % Semi-detached
                benchmarkoe = 20.468;
            case 3  % Terraced
                benchmarkoe = 7.6203;
        %disp(benchmarkee)
        end
    benchmarkair = 10;
    benchmarkwt = .346;
    benchmarkf = 60;


%evaluate single objective value. Aim for this value to be as low as
%possible indicating best option

%Apply constraint
```

```
      if twentypercentfloor > maxwindow

      singleobjective = 10;

      else %windowarea =< twentypercentfloor;

         singleobjective = (WEE*(embenergym2/benchmarkee)) +
(WOE*(openergym2/benchmarkoe))...
    - (WAP*(acceptpublic/100)) - (WAI*(acceptindustry/100)) +
(WAir*(airtightness/benchmarkair)) + ...
  (Wthickness*(wallthickness/benchmarkwt)) -
(Wfire*(fireperformance/benchmarkf));
      end



end
```