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The renovation of period timber-frame buildings in Southwest France

An environmental assessment of insulation materials and techniques for exterior timber-frame walls

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Abstract

In order to combat climate change and cut CO_2 emissions, the French government has instigated an ambitious renovation programme aimed at the thermal insulation of the existing housing stock. This will have a considerable effect on the renovation of period timber-frame houses, a fragile architectural heritage that in certain regions of France forms a considerable part of historic villages and town centres.

This study focuses on vernacular timber-frame buildings with brick or daub infill in SW France, and assesses the environmental impact of thermal renovation of exterior timber-frame walls. For the building assessment the French Excel-based tool, Cocon (2009) is used, which is linked to two French databases for life cycle analysis of building materials, Inies (2009) and Grecau (2009). Besides the environmental impact assessment, which is reflected by the scores for embodied energy, embodied carbon and resource depletion, Cocon also assesses the thermal performance by including parameters for thermal resistance, decrement delay and thermal inertia. For each of the 20 wall types in this study Cocon calculates an overall score based on these six parameters. The selection of wall types and insulation techniques discussed here is based on the outcome of interviews with builders, architects and building experts.

The impact assessment of the thermal insulation of 20 exterior timber-frame walls shows that the ‘conventional’ wall types with interior insulation (often mineral wool and plasterboard) generally have the worst overall scores. The highest scores are amongst the wall types with exterior insulation, because these make better use of thermal mass, which is an important parameter in the assessment. The wall with exterior woodfibre board insulation has the best overall score, due to its low embodied energy and good use of thermal mass. However, in most cases exterior insulation is not appropriate for conservation reasons, and interviewees say that keeping the exterior timbers and bricks (or rendered daub) exposed is an absolute priority.

Several wall types with insulation by ‘plant fibre and binder’ (e.g. earth& straw) also show good results. These natural materials are very compatible with the vernacular timber-frame walls and are an appropriate solution when exterior insulation is not desired for aesthetic reasons. Several so-called ecological solutions that do not perform well in the assessment are hempcrete, cellulose and insulation clay blocks.

An important conclusion from the study is that most builders are not specialised in restoration of historic buildings and therefore lack the necessary skills and knowledge about appropriate insulation materials and techniques. Furthermore there is lack of technical information on ecological building materials, reflected by a lack of official recognition. However, there is growing scientific evidence that natural and breathable materials are better for the environment, the building and the occupant. Further case studies and surveys are needed to demonstrate that current insulation techniques are not appropriate for the restoration of historic timber-frame buildings and can put these at risk.

Acknowledgements

Above all I would like to thank Luc Floissac, researcher at GRECAU Toulouse, and developer of the building assessment tool Cocon. Furthermore I thank all the people that participated in the interviews, and Mr. Gironnet, Architecte de Bâtiments de France, who kindly spoke to me on the phone. Many thanks also to my tutor, Melissa Taylor, for her help throughout the course. Thanks to Angela Thymides for proof reading the English text, and to Jean-Yves Brud for letting me print the necessary copies of the present study.

Timber frame house with wattle& daub in ruins (H.Valkhoff)

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List of abbreviations

BBC	*Bâtiments basse consommation*
EC	Embodied carbon
EE	Embodied energy
EPD	Environmental product declaration
FU	Functional unit
GHG	Greenhouse gas
HQE	*Haute qualité environnementale*
LCA	Life cycle analysis
RH	Relative humidity
RNE	Renewable energy
RT	*Réglementation Thermique*
VCL	Vapour control layer
VOC	Volatile organic compound
ZPPAUP	*Zone de protection du patrimoine architecturale, urbaine et paysager*

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Chapter 1 Introduction

1.1 Timber-frame heritage

The Southwest of France, and especially the area around Toulouse, has a tradition of earth building and brick architecture due to the abundance of clay in the region. The regional capital Toulouse is called *la ville rose*, named after its light red fired bricks that are characteristic of the architecture. Many of these Toulousian style buildings in the towns and villages of Midi-Pyrenees are timber-frame houses with brick infill (Fig.1). Besides the typical timber-frame facades with brick infill, one still can find all forms of earth building in the area, from daub, to cob, to adobe and rammed earth (Marcom, 2009). And many vernacular timber-frame buildings do not have the fancy brick work of the Toulousian or Albigensian town houses.They were built by peasants and craftsman from cheap materials such as timber and wattle and daub. Although a lot of these buildings were demolished in the 20th century, they still represent a considerable part of the building stock in many town centres in the region (Béa, 2009).

Fig. 1 *Typical timber-frame with brick infill in Albi (H.Valkhoff)*

This architectural heritage of vernacular timber-frame is very fragile and hardly protected in France (Béa, 2009). After the war, with the introduction of modern building materials, a lot of damage was done to these buildings, e.g. in the sixties and seventies through the use of cement renders (Marchal, 2009). Today these are largely replaced by 'breathable' lime renders. However, another threat seems to come from thermal insulation, which in the vast majority of cases is achieved by interior insulation with glasswool and plasterboard. Often insulation does more damage than good to timber-frame houses (Cuquel, 2009). 'Again we are ruining these buildings', says Collart (2009).

The French government has recently announced that it will combat climate change by a new refurbishment programme, whereby the number of energy-saving renovations will increase rapidly (JO, 2009). The French housing sector has to cut its greenhouse gas (GHG) emissions by 38% in 2020 (JO, 2009). More than 20 million dwellings will have to be renovated and insulated by 2050 (FFB, 2009-a). The ambitious Plan Bâtiment will be explained in the Literature Review, chapter 2.

1.2 Research question

In this context it is interesting to find out what the current renovation and insulation techniques for timber-frame buildings are. Is it true that a lot of renovations are badly done, with inappropriate materials, such as plasterboard and mineral wool? And do modern insulation techniques cancel out the vernacular qualities of these historic buildings, e.g. thermal mass and breathability? And do these insulation materials put timber-frame buildings at risk, e.g. through interstitial condensation? If so, are there more appropriate ways of insulating timber-frame houses in an environmental and energy-efficient way, without compromising the building fabric?

The research question is: How to renovate historic timber-frame buildings in SW France up to modern insulation standards, while preserving the environment and the vernacular qualities of the building, and reducing the embodied energy and embodied carbon?

The main objective of the French refurbishment task is to rapidly upgrade the thermal performance of the existing housing stock to better insulations standards (RT, 2007)[1]. Section 2.2 tries to assess what this ambitious energy saving policy means for historic buildings, and for timber-frame houses in particular. To be able to sketch a general diagnostic and show the urgency of the present situation several interviews were held with builders, architects and conservation experts. Firstly, to find out what the main problems are with period timber-frame buildings, e.g. humidity, decay, dry lining and energy-efficiency, and secondly to find out which renovation and insulation techniques and materials are currently used. Chapter 3 (Methods) will explain how the questionnaires were designed and how a group of ten interviewees was selected.

1.3 Assessment of different wall types

To assess the environmental impact of different renovation techniques the French building assessment tool Cocon (2009)[2] is used. This Excel-based software is linked to two major French databases with data for building products based on life cycle analysis (LCA). LCA calculates the environmental impact of all the energy and material flows in a production process Several LCA methods and their limitations will be explained in chapter 2. Different LCA databases can give different data for the same materials, depending on weighting methods, system boundaries and

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[1] La Réglementation Thermique des bâtiments existants (2007)

[2] CO_2CON, Comparaison de solutions Constructives, de Confort et d'émissions de CO_2

production processes. Transparency is therefore crucial and should allow for continuous checking of calculation methods.

Chapter 3 (Methods) explains why Cocon (2009) was chosen for this study. One of the reasons is that Cocon gives a transparent overall score for building elements based on six parameters (*see* 3.2.2). Besides this overall score Cocon gives the scores and values for the most important impact categories for our study : embodied energy and embodied carbon.

Like most building assessment tools Cocon is designed to look at the building as a whole, including operational energy use. However, assessing an entire building would require precise information from several case studies, which to my knowledge is not available. The focus of the study is on different renovation techniques for exterior timber-frame walls, and instead of looking at a whole building the assessment will compare a relevant number of wall types that show a good range of insulation materials and techniques. The aim of the assessment is not to compare case studies or pilot projects, but to present a more generally applicable model that helps to define the most appropriate insulation techniques for period timber-frame walls. Therefore the focus of the study is on building materials and embodied energy and not on 'operational' energy consumption.

1.4 Growing importance of embodied energy

Today most of the energy use and related GHG emissions in buildings are operational, and mostly due to heating (Ademe, 2006)[3]. At present roughly 10% of the energy used in buildings is associated with the embodied energy (EE) in materials (Gielen, 1997; Harris and Borer, 2005; Berge, 2009). The EE is the total primary energy consumed in a product's life cycle (Hammond and Jones, 2008). However, as we move towards highly insulated buildings, embodied energy and embodied carbon (EC) of building materials will become a major part of a building's energy use and GHG emissions (Harris and Borer, 2005). In more energy-efficient buildings the proportion of EE in the total energy consumption could well exceed 50% (Gielen, 1997).

Chapter 2.3 will explain the different calculation methods for EE and EC, and shows there is no scientific consensus on how to include renewable energy and the benefits of carbon storage.

In renovation projects the 'added' EE is generally not as high as in new build, because the majority of materials are already there and can be repaired or re-used, to a certain extent. However, demolition, building waste and use of new materials in renovation can have a considerable impact on the environment. Especially as the renovation market is rapidly growing and already represents 45% of the French construction market (Céquami, 2009).

Besides the environmental impact parameters used in Cocon, chapter 2 (Literature Review) will outline several other indicators. The most important building physics parameters, thermal resistance and thermal mass, are included in the assessment. Other parameters, e.g. airtightness, thermal bridging and vapour control, require simulation software and are therefore not included in the assessment. However, they are discussed in the context of existing literature and brought back into the Discussion in chapter 5.

Chapter 4 (Results) shows the outcome of the assessment per parameter, and the results per wall type are in Appendix IV.ii, including the exact cross-section of the 20 wall sections. Chapter 5 (Discussion) will analyse the results and put them in the wider context of existing literature. Important aspects that are more difficult to quantify and therefore left out of the assessment, e.g. health and indoor air quality, are also included in the Discussion. The Conclusion, (chapter 6) will examine the wider implications of the study for the construction industry. It will also discuss the limitations of building assessment tools, as well as areas for further research.

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[3] In 2003: heating 70 %, l'USE (electricity and appliances) 13 %, hot water 10,5 %.

1.5 Appropriate materials

Aspects that are hard to quantify, but crucial to the assessment, are the architectural beauty and the vernacular qualities of timber-frame buildings. Besides their aesthetic qualities these buildings, which are characterised by their natural hygroscopy and 'breathability' and the use of thermal mass, teach us about traditional techniques and materials. The study will clarify whether the use of natural and 'breathable' materials is appropriate and improves the energy-efficiency of these buildings (May, 2006).

Interviews and existing literature in chapter 5 (Discussion) will point out how important the conservation issue is, not only from an aesthetic point of view, but also from a building physics angle. The assessment and study of traditional building techniques and materials teaches us about the use and compatibility of contemporary materials, both conventional and ecological.

This is also the reason why the word 'renovation' is used instead of 'restoration'. The assessment does not only focus on vernacular materials which bring the building back into its original state, it also introduces innovative materials such as woodfibre board and insulation clay blocks that are 'more' or 'less' compatible with historic buildings. Furthermore, it is not certain that ecological materials will necessarily score well in the assessment, or that conventional materials will score badly. The assessment looks at a whole spectrum of qualities that make materials and techniques appropriate or not.

Fig. 2 *Renovated timber-frame house in Puylaurens (H.Valkhoff)*

Chapter 2 Literature review

2.1 Introduction

In the past few years a vast amount of literature has become available on the environmental impact of building materials. Many books focus on ‘low impact’ building, e.g. Woolley et al. (1997), Berge (2009) and Oliva (2008). Scientific articles by Thormark (2006), Miller (2001) and Morel (2001) look at the embodied energy (EE) of materials and conclude that this is of growing importance with buildings become more energy-efficient. Thormark (2006) looks at the EE of materials with a different recycling potential. Morel (2001) shows the positive effect on the EE by using local bulk materials, such as earth, and Miller (2001) looks at the contribution of transport to the EE of building materials.

Van Dam (2005) and Cornillier and Vial (2008) analyse the environmental performance of renewable, plant-based materials. Borjesson and Gustavsson (2000) and Upton et al. (2008) analyse the GHG mitigation potential of timber products through carbon sequestration. Renewable materials can store carbon through carbon dioxide that plants absorb during photosynthesis. Carbon storage in buildings can make a significant contribution to the reduction of GHG emissions from the construction industry (Valkhoff, 2009). However, section 2.3.3 shows that there is no scientific consensus on what to include in calculations of embodied carbon (EC).

Most of the literature and assessment tools focus on new buildings. Current studies of rehabilitation tend to focus on ‘operational’ energy saving and do not include embodied energy (MP, 2004). Studies of refurbishments with ecological materials, e.g. RAPPE (Floissac et al., 2008)[4], are under-represented, and most publications on period timber-frame are in the realm of building conservation. The articles of the Building Conservation Directory discuss restoration techniques - such as repair of wattle and daub by Pritchett (2001), or the repair of earth buildings by Bouwens (1997) - but rarely study the environmental aspects. There are few publications on the environmental impact of renovation techniques used for timber-frame houses. Organisations like CAUE[5] are waiting for studies like the current assessment (Cuquel, 2009).

It is therefore hard to present an extensive literature review on the subject of this assessment. The main text book literature used in the study, e.g. Berge (2009), Courgey and Oliva (2007) and Oliva (2008), focuses on the impact of building materials in general. However, many of the findings are also applicable to the renovation of timber-frame walls. Oliva (2008) gives several examples of appropriate and inappropriate renovation techniques and Bevan and Woolley (2008) mention hempcrete as an appropriate material for restoration.

Furthermore there is a vast amount of literature on lifecycle analysis (LCA) and the impact of building materials on climate change. Several European databases, e.g. Ecoinvent (2009), Oekobilanzdaten (KBOB Ecobau, 2009), ICE (Hammond and Jones, 2008), INIES (2009), provide data on lifecycle inventories, based on the international norm ISO 14040-44 (2006). However, figures for EE and EC from different sources tend to vary a lot (Harris and Borer, 2005). Even studies that comply with the international ISO standard show significant differences in methodology, with different weighting and system boundaries, leading to different results (Hammond and Jones, 2008).

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[4] The RAPPE report assesses the refurbishment of an old Toulouse style house (not timber-frame) and compares exterior insulation with polystyrene and with woodfibre board.

[5] CAUE, Conseil d’Architecture, Urbanisme et Environnement.

Because this study uses two databases for building products, INIES (2009) and Grecau (2009), section 2.3 will outline the possibilities and limitations of LCA. Section 2.4 will briefly explain the importance of several building physics parameters. But first it is necessary to outline the current French building and renovation context. Section 2.2 will give an overview of the national refurbishment task and tries to assess the consequences for the stock of historic timber-frame buildings in SW France.

Fig. 3 *Unrecognisable timber-frame building in Mirepoix (H.Valkhoff)*

2.2 The French refurbishment task

In 2009 the French parliament voted through a vast package of new environmental legislation, known as Grenelle 1 (JO, 2009)[6]. The government wants to cut the French GHG emissions by a factor 4 by 2050. One of the major plans in the package is the Plan Bâtiment, that sets the new targets and legislation for the construction industry. It contains a large section devoted to the refurbishment of the existing housing stock (JO, 2009). The housing sector in France is responsible for 43% of the primary energy consumption and 25% of the CO_2 emissions (Bourru, 2009). It will have to cut its GHG emissions by almost 40% in 2020 (JO, 2009). More than 20 million dwellings will have to be renovated and insulated by 2050, the cost of which is estimated to be more than 10 billion euros (FFB, 2009-a). The state has set a yearly target from 2013 of 400.000 renovations per year (JO, 2009). Targets for maximum energy consumption in existing buildings are set at 90 kWh/m²/year (Ademe, 2009), though the BBC Rénovation standard sets the target at 80 kWh/m²/year (Effinergie, 2009)[7].

In 2007 the economic activity in the renovation sector was estimated at 60.5 billion euros and represented 45% of the French construction market (Céquami, 2009). According to Céquami (2009) 40% of the renovation market concerns individual houses which are mostly renovated by small businesses with less than 10 employees[8]. But for a total number of 9 million renovations per year only 200.000 (4.5%) are satisfactory from an energy saving point of view (Inforénovateur, 2009).

To help individual house owners, the Plan Bâtiment provides several financial incentives, e.g. the 'eco loan' at 0% interest for major renovations, and tax breaks for thermal insulation and renewable energy technologies. The national confederation of craftsmen and small building companies, CAPEB (2009)[9], published a guide for builders to help them and their clients choose the right renovation techniques and insulation materials. According to CAPEB (2009) and Ademe (2009) 20-25% of the heat loss in new build is through the walls (Fig.4). Though one cannot simply extrapolate these proportions to renovation projects, this gives an indication of the importance of wall insulation.

Fig. 4 *Proportion of heat loss through different parts of the building fabric (CAPEB, 2009)*

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[6] The Grenelle de l'Environnement was a national debate on climate change and the environment that president Sarkozy and the ministry of Ecology and Sustainable Development organised in 2008 (JO, 2009).

[7] BBC, Bâtiment Basse Consommation.

[8] 60% of the renovations of individual houses are done by *artisans* (crafsmen), of which 70% have small businesses with less than 10 employees (Inforenovateur, 2009).

[9] CAPEB, La Conféderation de l'Artisanat et des Petites Entreprises de Bâtiment.

A large part of the rehabilitation task is coordinated by Cerqual[10], which supervises the renovation and energy certification of the existing housing stock built after 1948 (Cateret, 2009). The main focus, however, is on the blocks of flats built in the 1960s and 1970s. For the more dispersed stock of individual houses built before 1948, the national renovation programme NF Maison Rénovée starts in 2010 (Céquami, 2009)[11]. This programme aims at providing a national certification for the quality of renovation, with three levels of environmental performance: 'basic, effective and very effective', with the latter being equivalent to the HQE[12] and the BBC Renovation label. However, Céquami (2009) does not seem to make any distinction between architectural characteristics and building periods, and despite the huge refurbishment task nobody seems to know exactly what this implies for the large stock of historic buildings (Gironnet, 2009).

L'habitat ancien - 'old housing' before 1948 - represents roughly 10 million dwellings, which is one third of the existing housing stock (MP, 2004).The architectural qualities of this old stock are largely unknown (Marchal, 2009). To address these issues the national conservation organisation, ANVPAH[13], organised a workshop and a conference on sustainable development and energy saving in historic buildings (ANVPAH, 2009). And to fill the gap the government has commissioned a national survey of the energy consumption in houses built before 1948 (CETE, 2009)[14].

An earlier study showed a considerable discrepancy between the real energy consumption in old houses, which is relatively modest with an average of 168 kWh/m^2/year, and the outcome from computer simulations (MP, 2004). Case studies of 10 buildings showed the inadequacy of computer models in representing the heterogeneity and thermal qualities of the old housing stock (Marchal, 2009). Furthermore, the building physics of old houses built with traditional materials are very different from those built after 1948, and not as well understood (MP, 2004).

A study on architectural heritage (*patrimoine*) by CAPEB (2007) shows that 80% of the restoration projects in France are for non-listed buildings, for which in only 25% of the cases an architect gets involved. More than two thirds (67%) of the restoration projects concern individual houses, and despite the fact that there are no specific regulations for these non-listed buildings, their renovation requires a specific know-how (CAPEB, 2007). The craftsmen with the necessary restoration skills are generally much older, which makes the transfer of this know-how an important and urgent issue (CAPEB, 2007). Maisons Paysannes (MP, 2009) has created a 'skills resource centre' to collect and transfer this knowledge before it completely disappears.

At present it is impossible to get reliable data on the number and characteristics of historic timber-frame houses in SW France. Although period timber-frame is an important part of the old housing stock in Midi-Pyrenees and elsewhere in France[15], there is no regional of national inventory (Gironnet, 2009). However, from a small inventory in 12 towns and villages in the Tarn, Béa (2009)

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[10] Certification Qualité Logement (Cerqual), like Céquami is part of the CSTB and the certifying association Qualitel.

[11] Certification Qualité en Maisons Individuelles (Céquami), like Cerqual is part of the CSTB and the certifying association Qualitel.

[12] HQE Haute Qualité Environnementale – a national label for 'environmental' construction and renovation that assesses buildings according to 14 environmental criteria (Association HQE, 2009).

[13] ANVPAH, Association Nationale Villes et Pays d´Art et d´Histoire.

[14] BATAN, Opération Bâtiment Ancien.

[15] Departments of the region of Midi-Pyrenees, except for Les Landes which is in the Aquitaine region.

estimates that a third of the buildings in the town centres are historic timber-frame, though it is difficult to extrapolate. This heritage, which is typical for the Tarn and other departments of SW France, has suffered a lot of damage (Béa, 2006). Only very few timber-frame buildings in the region are listed as historical monuments, e.g. in Albi there are only two (Béa, 2009). Furthermore, Béa (2006) has not analysed the thermal performance of these houses, which was not the aim of the inventory.

Fig. 5 *Timber-frame with render onto daub in Mirepoix (H.Valkhoff)*

2.3 Life cycle analysis, embodied energy and embodied carbon

2.3.1 LCA: different methods and weighting

Life cycle analysis (LCA) identifies the total material and energy flows used to produce, transport and dispose of a building material or element, from ‘cradle to grave’, i.e. from the extraction phase, through all the production stages to the ‘end-of-life’ or waste disposal (Floissac, 2009-c). Haas (2002) believes LCA should consider the whole cycle, i.e. from cradle to grave and back to cradle again. To analyse the impact of a product most LCA studies use the ‘midpoint’ method, which quantifies the impact of material and energy flows for several impact categories, as defined by e.g. CML-2, one of the most widely used methods for characterisation[16]. Table 2.1 (next page) shows the LCA impact categories for the French Environmental Product Declarations (EPDs)[17] used in INIES (2009).

The ‘end point’ method is less common and looks at the damage energy and material flows do to ecosystems and human beings, by also taking qualitative parameters, such as biodiversity and human health into account (Ademe, 2008).

For each functional unit (FU) the LCA defines the life time of the product(s) and the quantities of materials (in kg) and primary energy (in MJ) needed to produce 1m^2 of building element. The system boundaries define what exactly is included in the inventory: additional materials and accessories (e.g. wrapping, nails, mortar, etc.); product waste and losses; maintenance, repairs and replacements during a product’s life time; and final waste caused at the ‘end-of-life’ stage (INIES, 2009). System boundaries also define if all transport stages from ‘cradle to grave’ are included, i.e. from the place of extraction to the factory gate, to the building site, and finally to the landfill, recycling centre or incinerator. The French EPDs include all transport stages, including ‘gate to site’ (INIES, 2009).

Generally capital goods and labour are not included in LCA (Haas, 2002). These include buildings, machines, offices, vehicles, tools, human resources, cleaning and other logistics. When capital goods are not included this may result in missing 30% of the environmental impacts (PRé Consultants, 2008). Therefore in the bigger databases, like Ecoinvent and USA Input Output, capital goods now are included (PRé Consultants, 2008).

The problem with all LCA is that the weighting method is rather arbitrary (Haas, 2002). Most databases, such as the Green Guide to specification (BRE, 2009-a) and INIES (2009) use the ‘panel method’, by which a panel of experts is asked to give an ‘impartial’ weighting of the impact categories. A BRE study shows that a ‘non-expert’ weighting by a cross-section of the population gives a totally different outcome (Hamilton et al., 2007).However, this did not stop BRE (2009) from only using the outcome of the expert panel as the official weighting for the Green Guide.

Other weighting methods are the ‘distance to target method’ which weighs the impact categories for set targets, e.g. for emission reduction. The Dutch assessment tool Milieuclassificatie Bouwproducten (NIBE, 2008) uses the ‘environmental cost’ method, which converts the environmental impact of different categories into external costs. NIBE (2008) also includes veto scores for undesired products such as tropical hardwood or PVC.

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[16] CML, Centrum voor Milieuwetenschappen Leiden, University of Leiden.

[17] FDES, Fiche de Déclaration Environnementale et Sanitaire.

Table 2.1 *Environmental impact per category for $1m^2$(80mm) of glasswool (INIES, 2009)*

Environmental impact	Total value life cycle / FU per year	Total value life cycle / FU per life time	Unit
Resource depletion	0,000169	0,00845	kg antimony equivalent
Total primary energy use	0,713	35,65	MJ
Energy use renewable	0,043	2,15	MJ
Energy use non-renewable	0,67	33,5	MJ
Water consumption	0,334	16,7	L
Solid waste (energy re-used)	0,00229	0,1145	kg
Hazardous waste	0,000339	0,01695	kg
Non-hazardous waste	0,0193	0,965	kg
Inert waste	0,00105	0,0525	kg
Radioactive waste	0,00000482	0,000241	kg
Climate change	0,0228	1,14	kg CO^2 eq.
Atmospheric acidification	0,000139	0,00695	kg SO^2 eq
Air pollution	3,4	170	m^3
Water pollution	0,00469	0,2345	m^3
Destruction of stratospheric ozone	Zero		
Photochemical ozone creation	0,0000101	0,000505	kg ethylene eq

2.3.2 Embodied energy data

The Introduction already pointed out that at present most of the energy use in buildings is 'operational' and due to heating and cooling. However, as buildings become more energy-efficient, EE will become the major part of a building's energy consumption (Harris and Borer, 2005; Gielen, 1997). Therefore the choice of materials with a low EE and a high potential for carbon storage is becoming increasingly important (Berge 2009).

The ecobuilding sector started to focus on EE in the 1970s, but since the growing importance of climate change, EE has become a concern for the whole construction industry. Woolley et al. (1997) defined the four leading principles of 'green' building as follows:

1. **reducing energy use;**
2. **minimising external pollution and environmental damage;**
3. **reducing embodied energy and resource depletion;**
4. **minimising interior pollution and health damage.**

To minimise the EE of a building one uses low impact and renewable materials that are locally sourced, and recycled or re-used (Woolley et al., 1997). Renovation and refurbishment, instead of new-build, also reduces the EE.

Fig. 6 *EE for three wall types in new build in kWh/m^2 (Marcom, 2008)*

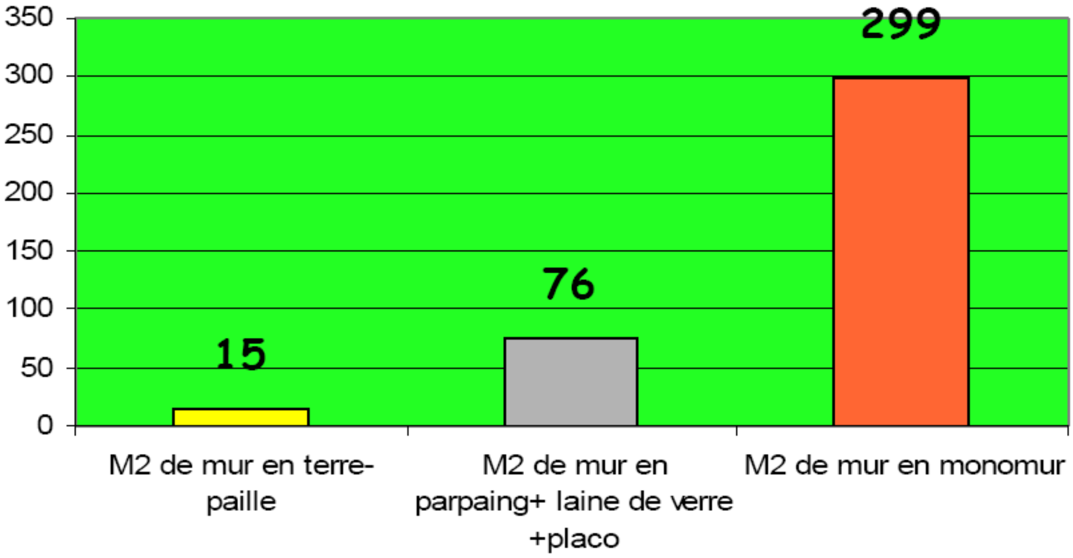

***Fig 6.** It is interesting that the so-called 'ecological' monomur (insulation clay bricks) has a higher EE than the traditional breeze block with mineral wool (299 vs. 76kWh). The earth&straw wall has by far the lowest EE. In this example the earth&straw wall is 40cm thick (300kg/m^3 density), giving a R-value of 3.6* m^{2}K/W; *the standard breeze block wall is insulated with 12cm glasswool (R=3.1), and the monomur is 37.5cm thick (R=2.7).*

Calculations of EE are complex and despite the international norm, ISO 14040-44, there is no political or scientific consensus on what should be included in the figures. The INIES database (2009) follows the French norm (NF P01-010) for EPDs. This defines an overall primary energy calculation divided into process energy (energy used during production), and 'material' or 'feed stock' energy (the combustion energy stored in the material). These are again divided into renewable and non-renewable energy (Table 2.2).

Table 2.2 *Types of energy in French EPDs (INIES, 2009)*

Total Primary Energy (E_p) *in MJ/m^2*	Process Energy		Feedstock Energy	
	Renewable	Non-renewable	Renewable	Non-renewable

Cornillier and Vial (2008) argue that it does not make sense to take the sum of these four types of energy to calculate the total primary energy (E_p), because the environmental impacts of different types of energy are not the same. The feedstock energy in wood is renewable and has not the same impact as the feedstock energy in plastics or other petrol derivatives such as PVC or insulation foams, which are non-renewable. However, in INIES (2009) they are calculated in the same way. Materials from mining and excavation (metals and minerals) do not contain combustion energy (except radioactive elements) and are therefore not allocated feedstock energy.

Cornillier and Vial (2008), Réseaux Ecobâtir (2009) and Floissac (2009-b) believe that the primary energy calculations in INIES are biased against plant-based materials. They think it is more realistic to use primary energy figures without feedstock energy, as is the case in the draft text for the European norm. According to Cornillier and Vial (2008) this only takes process energy into account, leaving out the feedstock energy which is already accounted for in other impact categories.

2.3.3 Embodied carbon, recarbonation, carbon storage

Embodied carbon (EC) of materials is measured in kg of CO_2 equivalent, reflecting how much CO_2 gives an equivalent global warming effect over 100 years. It is based on a GWP-100 (Global Warming Potential), defined by the Intergovernmental Panel on Climate Change (IPCC, 2007). For the calculation of EC of building materials there is often uncertainty about data because GHG emissions largely depend on the fuel mix used by the factory (Hammond and Jones, 2008). Because of the different fuel mix it is problematical to compare product data from different countries. In France, where 75% of electricity is of nuclear origin, energy-intensive industries (e.g. aluminium) would cause less CO_2 emissions than in countries where electricity is generated from coal or gas (Cornillier and Vial, 2008). However, a proper comparison should take the whole life cycle of nuclear energy and electricity into account, including construction, reprocessing, transport, storage of waste, and decommissioning.

Furthermore many LCAs do not fully take recarbonation of lime binders into account. Recarbonation of hydraulic binders (lime and cement) happens during the drying process, when CO_2 is re-absorbed from the air (Holmes, 2009). In theory pure limes, or 'air limes', are carbon neutral, meaning that in the full lime cycle they reabsorb up to a 100% of CO_2 emitted during the burning of the calcium carbonate, though it is hard to find reliable figures on recarbonation. Bevan and Woolley (2008) say that all the CO_2 emissions from burning limestone can be reabsorbed. The industry gives figures of 90% recarbonation for hydraulic lime renders and mortars (St Astier, 2006). Berge (2009) estimates recarbonation is 25% for concrete, 50% for cement renders and 80% for hydraulic lime renders (measured over 50 years).

Another aspect of measuring embodied carbon is that renewable materials fix CO_2 and store carbon. One kilogram of dry plant matter contains about 0.5 kg of carbon, which corresponds with 1.8 kg of CO_2, sequestered from the atmosphere through photosynthesis (Berge 2009). Storing carbon 'buys time' for combatting climate change, since the carbon locked in the buildings will not be released back into the atmosphere before the building decays (Berge, 2009). Assuming that the plant matter extracted is again replanted this will increase the overall stock of plant-based materials in the economy (Berge, 2009). At the end of the building's life renewable materials can be reused or are still available as an energy source (Harris, 2009).

Nowadays one reads many claims for renewable materials storing *x* number of tonnes of carbon or CO_2 in a building. According to Harris (2009) an average timber-frame house can store around 4 t CO_2. Berge (2009) believes a 120 m^2 house can store 32 t CO_2, using a relatively low timber ratio of 150kg/m^2. Boutin et al. (2006) find the net carbon sequestration of a 26cm hempcrete wall is 35 kg CO_2eq per m^2 (GWP-100). Marcom (2008) shows a earth&straw wall stores 52 kg CO_2eq per m^2.

In many LCAs carbon sequestration is not fully included because at present there is no scientific consensus (Cornillier and Vial, 2008). Because of the complexity of the argument the ICE database does not include carbon storage (Hammond and Jones, 2008). The authors quote Amato (1996) saying that the inclusion of carbon sequestration only makes sense in a wholly sustainable 'steady state' of production and consumption, meaning that all timber and plant fibre materials used in building are also replanted, which may not be the case.

Numerous studies show how difficult it is to assess the mitigation effects of carbon sinks and carbon storage. Borjesson and Gustavson (2000) conclude that the mitigation efficiency of carbon storage depend on the length of forest rotations, and will be higher for the first rotation and decrease with following rotations. Upton et al. (2008) found remarkable differences in carbon sequestration rates for different forests in the US. Therefore, the net carbon balance of renewable materials is part of a complicated ecology, depending on whether they are produced in sustainable forestry and agriculture (Valkhoff, 2009).

The main controversy regards carbon storage is about what happens at the 'end-of-life' stage[18] :

1. ***incineration*, releasing CO2, with or without energy use and carbon capture;**
2. ***landfill or decomposition,* releasing methane with or without capture and energy use;**
3. ***recycling*, causing fewer emissions, depending on the recycling process;**
4. ***reuse*, no emissions yet, a possibility of stocking carbon for some time again.**

Some LCA specialists argue that the ISO-14040 norm should follow the 'carbon neutral' method, which means carbon storage is not taken into account because the carbon stored in a plant is released later in its life cycle, either as carbon dioxide when incinerated, or as methane when decomposed (Cornillier and Vial, 2008). Despite the controversy carbon storage is becoming rapidly recognised as an important issue. The French timber federation, FCBA, systematically includes carbon storage in its product declarations for INIES (FFB, 2009-b). Databases like Ecoinvent (2009) and Grecau (2009) take carbon storage into account. And the British Standards Institute has developed a common standard for carbon footprints, PAS-2050, which includes carbon sequestration (BSI, 2008).

2.3.4 LCA: review and comparison

Though INIES has its standards committee[19], the product declarations are rarely peer reviewed or analysed by an independent expert (Floissac, 2009-b). Because of the high cost of LCA, industries often choose to combine several products and make 'generic' EPDs (Réseaux Ecobâtir, 2009). And because most producers of 'ecological' materials cannot afford LCA there is a lack of environmental

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[18] This list is based on several sources, e.g. EST (2009).

[19] Conseil de Surveillance, part of the Direction Générale de l'Urbanisme de l'Habitat et de la Construction (DGUHC) of the Ministry for Ecology, Energy, Sustainable Development and the Sea.

information for these products (Réseaux Ecobâtir, 2009). Hempcrete was, besides timber, one of the first ecological building materials for which a full LCA was completed (Boutin et al., 2006). And Grecau (2009) and Areso (2009)[20] are working on a LCA for unfired earth bricks. There is also a LCA on hemp batts and sheepswool insulation (Murphy and Norton, 2008). An interpretation of the data from this study by May and Newman (2008) shows that Isonat hemp batts have a much better carbon balance than Rockwool (EC = 0.35 kg CO_2eq/m^2, compared to 1.2 kg CO_2eq/m^2)[21].

Despite the limitations of LCA and different methodologies, it can be interesting to compare data from different sources and databases. A comparison of INIES data for insulation materials with the Swiss database Oekobilanzdaten gives striking differences (Table 2.3). Oekobilanzdaten (KBOB Ecobau, 2009) figures for EE are on average 1.5 times higher (Réseaux Ecobâtir, 2009). Another example is the comparison of industry data for mineral insulation with the internationally renowned database Ecoinvest (2009), *see* Fig.7, p.25.

When comparing LCA data from different sources one should always be aware of the different methodologies, system boundaries and weightings. Therefore, for each building assessment tool, based on LCA data, one has to carefully analyse these calculations. The product data in Grecau and INIES are a lot more transparent than those in the Green Guide (BRE, 2009-a), and therefore easier to verify. Appendix III.ii gives a further comparison of data from different sources, explaining the limitations of data used in the assessment tool Cocon (2009).

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[20] ARESO, Association Régionale d´Ecoconstruction du Sud-Ouest.

[21] Note that the EC of Isonat is particularly high in this case, because of its high density (35kg/m2) and the fact it is imported from France (Murphy and Norton, 2008).

Table 2.3 *Comparison of glasswool data from INIES (2009) with Oekobilanzdaten (2009)*

Glasswool batts	Width mm	Density kg/m³	Thermal conductivity W/mK	Total Primary Energy MJ/m² INIES	Total Primary Energy (extrapolation) MJ/m² OEKOBILANZ	Ratio OEKOBILANZ : INIES
TP 216 revêtu kraft	100	19	0,037	51,5	92	***1.79***
TP 238 revêtu kraft	100	30	0,032	96,5	145,2	***1.50***
TI 212 revêtu kraft	100	12	0,04	38,5	58,1	***1.50***
Isoconfort 32	100	11	0,04	82,5	53,24	***0.65***
Isoconfort 38	100	11	0,04	49,7	53,24	***1.07***
Classic 040	100	11	0,04	31,3	53,24	***1.70***
GR 32 Nu	100	26	0,032	95,3	125,84	***1.32***
Glasswool P1052	100	30	0,032	96,2	145,2	***1.51***
Monospace 35 contact	100	18	0,035	72,5	87,1	***1.20***
Glasswool 20/M00021	100	11	0,04	19,5	53,24	***2.73***

(source : Réseaux Ecobâtir, 2009)

Fig. 7 *Comparison of glasswool data from Knauf and from Ecoinvest for LCA impact categories*

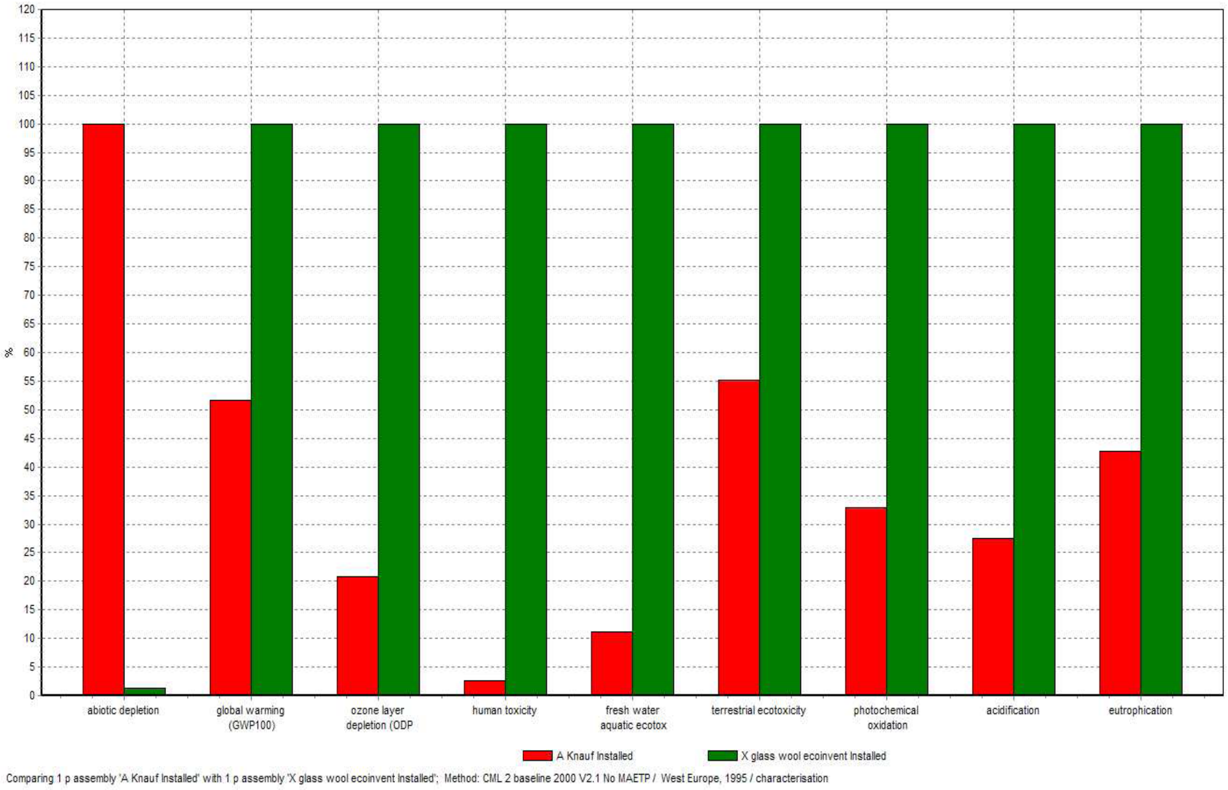

Fig. 7 *shows that for the same functional unit and LCA impact categories industrydata (red) can differ considerably from independent data (green). Only for abiotic resource depletion are the Knauf data (red) much higher; for all the other impacts the Knauf data are 50% or more lower than those of Ecoinvest (2009). The Ecoinvest data are based on a European study of 12 glasswool factories (Murphy and Norton, 2008).*

2.4 Building physics parameters

The use of R-values alone, as indicators for thermal performance, is inadequate (May and Newman, 2008). An assessment of thermal performance should also include other indicators, such as airtightness, thermal bridging, thermal mass, and hygroscopy or breathability. R-values are measured in a research lab, in a dry and steady state, which in real buildings rarely exists (Bevan and Woolley, 2008). Research by Evrard and Herde (2005) shows how dynamic thermal performance can be very different from steady state situations, where hemp walls perform better than one may expect from simple R-values, due to thermal mass, hygroscopy and lack of thermal bridging (Bevan and Woolley, 2008).

2.4.1 Thermal mass and inertia

The use of thermal mass is one of the main design principles of bioclimatic architecture (Courgey and Oliva, 2007). Traditionally daub and brick-filled timber-frame buildings have a reasonably high thermal mass, not only in the walls but also in the earth floors for all storeys of the house. However, with modern renovation techniques, aimed at insulation and building with light-weight materials, timber-frame buildings lose all their thermal and hygroscopic qualities (Interviews, 2009). Insulation is mostly aimed at increasing thermal comfort in winter, but often reduces thermal comfort in summer through diminishing thermal mass (MP, 2004). Given the hot dry summers in SW France, and the high diurnal temperature changes, thermal mass is an important factor in energy-efficient renovation. Thermal mass will be more effective with exterior insulation which increases both the decrement delay (‘summer comfort’) and thermal inertia (Floissac, 2009).

Thermal admittance or inertia ($Wh/m^2.K$) is the ability of a material or building element to exchange heat when subject to variations in temperature, e.g. over a 24-h period (McMullan, 2007). Courgey and Oliva (2007) define thermal inertia as the product of thermal capacity and thickness (S.d). Thermal capacity (S) is the product of density (*p*) and specific heat capacity (C) ($S= p.C$, in $Wh/m^2.K$). Heavy weight materials such as stone and concrete have a high specific heat capacity and therefore a high thermal mass or inertia (Table 2.4). The greater the thermal inertia, the smaller the temperature swing in the building (McMullan, 2007).

However, there often is confusion regards what is meant by thermal inertia and decrement delay. The latter indicates the thermal response, i.e. the number of hours between the highest outdoor and the highest indoor temperature, and is often called ‘summer comfort’. A light-weight roof will typically have a decrement delay of 2 hours, whereas a more heavy-weight roof using insulation materials with a higher density can have a decrement delay of 10 hours or more (May and Newman, 2008).

Thermal inertia, also called sequential inertia, is a more long-term effect of thermal mass which is harder to achieve (Floissac, 2009-a). The French Réglementation Thermique (RT, 2005) defines three classes of inertia: hourly (1 hour), daily (24 hours) and sequential (12 days). The daily inertia corresponds with decrement delay. To achieve sequential thermal inertia requires a lot more thermal mass, which also allows a building to stock solar energy in the winter for several days (Courgey and Oliva, 2007). *See* Appendix III.i for the calculation of thermal inertia in Cocon.

Table 2.4 *Thermal inertia of different walls* (Courgey and Oliva, 2007)

Wall section	Thermal inertia (Wh/m2.K)
35 cm Earth or daub wall (1900 kg/m^3)	275
25 cm Brick wall (2300 kg/m^3)	163
20 cm Concrete wall	128
20cm Timber wall (pine)	60/44
OSB wall with 10 cm woodwool (250kg/m^3)	30/20
Plasterboard wall with 10 cm glasswool	8

2.4.2. Thermal bridges and airtightness

In a period timber-frame house all exterior sections of studs, joists, floors and wall plates are potential thermal bridges. Measuring thermal bridging for separate building elements, e.g. in the case of this assessment, does not make much sense, as most thermal bridging occurs between elements (wall, roof, floors, windows). Whereas u-values measure the 'repeating' heat loss through thermal bridges, y-values give the heat loss of all 'non-repeating' thermal bridges, which is typically much higher (May and Newman, 2008). For example a new timber-frame house can have a repeating thermal bridge of 8%, whereas when all non-repeating thermal bridges (corner studs, wall plates, openings, floors) are included the total thermal bridging will be 30% (May and Newman, 2008). Better insulation often increases non-repeating thermal bridging, because of concentrating the heat loss. The same problem arises for achieving airtightness in period timber-frame buildings. Without a degree of airtightness insulation is pointless (May, 2005)[22]. However, Gironnet (2009) wonders if one should even try to achieve airtightness in buildings that are meant to 'breathe'. This shows there is much confusion on the subject, and therefore the next section will discuss the complicated relationship between airtightness and 'breathability'. As we try to improve airtightness and thermal performance, breathability has become a critical issue (May, 2005).

2.4.3 'Breathability'

Whether to use vapour barriers or vapour control layers (VCLs) to avoid interstitial condensation is a big debate in the ecobuilding industry (Collart, 2009). Oliva (2008) maintains that most VCLs are badly applied and therefore increase the problem of condensation. The condensation is concentrated in the areas where the VCL is not airtight and where the damage is worse than if it was spread out over the whole wall or envelope. Thermal bridges act as catalysts and also become 'vapour bridges' (Oliva, 2008). Another consequence of the VCL is that it obliges the builder to install a mechanical ventilation system to get rid of humidity (Oliva, 2008). Furthermore the VCL stops the wall from breathing and acts as a barrier to the capillary action in the wall, by which the wall seasonally dries out through evaporation of excess humidity on the warmer side (Oliva, 2008). In winter this is normally the inside, in summer the outside.

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[22] May refers to the CIBSE Guide to building services for historic buildings (2002), costs 84£ for non-members.

It has been long understood by building conservationists how important it is to have ‘breathable’ materials in historic buildings (May, 2006). Breathability is the result of three important physical qualities : vapour permeability, hygroscopicity and capillarity (May, 2005). Ecobuilders and conservationists tend to look for other means of moisture control, e.g. ‘hygroscopic buffering’, which is traditionally used in timber-frame and earth buildings. This buffering effect is particularly useful in kitchens and bathrooms where intermittent production of steam is absorbed to be released later (Padfield, 1998). Therefore a ‘breathing’ wall is made of materials that are hygroscopic, ‘capillary’ and vapour-open, with an increasing permeability towards the exterior so water vapour can easily migrate (Oliva, 2008).

As a rule of thumb the breathing wall has 5 times the vapour resistance (μ=g/m^{2}s.P)[23] on the warm (in)side than the cold (out)side (Harris and Borer, 2005). In the UK this 1:5 rule has been included into the code of practice BS 5250 (2002). In order to achieve this it is important that the exterior (lime) renders have a very low vapour resistance, which is generally the case for air limes (CL), but not for all hydraulic limes (NHL), especially when they are made waterproof with a hydrofuge (Oliva, 2008). Consequently the interior layer should have a much higher vapour resistance, e.g. cork, or plasterboard with cellulose coating. Although Cocon does not quantify breathability, the issue is discussed in chapter 5.

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[23] In the UK vapour resistance (r) is measured in MNs/gm. On the continent vapour resistivity is measured as a ratio of still air (μ=1). To get the European unit μ one has to divide the UK unit r by 5 (May, 2005).

Chapter 3 Methods

This chapter will explain why the French building assessment tool Cocon(2009) was used to compare the environmental impact of different renovation techniques for period timber-frame. Section 3.1 explains the working of Cocon and compares it to other assessment tools. The following section on data gathering (3.2) first explains how the interviews were held (3.2.1), and then points out the limitations of the LCA data used in Cocon (section 3.2.2 and 3.2.3).

Note that due to the word limit a large part of the data comparison in section 3.3.3 'Lack of data and extrapolation' is in Appendix III.ii.

3.1 Cocon: assessment of timber-frame walls

3.1.1 Building assessment tools

Cocon is an Excel-based software package for the environmental impact and energy assessment of buildings and building materials. It was developed by Grecau[24], the combined research lab for the School of Architecture of Toulouse and Bordeaux (Floissac, 2009-a). Like other building assessment tools, such as Envest-2, Elodie, Bilan Produit or NIBE Milieuclassificaties Bouwproducten[25], it assesses the impact of building materials for several environmental impact categories, e.g.

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[24] GRECAU Groupe de Recherche Environnement Conception en Architecture et Urbanisme, Laboratoire de l'Ecole Nationale Supérieure d'Architecture de Toulouse et de Bordeaux.

[25] Envest2 (BRE, 2004), Bilan Produit (Ademe, 2008), Milieuclassificaties Bouwproducten (NIBE, 2009); Elodie (CSTB, 2008).

embodied energy, climate change, and resource depletion. The data for these impact categories come from LCA databases.

The main databases Cocon uses are INIES (2009) and Grecau (2009). INIES (2009) contains the French industry's Environmental Product Declarations (EPDs)[26]. Grecau (2009) has its own database which, besides the INIES data, contains data for ecological materials from various European sources, e.g. Oekobilanzdaten im Baubereich (KBOB Ecobau, 2009).

The main reasons for using Cocon are that it uses French databases and insulation standards, and that besides the environmental impact parameters it includes two thermal performance parameters assessing the short and long-term effects of thermal mass. The fact that Cocon has been developed by Grecau, which is based in Toulouse (the area of the survey), made it possible to make this study part of the continuous updating and refining process of the assessment tool.

Comparable French tools, e.g. Elodie (CSTB, 2008) and Bilan produit (Ademe, 2008) are less appropriate for this study for several reasons. Bilan Produit is Excel based and uses the Swiss Ecoinvest (2009) database, but is not only for building products. Elodie is designed for the construction industry and uses data from INIES (2009), but does not contain additional information on ecological materials, which Grecau (2009) does. In Elodie one can only compare products and building elements, not a whole building. Furthermore the interface of Elodie is not very user friendly, whereas Cocon is Excel based, which makes it easier to present data in translated format, i.e. English (note that the main three French tools are solely in French).

The British counterpart, Envest-2 (BRE, 2009-b) uses data from the Green Guide to Specification, which to date remain fully untransparent (May 2008). The Green Guide only gives summary ratings for building elements, based on Ecopoints, and does not show the individual impacts of the materials (BRE, 2009-a). The impact assessment is only useful and transparent when LCA data are presented with their true values and units, which is the case in INIES (2009) that besides the full LCA study puts a summary sheet with the impact categories on-line (*see* Table 2.1). Cocon is largely based on INIES and is therefore a lot more reliable and transparent than its BRE counterpart.

3.1.2 Parameters and impact categories

Building performance parameters

Cocon takes three building physics parameters into account: thermal resistance, decrement delay and thermal inertia. The R-value of building elements and materials is compared with French insulation standards, such as the Réglementation Thermique (RT, 2005)[27] and the label for low energy buildings, BBC Rénovation (Effinergie, 2009). One can also choose other energy standards, e.g. Passive House, but these are not appropriate for renovation.

The other two parameters give an indication of the thermal mass, which will have a positive effect on evening-out temperature peaks in summer and allow 'storage' of passive 'solar gain' in winter. The decrement delay parameter is also called 'summer comfort', and indicates the time lag (in number of hours) between the highest outdoor and the highest indoor temperature. The thermal inertia parameter measures 'sequential inertia' (in kJ/m^{2}K), a more long-term storage effect of thermal mass, for which it is harder to achieve a good score (*see* 2.4.2).

Cocon also allows one to calculate the overall inertia for an area or a room (*zone d'inertie*) which, however, is not in the scope of the assessment. Soon there will be Cocon compatible software

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[26] FDES, Fiche de declaration environnementale et sanitaire.

[27] RT-2005 is used in Cocon, though there is a special insulation standard for existing buildings, RT-2007.

available, Parois Respirantes, that measures the risk of condensation in different parts of the building envelope (Floissac, 2009-d). A parameter that Cocon does not take into account is thermal bridging, which requires simulation software.

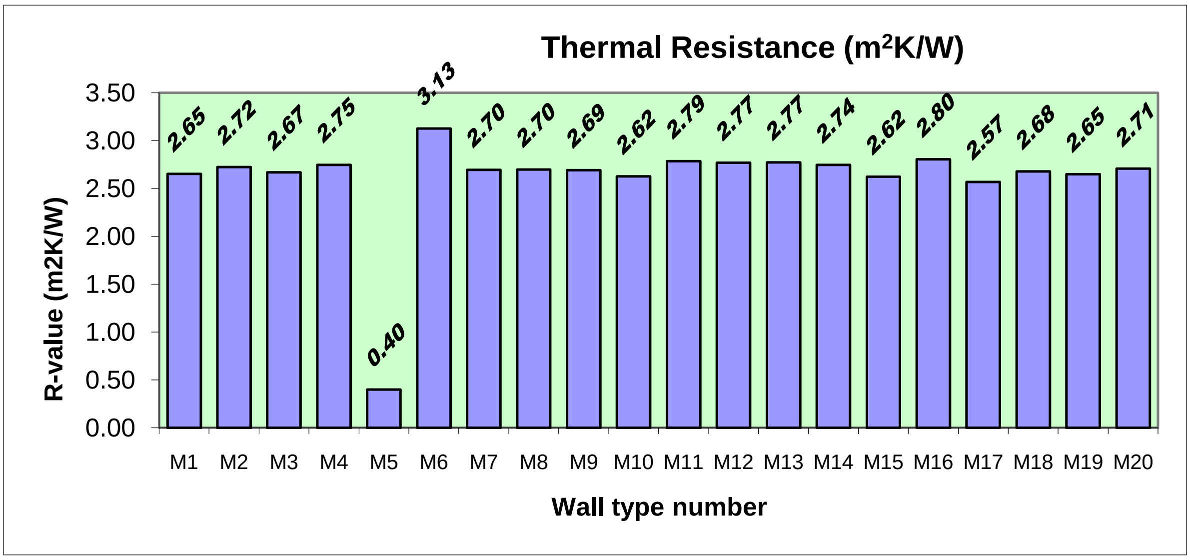
Most builders interviewed for this study leave a cavity of 4cm or 5cm between the outside wall and the insulation material, which should be fully ventilated to allow humidity to escape, but often is not. When fully ventilated the cavity will have a negative effect on the thermal performance. When not ventilated at all a cavity this wide, even when completely airtight, (which often is not the case), hardly increases the insulation value of the wall. In the assessment of the conventional wall types (M1-M6) we considered a non-ventilated air gap of 4 cm ($\lambda = 0.23$) a reasonable average.

Environmental impact parameters

Although Cocon shows the values for impact categories commonly used in LCA, it only uses three environmental parameters. The most interesting for this study are embodied energy (EE), measured in kWh/m^2, and embodied carbon (EC) or climate change, measured in kg CO_2eq/m^2. Though resource depletion is an important category. It is measured in kg equivalent of antimony (kea), but harder to quantify and therefore is more difficult to interpret its score (*see* Appendix III.i).

The functional unit in LCA is usually one square metre of building element for a certain life time (50-100 years). To be able to compare the environmental impact of wall sections made from different materials it is better to compare functional units with a similar thermal resistance. In this study an average R-value of approximately 2.7 (m^{2}K/W) was chosen, based on the RT (2007) and the average of 8cm of mineral wool that builders said they used (Fig. 8).

Fig. 8 *Thermal Resistance for walls M1-M20*



To achieve a similar R-value to other insulation materials than glasswool sometimes requires adding an extra cm of material. Cocon allows for any thickness, although not all sizes are available on the market. E.g. 9 cm of woodwool is not common, it is sold in 8 or 10cm, and some builders use 7.5cm of glasswool instead of 8cm. The main argument, however, was to be able to compare wall sections with similar insulation values for the same functional unit. The exceptions are M5, the uninsulated daub wall, with a very low R-value, and M6, the Monomur (insulation clay bricks) which comes in blocks 30cm thick, with a high R-value.

Life time

In most LCAs the life time of the building materials for the functional unit, given by the industry, is between 50-100 years. In the *option* sheet in Cocon one can choose between the ‘linear’ and the ‘rounded’ calculation method, which defines the number of replacements of certain elements which have a life time that is shorter than the life time of the whole building. In this study the linear method is used, which is more precise (*see* Appendix III.i). When one considers a given life time for a material which is too long one can change this in Cocon, and when there is no official LCA for a material the life time is estimated by Grecau (2009). Obviously the life time plays a major role in the overall environmental impact of a building element. Another important factor is the ‘end-of-life’ of a product, which defines what will happen with the material once it has to be replaced. Will it be reused, recycled, incinerated or sent to landfill? (*see* §2.2).

Comparison of wall types

This study does not look at a building as a whole, but compares the impact of different exterior wall types used in renovation of period timber-frame. Therefore the comparison of the wall types was kept as uniform and ‘simple’ as possible, and the functional units do not include windows, doors, or other openings. The selection of the materials in the cross-section of the 20 different wall types is partly based on the outcome of the interviews. They are divided into four categories (Table 3.1).

Table 3.1 *Four categories of wall types in the survey*

Wall types	*Number*
I. Conventional wall types with interior wall insulation : using ‘conventional’ renovation and insulation techniques and materials, generally ‘doubling’ with mineral wool and plasterboard or clay blocks.	M1 - M5
II. Ecological wall types with interior wall insulation : using ‘ecological’ renovation and insulation techniques and materials; e.g. ‘doubling’ with woodwool, cork or cellulose, and fermacell or clay blocks.	M6 – M10
III. Ecological wall types with plant fibre and binder : using ‘ecological’ renovation and insulation techniques and materials; making ‘solid’ walls with an added interior layer of plant fibre and mineral binder, e.g. hempcrete and earth&straw.	M11 – M15
IV. **Wall types with exterior wall insulation :** using both conventional and ecological insulation techniques and materials; insulating from the outside, e.g. cladding.	M16 - M20

Based on the calculations for the six parameters Cocon calculates an overall score for the wall types (Table 3.2). The same can be done for other sections of the envelope, i.e. interior walls, floors, roof, etc. The overall score for a building element is based on the individual scores for each of the six parameters (*see* Appendix III.*i.* for thresholds). The weighting coefficient for each category is 1.0, but can be altered by the user to put extra weight on one or two of the parameters.

The summary tables give the overall score for the wall section, and the values and scores for the six parameters. An example is shown in Table 3.2. (for all the summary tables *see* Appendix IV.ii). It also gives the volume and the weight of the building element and shows the part that is ‘biosourced’, i.e. made of renewable materials derived from plant-based sources. The carbon tax is based on the value for EC, using a price of 17€ per ton of CO_2 set as a target in the draft carbon tax bill by the French government (Floissac, 2009-a).

Table 3.2 *Scores and values for six parameters, wall type M1 (brick, glasswool, plasterboard)*

Summary Table *M 1*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Weight 'bio sourced'
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
8.5	**177.5**	**8.2**	**39.7**	**7.4**	**0.0281**	**10.3**	**47.4**	**207.6**	**23**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Volume 'bio sourced'**
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^3/m²*	*m^3/m²*	*%*
0.67 €	**2.65**	**13.6**	**5.7**	**9.5**	**24**	**1.9**	**0.030**	**0.355**	**8**

Table 3.3 *Wall section with layers of materials*

M1 Brick, glasswool, plasterboard	Source	Width	State
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Bricks (1450 -1500 kg/m^3) λ=0,550	GRECAU	10	
Lime render (1550 kg/m^3) λ=0,700	GRECAU	3	
Cavity 40 mm λ=0,230	GRECAU	4	
Glasswool batt IBR NU 80 mm (11 kg/m^3) λ=0,040	INIES	8	
Plasterboard Placodur BA13 (990 kg/m^3) λ=0,250	INIES	1.3	
Wall paint AQUARYL SATIN (1360 kg/m^3) λ=1,600	INIES	1 u	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130	GRECAU	3	existing
Metal frame for plaster board (19 kg/m^3) λ=0,141	GRECAU	1 u	

Each building element or wall type contains different layers of materials (in cm or as units), and is always calculated from exterior to interior. The table with the wall sections also shows which database is used for each specific material (Table 3.3).

*For an overview of all the individual summary tables and wall sections, **see Appendix IV.ii.***

Accessories

The timber-frame itself (studs, plates, joists and other beams) is not accounted for in the assessment and therefore added as 'accessories'. This means the timber is not included in the calculations for thermal performance. In most cases the original timbers are kept or reused, and not replaced, which means they are considered 'existing' and therefore not included in the environmental impact assessment either. When bricks or daub are reused or left in place as infill one considers them 'existing' as well. Again this means they are not included in the environmental impact assessment, though they *are* included in the thermal calculations because they are not considered accessory. Other accessories, e.g. metal or wood frames for boards and infill are excluded from the thermal calculations, though they are included in the environmental impact assessment because they are considered 'new'. Note that in column *State* only 'existing' will be indicated, thus all other materials are considered by default as new (Table 3.3). Small items and accessories, e.g. screws, nails, hooks, straps, glues, silicon, mortars, etc. are only accounted for when they are included in the EPDs in INIES (2009), but are not accounted for in Grecau (2009). A general rule is that they are only included in LCA when their weight represents more than 1% of the functional unit (Haas, 2002).

Renewable energy

There is a possibility in Cocon to choose between 'with' or 'without' renewable energy (RNE). The reason for including RNE in this assessment is that most data are based on EPDs in INIES (2009) which include renewable energy, despite the fact this is controversial (*see* 2.3.2). The problem with the primary energy data in Grecau (2009) is that often there are no specific data available on renewable or non-renewable energy. This can lead to zero scores on embodied energy (EE), simply because Cocon uses 0.00 when there are no data.

3.2 Data gathering

3.2.1 Interviews

A series of ten interviews was held with professionals in the regional building trade to find out what the current renovation and insulation techniques are for period timber-frame, which helped to define the different wall types in the assessment. Recorded interviews of 25 minutes were held amongst a pre-selected group of 5 builders, 2 architects, 1 building expert, 1 conservation expert and 1 supplier of 'ecological' materials (*see* next chapter, Table 4.1). The aim of this small sample was to get a feel for the regional context and make sure the research question is pertinent and relevant to what is happening in the field. To find out what the main problems are – humidity, decay, problems with dry lining, energy-efficiency – and to find out which techniques and materials are currently used. The stratified sample was large enough to answer the specific questions, without it being statistically representative.

Appointments were made, and all interviewees were visited to avoid sending out questionnaires and obtaining a limited response. For practical (and environmental) reasons the interviews were held in a radius of 50km around Puylaurens, in the departments of the Tarn and Haute-Garonne (Midi-Pyrénées). All builders interviewed are specialised in renovation - *not* restoration - and mostly work for their own small companies of between 1 and 10 employees. As seen in section 2.2 the majority of renovations of individual houses are done by *artisans* (craftsmen) in very small companies (Céquami, 2009).

Based on the guidelines set by Gillham (2005) a semi-structured list of questions was developed, with a mix of 25 closed and open questions (Appendix IV.i). The questionnaire was divided into three main categories: 1.*renovation techniques* 2.*insulation techniques* 3.*ecobuilding and materials*. The questions in the first two categories were designed to select the different wall types for the assessment. The third category of questions was formulated to find out about possible barriers to 'eco renovation'. The questionnaire for the two CAUE consultants was different, and their answers were not coded but used as citations in the text. All the other answers to the questionnaires were coded following the guidelines by Gillham (2005). The tables with the coding are in chapter 4.2 and Appendix IV.i.

Appendix IV.i also contains an example of the questionnaire and an extensive written account of the interviews, based on the transcriptions translated from French to English. A summary of this account is given in chapter 5.2. The majority of the interviews were recorded and are available (in French) in WAVE format on the CD that is included. This CD also contains the transcripts in French and the two Excel workbooks of Cocon used for the assessment.

3.2.2 Databases and data checking

Both the database of Grecau (2009) and the building assessment software, Cocon (2009), are largely based on LCA data from the official French database for building materials and products, INIES (2009). INIES was developed in 2004 by the Direction of Urbanism, Housing and Construction (DGUHC), Ademe, AFNOR and CSTB[28]. It is comparable with the Green Guide to Specification (BRE, 2009-a), although INIES does not provide overall scores or ratings for building elements. Also INIES (2009) puts all the available EPDs on-line, including the whole LCA studies. It also provides a summary of the environmental impacts categories (*see* 2.3).

Most French LCA studies use the software TEAM (Ecobilan, 2009). This is accredited by the Association HQE (2009). Like most LCA-based databases, INIES (2009) largely provides information on conventional industrial materials, such as concrete, cement, mineral wool, PVC, polystyrene and Kingspan, and hardly contains 'eco products'. This is one of the reasons why ecobuilding organisations in France, e.g. Réseaux Ecobâtir (2009), are very critical of INIES. And though the INIES data are a vast source of information, one has to read the EPDs very carefully for each product to know which steps in the production processes are included, i.e. which system boundaries are applied and which weighting methodology is used.

For the time being Grecau (2009) and Cocon have to rely on more general sources for most eco products for which there simply are no LCAs. These sources give an estimation of embodied energy (EE) and embodied carbon (EC), e.g. Oekobilanzdaten (KBOB Ecobau, 2009) and Oliva (2008). Or they consist of industry data from producers, e.g. Claytech, Pavatex, Warmcel, Fermacell, etc. In this study other notable European sources on EE and EC were used for comparison, e.g. Berge (2009), Oekobilanzdaten (KBOB Ecobau, 2009) and the British database ICE (Hammond and Jones, 2008), *see* Appendix III.ii. Unfortunately BRE does not give the raw LCA data on which the overall scores in the Green Guide (BRE, 2009-a) are based. For an example of why it impossible to use the Green Guide for cross-referencing, see Appendix III.ii.

Despite its limitations, INIES is a good starting point and at present probably the most reliable French database for building products. However, for all the wall types in the assessment it was necessary to have a close look at the data and references for the chosen materials, to check whether the Grecau and INIES data in Cocon were correct, up to date, and apt for use in this assessment. In cooperation with Floissac (2009-a) this led to some refinements in Cocon and some modifications and updates in the Grecau database.

For example the thermal conductivity (λ) for hemp in Grecau was based on old sources. More recent sources, e.g. Bevan and Woolley (2008) and Oliva (2009) give a lower λ of around 0.10 (W/m.K), now used in Cocon. This puts up the thermal resistance and therefore the overall score of hemp and lime in the assessment. Furthermore, the weighting of thermal inertia seemed rather high in Cocon, leading to very low scores, even for walls with exterior insulation. To adjust this small imbalance the upper limit of the inertia parameter was lowered from 300 to 250 (Floissac, 2009-a). Another refinement considered the data for timber, based on new EPDs, which now take carbon sequestration fully into account (FFB, 2009-b).

Inevitably, the databases are constantly refined and updated, and every new EPD is immediately integrated into Grecau (2009). It is crucial that the LCA data as well as the extrapolation from other sources are accessible and fully transparent, which is not always the case (*see* 2.3 and Appendix III.ii).

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[28] DGUHC La Direction Générale de l'Urbanisme, de l'Habitat et de la Construction (Ministère de l'Ecologie, de l'Energie, du Développement durable et de la Mer) ; ADEME Agence de l'Environnement et de la Maîtrise de l'Energie; AFNOR Association Française de la Normalisation;CSTB Centre Scientifique et Technique du Bâtiment

3.2.3 Lack of data and extrapolation

LCA studies are expensive and according to Floissac (2009-a) cost around 10.000 euro, so it is difficult for smaller producers to provide such data. Even bigger industries work together with their competitors on ‘generic’ LCAs for INIES (2009). In many combined EPDs, therefore, the industry uses averages for a number of similar products made in slightly different shapes, weights and dimensions. In these cases, e.g. for fired bricks, it is hard to get a clear picture of the energy mix used in a specific factory or to get a clear idea of real transport costs.

At present INIES (2009) barely covers very common building materials, such as fired bricks, lime mortars, wood cladding, etc. Simply because the industry has not provided EPDs on these products yet. So far there are only two types of fired clay bricks in the database, both hollow bricks (clay blocks), which are most common in France. There are no data on plain fired bricks, which have to be calculated by extrapolation (*see* Appendix III.ii).

The main problem with data for lime renders and mineral mortars in Grecau and INIES is that they do not take recarbonation into account (*see* 2.3.4). This explains the relatively high share of the renders in the total EC for most wall types in the assessment (*see* Ch. 4 and 5).

As mentioned earlier, for sawn timber and wood cladding the extrapolation in Grecau has recently been updated (Floissac, 2009-a). Due to the controversial LCA methodology in INIES, which includes feedstock energy, the wood and timber figures show a rather high EE, though they do take carbon storage into account (*see* 2.3.2). The cork data in Grecau (2009), for which there is as yet no EPD, are still not satisfactory and show huge differences for products with similar densities (see Appendix III.ii).

For a more detailed account of choices and extrapolations in the assessment, see ***Appendix III.ii****.*

Chapter 4 Results

4.1 Introduction

The interviews clearly demonstrated the current techniques for renovation of period timber-frame buildings in Midi-Pyrénées. The outcome was used to select the 20 wall sections included in the assessment (*see* Table 4.4). The wall types are divided into 4 categories : *conventional* , *ecological plant fibre and binder* and *exterior insulation* . The comparison is between the same functional units of 1m^2 of wall with similar R-values (*see* 3.2).

The terms 'conventional' and 'ecological' are indicative. 'Conventional' refers current industrial building techniques which are also common in renovation. 'Ecological' implies the use materials and techniques that have a low impact on the environment. This does not mean that conventional materials and techniques always have a much higher environmental impact. They can even have a low embodied energy (EE), e.g. glasswool, while providing good thermal insulation which both are beneficial for the environment, though there may be negative impacts such as pollution, toxicity and health risks (*see* 5.2.6). On the other hand, ecological materials and techniques, such as the 'monomur' or hempcrete, can have a high EE (and EC) and therefore do not perform well in the assessment.

The assessment is largely based on *quantitative* criteria, reflected by the scores and values of the six parameters (Table 4.4). Section 5.3.6 will discuss the more *qualitative* criteria of which the impact is more difficult to quantify, e.g. health, indoor air quality, re-use, availability of skills, labour intensity, and heritage.

*For an overview of all the scores, see Table 4.4. For the individual summary tables and wall sections, see **Appendix IV.ii.***

4.2 Interviews and coding

A series of ten interviews with builders and building experts was held to find out what the main renovation techniques are (*see* 3.2.1). The response was very satisfactory, all people contacted were eager to participate in the survey. The builders are all specialised in renovation - *not* restoration - and mostly work for their own small companies of between 1 and 10 employees (Table 4.1).

Table 4.1 *List of interviewees*

Name	*Trade*	*Town (department)*
A. Mr.Alexandrov	General builder (renovation)	En Bonhoure (81)
B. Mr.Bonnet	General builder (renovation)	Puylaurens (81)
C. Mr.Parro	General builder (renovation)	Saint Germain (81)
D. Mr.Douze	Eco builder (carpenter)	Sorèze (81)
E. Mr.Drouilleau	Supplier eco building materials	Dourgne (81)
F. Mr.Floissac	Researcher (Grecau)	Toulouse (31)
G. Mr.Collart	Architect	Verfeil (31)
H. Mr.Marcom	Eco builder (mason)	Lanta (31)
I. Mme. Cuquel	Architect (CAUE)	Albi (81)
J. Mme. Béa	Conservation expert (CAUE)	Gaillac (81)

The questionnaire was divided into three main sections: 1.*renovation techniques* 2.*insulation techniques* 3.*ecobuilding and materials*. Most respondents were able to answer the majority of questions, though some builders were more at ease with section 1. and 2. When answering section 2 some builders mentioned they do not always apply the insulation materials themselves, because this is often done by a *plaquiste* (plasterboard installer).

The answers were coded following the guidelines by Gillham (2005) (*see* Table 4.2). More open questions that were hard to code are left out of the coding table. The rest of the coding tables, including an example of the questionnaire and a written account of the interview results (in English), are in Appendix IV.i. The interview with the building experts from CAUE (81) is not coded, because it was based on a different set of questions (*see* Appendix IV.i for the French version).

The interviews made it clear that the research question was relevant: all builders understand that the renovation and insulation of period timber-frame houses is a delicate job, not always done according to the best available techniques. A summary of the interviews is given in chapter 5.2. where their outcome is discussed in relation to existing literature and the results of the assessment.

Interview coding tables

Explanation of the coding (method Gillham, 2005): The respondents are coded by capital letters, in alphabetical order (*see* Table 4.1). The numbers are the question numbers (*see* Table 4.2). The lower case letters indicate the different answers to a question. The questionnaire is in Appendix IV.i.

Table 4.2 *Coding of interview questions 1-4*

1. Problems and diagnostic	**3' Techniques** *Infill*	**3'' Techniques** *Insulation*	**4. Type of insulation**
Humidity A1a,B1a,C1a,E1a,F1a,G1a	*Bricks (exposed)* A3'a, B3'a, C3'a, G3'a, H3'a	*Interior: plaster board and insulation* A3''a, B3''a, C3''a, D3''a, H3''a	*Glasswool* A4a, B4a, C4a, H4a
Structural (modifications) G1b, D1b, H1b	*Hollow bricks (render)* A3b, B3'b, C3'b, D3'b, G3'b	*Interior: hollow brick and insulation* A3''b, C3''b	*Rockwool* A4b, B4b, C4a, D4b
Daub in bad shape A3c, G1c, D1c	*Take out daub* A3c, B3'c, C3'c, D3'c	*Interior: hempcrete* E3''c, G3''c	*Hempcrete* G4c
Cement renders D1d	*Render old daub* B3'd, C3'a, D3'c	*Interior : earth and wood shavings* G3''d	*Sheepswool* G4d
Termites B1e	*Remake daub(cob)* G3'e, H3'e	*Exterior: wood cladding* E3''e, F3''e	*Woodwool* D4e, H4e
	Reuse old floortiles B3'f	*Monomur* A8f, B24f	*Cork (pallets)* G4f, F4f
	Unfired Bricks G3'g, H'3g		*Wood shavings* F4f
	Hempcrete (lime) G3'h		*Straw (bale)* F4f
	Earth and straw G3'i, H3'i		
	Earth and shavings F3'j, G3'j		
	Strawbale F3'j		

Table 4.3 *Coding of interview questions 4-8*

5. Timber exposed	6. Type of exterior render	8. Preferred technique	9. Most difficult
YES, aesthetics A5a, C5a, D5a, G5a, H5a	*Lime (NHL)* A6a, D6a, F6a, H6a	*Timber and bricks exposed* A8a, B8a, C8a, G8a	*Humidity* F9a, G9a
YES, let the timber continue to work B5b	*Lime (CL)* A6a, B6b, E6*b, G6b, H6b	Earth& straw H8b	*Restore the old timber structure* A9b, B9b C9b, D9b, H9b
		Rammed earth E8c	*Choice of insulation* E9c
NO, infiltration of water and air F5c	*Ready Mix (CL-NHL)* C6c	*Monomur* A8d	
	Earth F6d, H6d	*Hempcrete* D8e, G8e	
		Strawbale F8f	

Table 4.4 *Overall results of assessment of 20 wall types in Cocon*

Wall type	Wall number	Overall score	Width	Embodied Energy		Embodied Carbon		Resource depletion		Thermal Resistance		Decrement delay		Thermal inertia		Carbon tax	Volume	Weight	Volume Bio sourced	Weight Bio sourced
		1 to 20	*cm*	*kWh per m^2*	*Score*	*kg CO2eq per m²*	*Score*	*kea per m²*	*Score*	*m² K/w per m²*	*Score*	*h / m²*	*Score*	*kJ/m²K per m²*	*Score*	*€ / m²*	*m^3*	*kg*	*%*	*%*
Brick, glasswool, plasterboard	M1	8.5	26.5	177	8.2	40	7.4	0.02814	10.3	2.65	13.6	5.7	9.5	24	1.9	0.67	0.355	207.6	8	23
Clay block, glasswool, plasterboard	M2	9.7	27.5	144	10.4	36	7.6	0.00528	15.2	2.72	14.0	5.6	9.3	24	1.9	0.61	0.365	165.2	8	29
Old daub, glasswool, plasterboard	M3	11.2	29.5	100	13.4	32	7.9	0.00124	19.4	2.67	13.7	6.5	10.9	24	1.9	0.54	0.385	269.1	10	22
Brick, glasswool, clay block	M4	9.4	32.0	201	6.6	50	6.7	0.02960	10.2	2.75	14.2	7.9	13.2	71	5.7	0.85	0.350	267.0	9	18
Old daub, no insulation	M5	10.2	13.0	30	18.0	13	9.1	0.00000	20.0	0.40	1.1	4.6	7.6	70	5.6	0.22	0.160	206.5	23	28
Brick and monomur	M6	8.1	49.0	355	0.0	135	1.0	0.10341	6.6	3.13	16.3	22.5	20.0	61	4.9	2.29	0.520	444.6	6	11
New daub, woodwool, clay block	M7	13.9	32.0	72	15.2	-3	10.2	0.00203	18.0	2.70	13.9	12.4	20.0	77	6.2	-0.05	0.350	367.1	38	23
Brick (reuse), cork board	M8	13.1	26.0	60	16.0	-3	10.2	0.00000	20.0	2.70	13.9	9.4	15.7	36	2.8	-0.06	0.290	236.3	48	23
Old daub, cellulose, Fermacell	M9	11.8	28.0	144	10.4	18	8.8	0.00010	20.0	2.69	13.9	8.3	13.8	45	3.6	0.31	0.334	290.9	48	30
Old daub, wood fibre board	M10	14.3	28.0	37	17.5	-13	10.9	0.00000	20.0	2.62	13.5	11.8	19.6	54	4.3	-0.22	0.310	321.6	43	26
Hempcrete	M11	11.2	31.0	152	9.9	-4	10.2	0.03250	9.9	2.79	14.4	10.8	17.9	58	4.6	-0.06	0.357	198.0	30	44
Earth and straw	M12	14.7	36.0	85	14.3	-39	12.6	0.00008	20.0	2.77	14.3	16.0	20.0	86	6.9	-0.66	0.407	226.5	75	75
Woodchip and lime	M13	10.1	45.0	290	0.7	-47	13.1	0.06818	7.8	2.77	14.3	18.6	20.0	62	5.0	-0.80	0.497	297.5	74	80
Earth/straw, woodwool, Fermacell	M14	13.9	25.0	70	15.4	-15	11.0	0.00001	20.0	2.74	14.1	10.6	17.6	63	5.0	-0.26	0.285	196.2	68	59
Old daub, earth and straw	M15	14.8	38.0	35	17.6	-22	11.5	0.00000	20.0	2.62	13.5	15.3	20.0	81	6.5	-0.38	0.410	332.5	58	37
Wood cladding, glasswool, old daub	M16	13.6	29.7	147	10.2	17	8.9	0.00076	20.0	2.80	14.5	8.4	14.0	177	14.1	0.29	0.327	266.7	20	45
Polystyrene, old daub	M17	12.2	26.0	124	11.7	39	7.4	0.00522	15.2	2.57	13.2	7.0	11.6	175	14.0	0.66	0.290	286.3	13	20
Slate cladding, woodwool, old daub	M18	15.0	27.5	120	12.0	-10	10.6	0.00026	20.0	2.68	13.8	10.6	17.7	198	15.9	-0.16	0.324	300.2	46	42
Woodfibre board, unfired bricks	M19	15.9	25.0	36	17.6	-18	11.2	0.00001	20.0	2.65	13.7	11.4	19.0	176	14.1	-0.30	0.280	257.8	56	42
Woodfibre board, old daub	M20	16.6	28.0	28	18.1	-20	11.3	0.00000	20.0	2.71	13.9	12.3	20.0	202	16.1	-0.34	0.310	327.8	46	27
	Average	12.4	30.1	120	12.2	9.3	9.4	0.01384	16.6	2.61	13.4	10.8	15.9	88	7.1	0.16	0.345	273.3	37	34

4.3 Assessment data per parameter

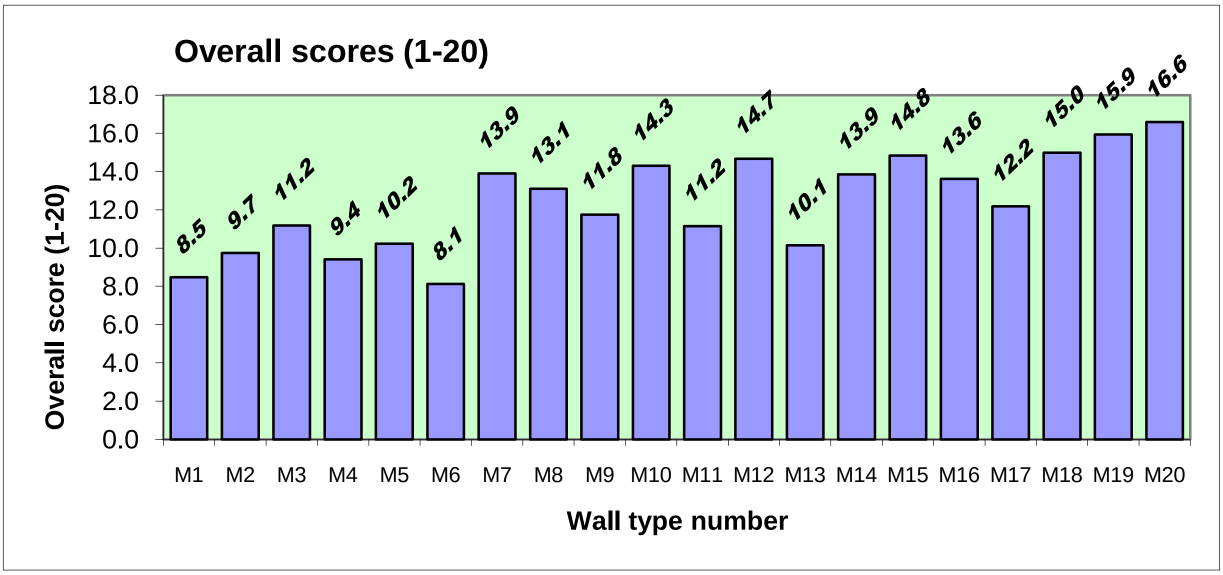
4.3.1 Overall scores (1-20 points)

*For the individual summary tables and wall sections, see **Appendix IV.ii**.*

The best performing wall types in the assessment (M18, M19, M20), with excellent overall scores above 15, are all amongst the 4th category of walls with exterior insulation (Fig.9). The highest scores are the walls with woodfibre board insulation (M19, M20). M20 has the highest thermal mass of all wall types, reflected by an excellent decrement delay and thermal inertia. Of the walls with interior insulation it is also the one with woodfibre board (M10) that has the highest overall score. The woodfibre board walls have a very low EE and store a fair amount of carbon (*see* sections below). Note that the EE and EC are mainly due to the lime renders (*see* Ch 5.). The Pavatex woodfibre board (9cm) itself has a very low EE (1 kWh/m^2) and stores 28 kgCO_2eq/m^2.

Despite the exterior insulation, which gives the more conventional wall types M16 and M17 good scores for thermal inertia (though not for decrement delay), these wall types do not perform as well as expected. This is mainly due to their high EE and EC (*see* sections below), especially for the wall with polystyrene insulation (M17) which therefore gets a mediocre overall score of 12.2.

Fig. 9 *Overall scores for walls M1-M20*



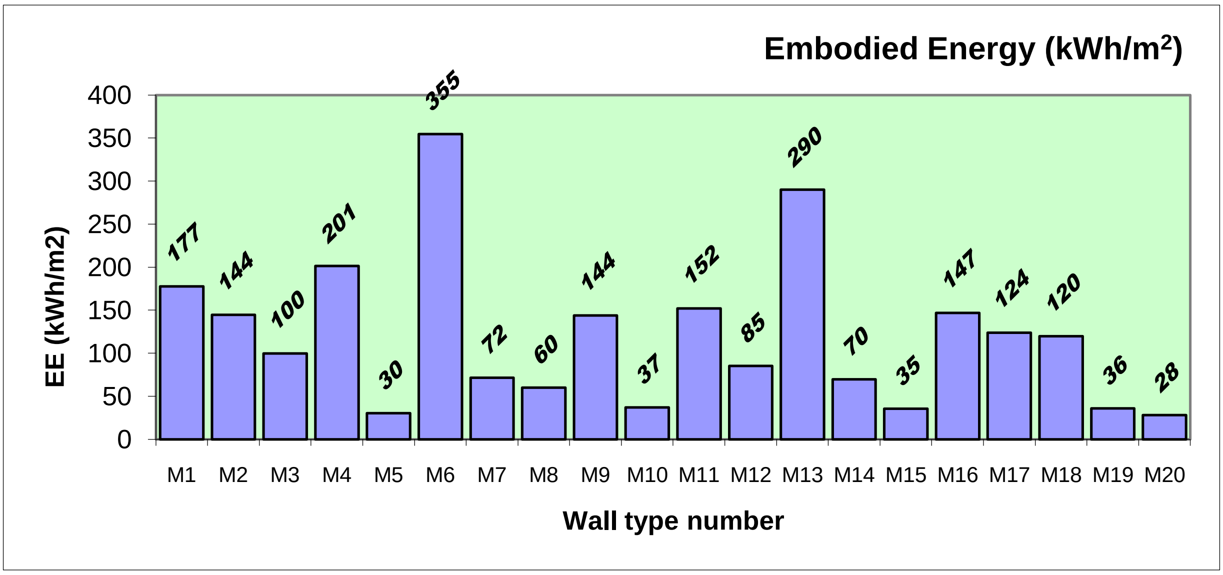
It is clear from the comparison that the conventional wall types (M1-M5) have the lowest overall scores, partly due to their lack of thermal mass and the use of fired bricks that have a very high EE (*see* 4.3.2). This is also the reason why the daub wall with *no* insulation (M5) gets a higher score (10.2) than some of these wall types, due to its low EE and reasonable thermal mass. When comparing M1 and M4, using clay blocks instead of plasterboard increases the thermal mass and puts the overall score up by almost 1 point. Note that the ‘ecological’ *monomur* (M6), which has a good thermal mass, has the lowest score of all wall types. This is due to its high EE and EC and a bad score for resource depletion (*see* sections below).

It is notable that amongst the plant fibre filled walls, hempcrete and woodchip&lime do not achieve the higher scores of other ecological materials, such as wood fibre board or earth&straw. This is largely due to the high EE of the lime binders, which also causes a low score for resource depletion (*see* 4.3.4). The 'eco wall' with cellulose insulation (M9) does not achieve a satisfactory score either.

4.3.2. Embodied energy (including RNE)[29]

The assessment shows that conventional wall types (M1-M4) do not necessarily have a high EE. Most of the EE in these walls is due to the use of fired bricks, not to glasswool. Keeping the old daub (M3) or reusing the bricks (M4b, *see* Appendix 4.ii) gives a reasonably low EE, even compared to some of the 'environmental' solutions. Amongst the ecological wall types, the *monomur* (M6) and the woodchip&lime (M13) and hempcrete wall (M11) have a rather high EE. Surprisingly high is the EE for the cellulose wall (M9) and the wall section with wood cladding (M16). Note that most of the EE of the cellulose wall is due to the lime renders and wooden frame. The cellulose insulation itself has a very low EE (4 kWh/m^2). *See* Appendix IV.ii.

Fig. 10 *Embodied Energy for walls* M1-M20



The *monomur*, with exposed bricks on the outside and 30cm thick insulating bricks on the inside, has by far the highest EE of all wall types (Fig.10). It even gets a zero score for EE because it is above the upper level of 300 kWh/m^2 set in Cocon (*See* Ch.3). Even after subtracting the EE of the exterior red bricks (108 kWh/m^2), assuming they are reused, the overall score of the *monomur* is still very low (9.1).

The wall types with the lowest EE are the ones with woodfibre board insulation (M10,M19,M20). The wall with earth&straw onto old daub (M15) is also a good example of a wall with a low EE. Because there is no EPD for these materials it is unlikely that the transport to the building site is included in the data. This would especially put up the EE for woodfibre board which is imported from Switzerland.

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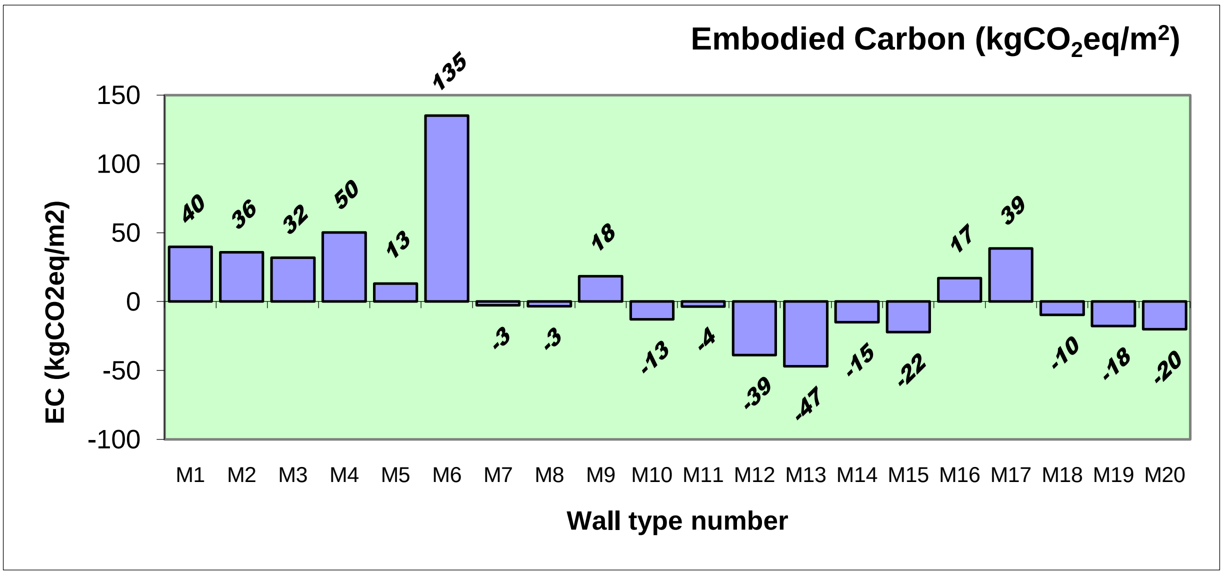
[29] RNE Renewable Energy, for explanation, *see* Ch.2.3

Fig. 11 *Timber-frame with brick infill and monomur insulation (H.Valkhoff)*

4.3.3. Embodied carbon (climate change)

All conventional wall types (M1-M5) have a positive EC, whereas all the ecological wall types, with the exception of M9 (cellulose), store carbon to a lesser or greater extent (shown by the negative EC in Fig.12). The enormous carbon footprint of the *monomur* is striking (M6). The woodchip&lime wall (M13) has the best carbon balance and stores 47kg of CO_2eq/m^2. Second comes the earth&straw wall (M12) which stores 39 kg of CO_2eq/m^2. The hempcrete wall does not have such a good carbon balance, because of the CO_2 emissions caused by the lime renders (*see* 5.2.3).

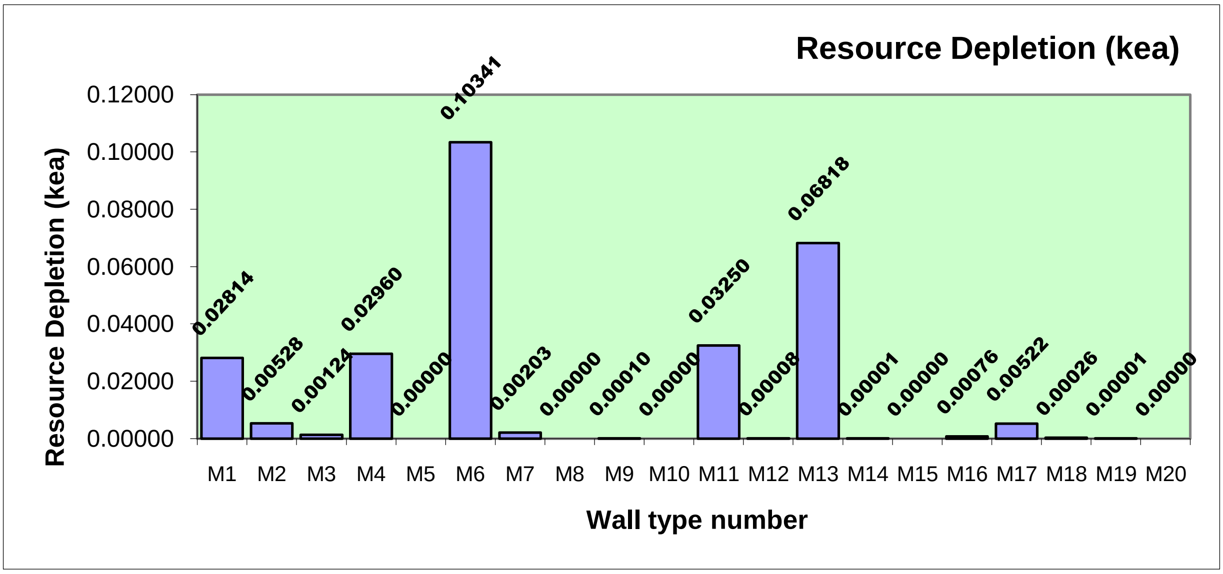
Fig. 12 *Embodied Carbon for walls M1-M20*



4.3.4 Resource depletion

The values for resource depletion (measured in kg antimone per m^2) vary so much that it is hard to interpret the results. It is clear that the wall types with a high EE also have a 'high resource depletion' (Fig.13).

Fig. 13 *Resource Depletion* for *walls M1-M20*



4.3.5 Thermal resistance (R-value)

At present, the builders interviewed mostly use 8cm of mineral wool, which brings the thermal resistance of most walls up to 2.7 m^{2}K/W (*see* 3.1.2). Cocon uses the Réglementation Thermique (RT, 2005) which requires a minimum thermal resistance of R=2.0 (m^{2}K/W). This is less strict than the more recent RT (2007) which imposes a minimum R-value of 2.3 for existing buildings. Fig. 14 and Fig. 15 show that most wall types in the assessment are at the top range of the 2005 standard.

Fig. 14 *Comparison of thermal resistance walls M1-M10 against RT-2005* (m^{2}K/W)*

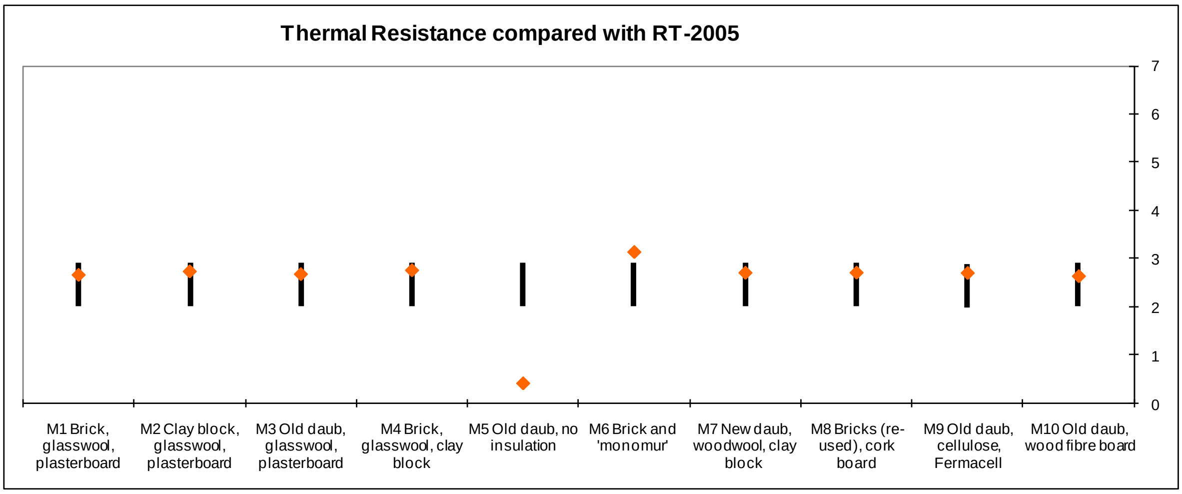
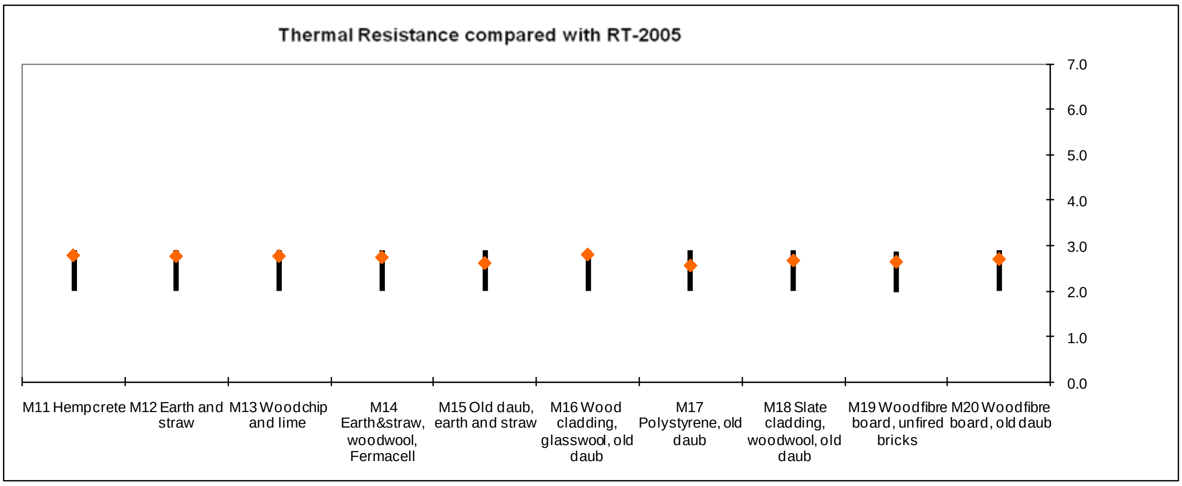


Fig. 15 *Comparison of thermal resistance walls M11-M20 against RT-2005 (m^{2}K/W)**



*RT-2005 used in Cocon: R_{min}=2.0 and R_{max}=2.9. The RT-2007 for renovation: R_{min}=2.3 and R_{max}=2.8
The BBC [30] renovation standard is very similar: R_{min}=2.1 and R_{max}=2.9.

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[30] BBC Rénovation (Effinergie, 2009) Bâtiments Basse Consommation

4.3.6 Thermal mass indicators

Two of the three parameters for thermal performance give an indication of thermal mass, which has a positive effect on evening-out temperature peaks. Decrement delay is a short-term indicator, also called 'summer comfort', whereas thermal inertia is a more long-term indicator of thermal mass (*see* 2.4.1). From Fig. 16 and Fig. 17 it is clear that exterior insulation is the best way of using thermal mass. It also shows that most forms of interior insulation, especially mineral wool and plasterboard (M1,M2,M3), completely cancel out the beneficial effects of thermal mass. The same is true for using cork (M8) or cellulose (M9) as interior insulation. Changing the plasterboard for a 5cm clay block (e.g. M4) gives a considerably better thermal mass.

Fig. 16 *Thermal inertia for walls M1-M20*

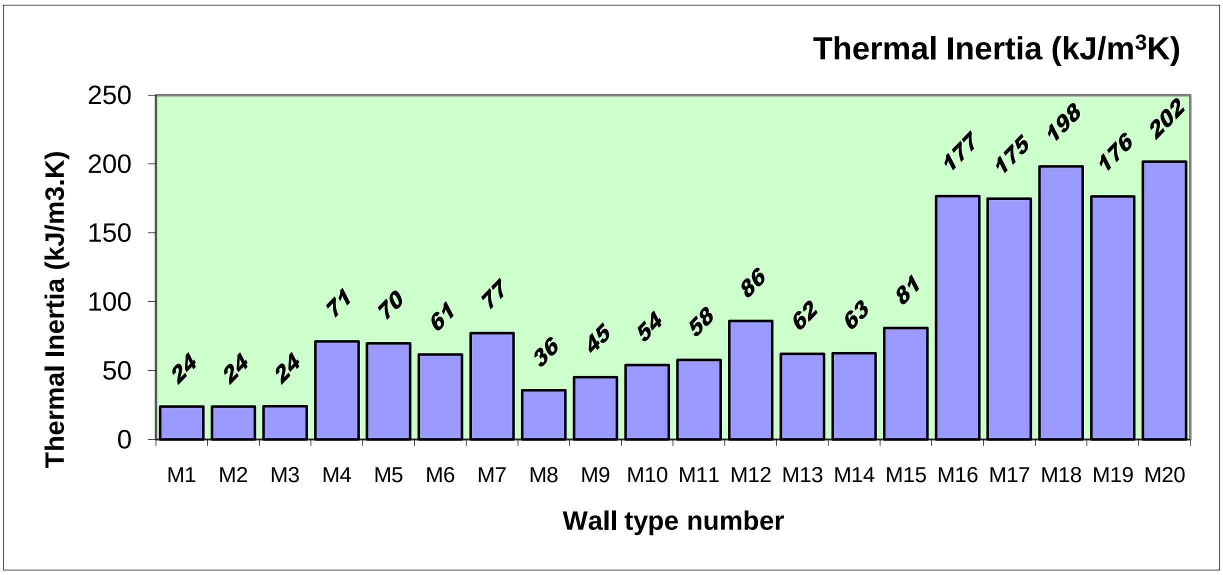


Fig. 17 *Decrement delay for walls M1-M20*

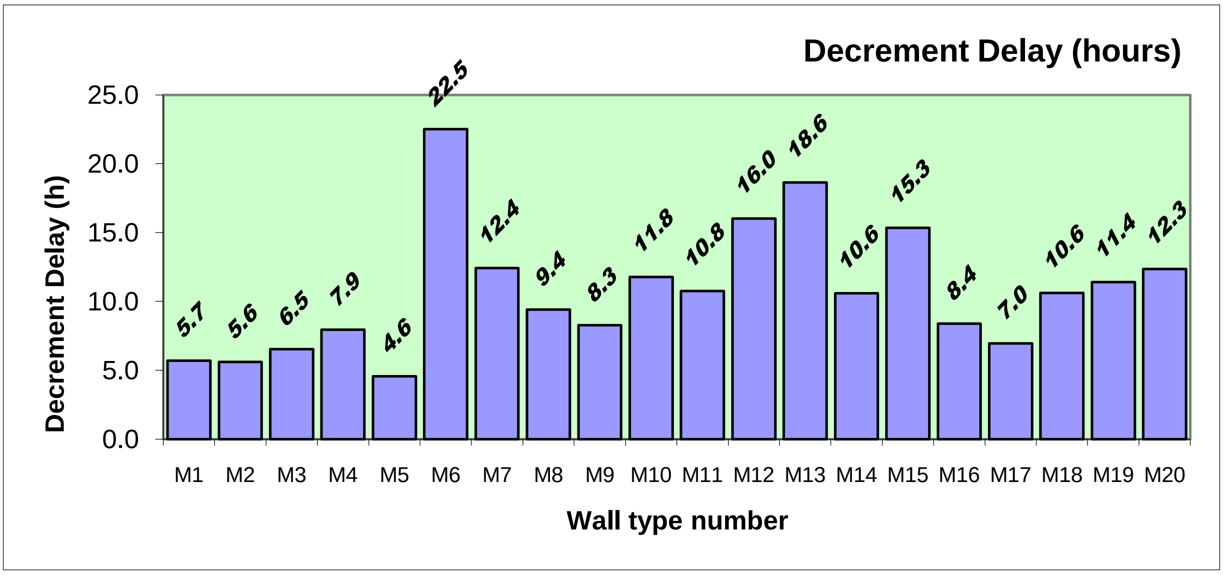
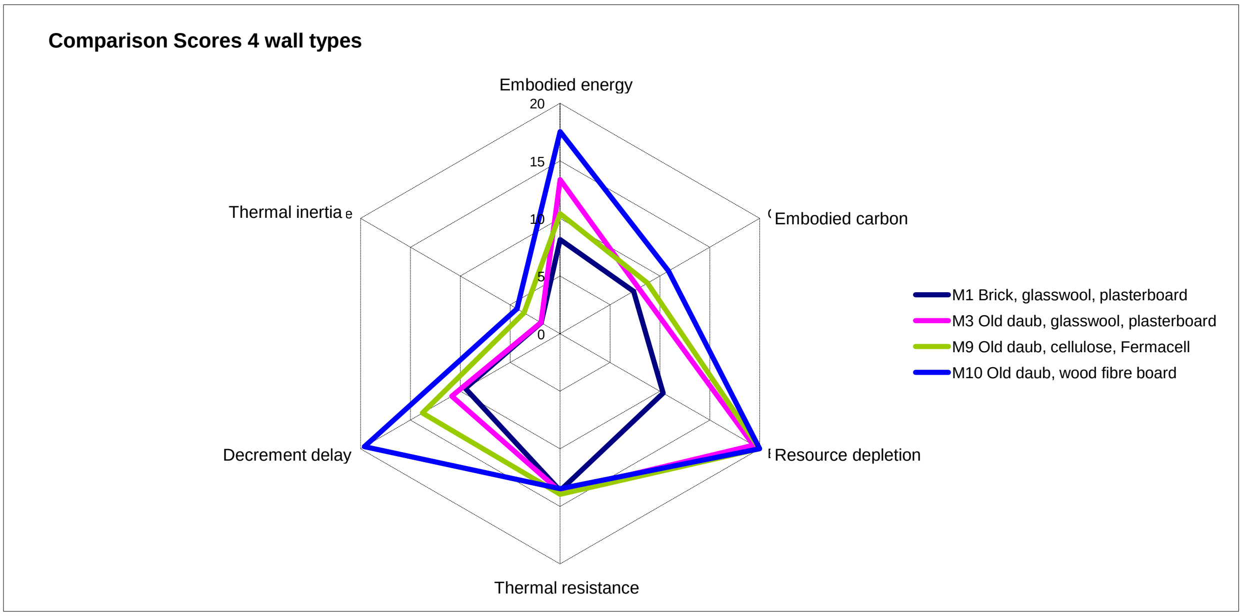


Fig. 16 and 17 (above) show the difference between the two parameters for thermal mass. The walls with the highest thermal inertia are not the same as the walls with a high decrement delay. For example the walls with plant fibre and binder insulation generally have a good decrement delay, but a low thermal inertia. The walls with exterior insulation all have a high inertia, but not always a high decrement delay (e.g. M16, M17).

Comparison of interior with exterior insulation in spider diagrams

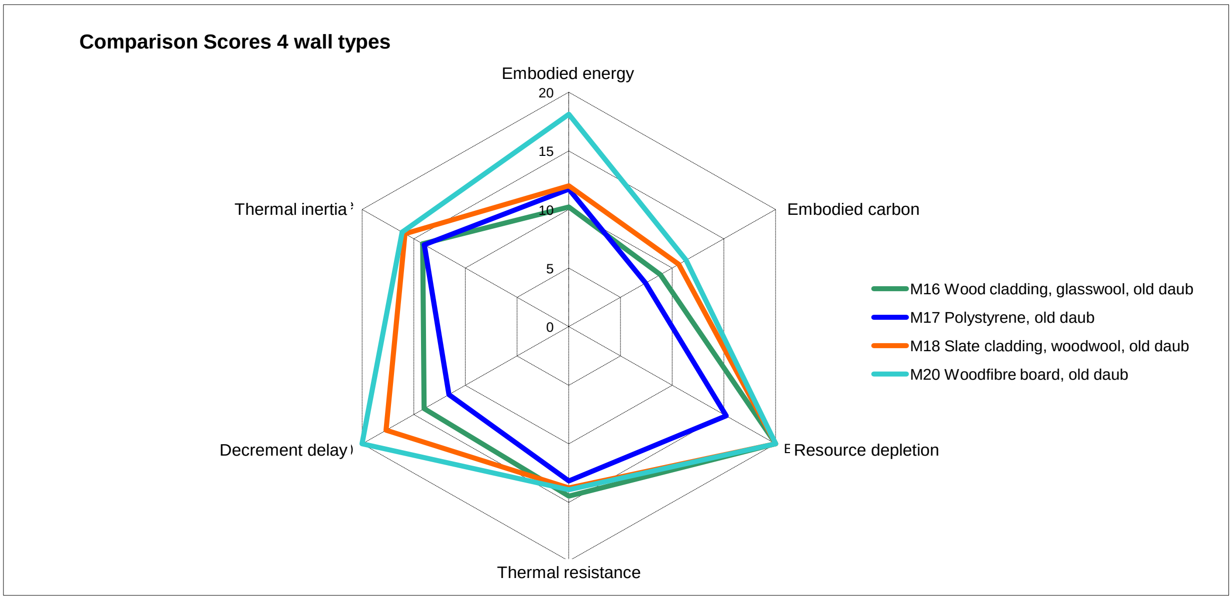
The spider diagrams for different sets of wall types clearly show the differences in thermal mass. Despite the differences between the 4 wall types with interior insulation (Fig.18), it is clear from the dent in the diagram that they all score badly on thermal inertia, although the ecological wall sections M9 and M10 score quite well on decrement delay, as seen in Fig. 17.

Fig. 18 *Comparison of six scores for walls M1,M3,M9 and M10 (interior insulation)*



The difference between the exterior insulation wall types is striking (Fig. 19 p.50). Here the left side of the diagram is much more rounded, due to a better thermal inertia *and* decrement delay. However, on the right side of the diagram most plots are still rather flat, due to the mediocre scores for EC.

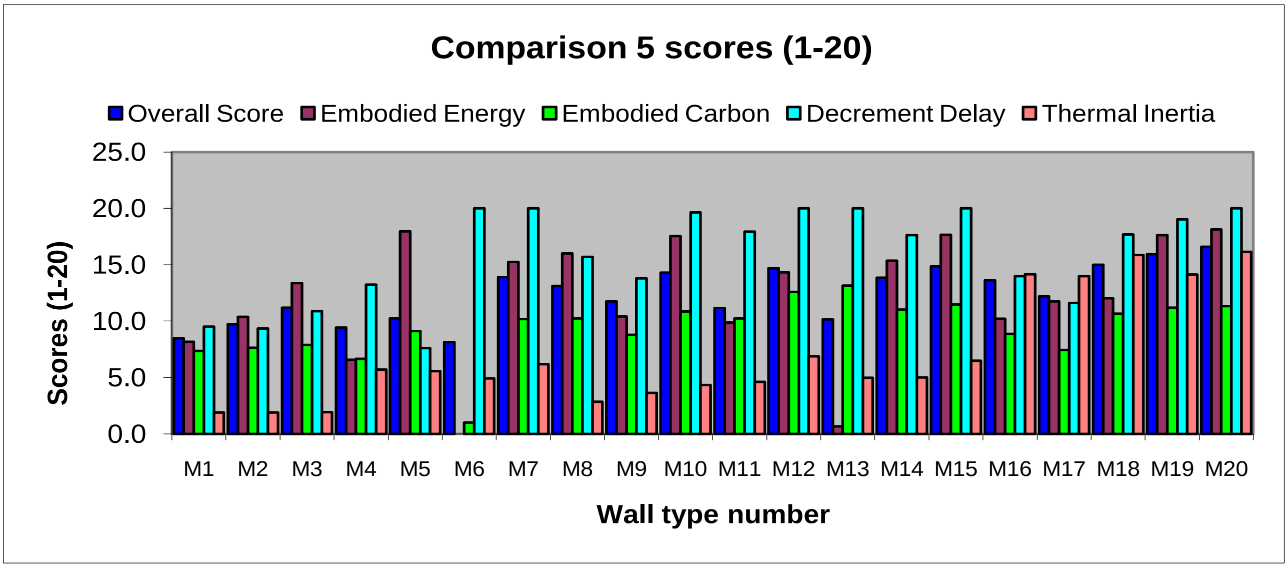
Fig. 19 *Comparison of six scores for walls M16, M17, M18, M20 (exterior insulation)*



Comparison of 5 scores in one chart

Fig. 20 gives a comparison of the scores for the 4 main parameters, plus the overall score. Though there is a lot of information in the chart, it clearly shows that wall types with a low overall score often perform badly because of low scores on EC and thermal inertia, with the exception of the monomur (M5) that has a low overall score because of its high EE. The walls with exterior insulation clearly show a more balanced distribution of scores.

Fig. 20 *Comparison for wall M1-M20 of the scores for 4 parameters and the overall score*



4.4 Assessment data per wall type

Because of word limitation this section, which includes the individual summary tables and wall sections, is given in ***Appendix IV.ii***

Fig. 21 *Renovation in Albi with old and new bricks (H.Valkhoff)*

Chapter 5 Discussion

In this chapter the results presented in chapter 4 will be discussed in relation to existing literature. Section 5.1 gives a summary of the interview results. Section 5.2.1 to 5.2.4 will discuss the results of the impact assessment, following several themes summarising the most important conclusions. Section 5.2.5 will discuss the important issue of 'breathability' and interstitial condensation. And section 5.2.6 will raise the question of qualitative aspects that were not part of the assessment.

For reference the text will refer back to the result, tables and graphs in chapter 4, and the summary tables and wall sections in ***Appendix IV.ii****.*

5.1 Interviews and existing literature

Most respondents name humidity as the main problem and danger for period timber-frame buildings (*see* 4.2 and Appendix IV.i). This is mostly due to rising damp from cellars and ground floor walls and interstitial condensation. This can cause decay, bad indoor air quality (moulds) and encourage insect infestation. Another problem often mentioned in the diagnostic is the deterioration of the timbers due to bad repairs, modifications, or bad maintenance.

All interviewees seemed to agree that the original daub is often in too bad a state to restore, or that this would take too long. The centuries old daub is still considered to be an inferior material and is often demolished and replaced by bricks or clay blocks. Marcom (2009) has used a sort of cob (*bauge*) as infill, a heavy mix from hemp and earth lightly rammed into shuttering. When the daub is in good condition it is usually repaired (not restored !) by filling the holes and fixing the wattles. On the outside it is mostly lime rendered onto a chicken wire mesh that holds the daub together, either with or without the oak timbers exposed.

Nowadays, clients often ask for the typical Toulousian style facade, with red bricks and timbers exposed (Bonnet 2009). When red bricks are too expensive, or when the client decides not to leave the facade exposed, hollow bricks (clay blocks) are used for infill. In that case all walls are rendered on the inside and outside to increase waterproofing and airtightness.

The most commonly applied insulation technique for period timber-frame buildings, according to most respondents, is by 'doubling' the wall on the inside with plaster board and mineral wool. This is frequently done by a *plaquiste* ('plasterboarder'), not the builder himself. Cuquel (2009) and Gironnet (2009) point out that inappropriate insulation can cause a lot of damage to period timber-frame buildings. The problem is the general lack of knowledge; most builders are not specialised in restoration and often do not know the appropriate techniques (Cuquel, 2009). In the past renovations were often done without sufficient knowledge and have done much damage, to the point of ruining the building (Marchal, 2009). Lack of knowledge amongst contracters is cause number one in Ten Ways to ruin an old building (Taylor, 1998).

One in two builders do not put in any form of vapour control layer (VCL), and believe that the humidity is evacuated through the more or less ventilated cavity (*see* Ch 2). The CAUE (2009) also advises the use of a ventilated cavity for period timber-frame. All builders interviewed strongly believe that timber-frame walls should breathe. If the walls don't breath the humidity can creep up as high as 2 meters (Alexandrov, 2009).

This is why they all use lime renders, and often 'air lime' instead of hydraulic lime because this is the most suitable material for this type of buildings. Not only because it lets the building breathe, but also because it is very flexible and less likely to crack. Cement renders are hardly used anymore, due to the enormous damage these have done in the past.

Cement was used on a large scale in historic buildings from the 1950s until the 1980s and has done a lot of harm (Béa, 2009). The same was true in the UK according to Bouwens (1997), where failures due to the use of cement renders have been dramatic, involving the collapse of large sections of walls. Painting the exterior walls can have the same effect, as modern paints trap moisture in the wall (Bouwens, 1997).

Fig. 22 *Example of cement render onto period timber-frame in Mirepoix (H.Valkhoff)*

There is quite some awareness of the embodied energy of building materials amongst the interviewees. Builders know where a lot of the materials are produced or originate. Most of the bricks, the lime and the sand are from the Southwest of France. Alexandrov (2009) says he gets his bricks from Imerys, because he knows they are made locally. The more we use local building materials the less we create transport, which at the end of a project can result in one or two lorries less on the road (Alexandrov, 2009). Marcom (2009) calls vernacular materials 'first hand' materials, i.e. building materials that come from the immediate environment, not from a factory or building yard: e.g. wood, stone, earth and plant fibres.

None of the builders interviewed knew about LCA or the EPDs in the database INIES (2009), which confirms the outcome of a survey by CAPEB (2008)[31], which shows that 49 % of builders have never heard of EPDs, and only 18% have looked at them.

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[31] La Conféderation de l'Artisanat et des Petites Entreprises de Bâtiment (CAPEB, 2008).

Keeping and improving the aesthetic qualities is the absolute priority for most respondents. Except for the building expert, they all want to keep the oak timbers and regional style red bricks or daub exposed, if possible. Like in the UK it has become fashionable to remove render to expose the timbers, though this is likely to compromise the building and accelerate the decay of the previously protected structure (Pritchett, 2001). Most interviewees believe that in most cases exterior insulation is not appropriate for period timber-frame. For conservation reasons one often cannot insulate from the outside, which technically would be better (Cuquel, 2009). Cuquel (2009) says: 'We really don't know what the solution is.'

Fig. 23 *Renovation of timber-frame building in Albi (H.Valkhoff)*

5.2 Conclusions from the assessment

5.2.1 Exterior insulation gives the best results

As pointed out in chapter 4.3 the three best performing wall types are all within the 4th category of walls with exterior insulation (Table 5.1). The highest overall scores are for the walls with woodfibre board (M19, M20), which have a low embodied energy (EE), a negative embodied carbon (EC) and a very good thermal inertia and decrement delay (*see* Tables 4.4 and Appendix IV.ii). Besides keeping the thermal mass, exterior insulation reduces the heat loss due to thermal bridges (*see* 2.4.2). According to Floissac (2009-b) woodfibre insulation board provides a good solution for exterior insulation in most rehab projects, not just for timber-frame, as it is an industrial product that builders can quickly become familiar with.

Table 5.1 *Wall types in order of performance (overall score)*

	Wall No.	*Wall type*	*Overall score*
1	M20	Woodfibre board, old daub	16.6
2	M19	Woodfibre board, unfired bricks	15.9
3	M18	Slate cladding, woodwool, old daub	15.0
4	M15	Old daub, earth and straw	14.8
5	M12	Earth and straw	14.7
6	M10	Old daub, woodfibre board	14.3
7	M14	Earth and straw, woodwool, Fermacell	13.9
8	M7	New daub, woodwool, clay block	13.9
9	M16	Wood cladding, glasswool, old daub	13.6
10	M8	Brick (re-use), cork board	13.1
11	M17	Polystyrene, old daub	12.2
12	M9	Old daub, cellulose, Fermacell	11.8
13	M3	Old daub, glasswool, plasterboard	11.2
14	M11	Hempcrete	11.2
15	M5	Old daub, no insulation	10.2
16	M13	Woodchip and lime	10.1
17	M2	Clay block, glasswool, plasterboard	9.7
18	M4	Brick, glasswool, clay block	9.4
19	M1	Brick, glasswool, plaster board	8.5
20	M6	Brick and *monomur*	8.1

Foroverall results see Table 4.4. and for summary tables and wall sections, see Appendix IV.ii

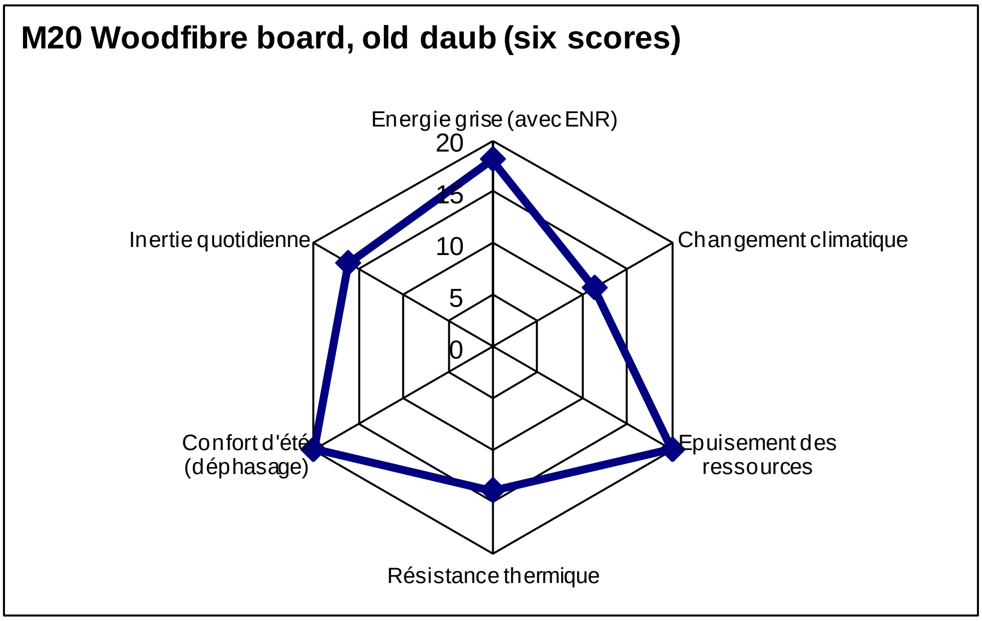
The advantages of exterior insulation have been shown in 4.3.6. The assessment also confirmed that most forms of interior insulation, especially mineral wool and plasterboard, completely cancel out the beneficial effects of thermal mass. The same is true for using cork or cellulose as interior insulation. Section 4.3.6. also showed that the walls with the highest thermal inertia do not necessarily have a high decrement delay and vice versa (also *see* 5.2.2).

Thermal mass can also be achieved in other parts than exterior walls, e.g. floors and indoor walls. In most timber-frame houses in SW France the daub indoor walls and earth floors with heavy terra cotta tiles traditionally provided a high thermal mass. Often these old walls and floors are demolished and replaced by plasterboard and wooden floors (Interviews, 2009). Only in some ecological or 'conservationist' renovations are these vernacular qualities kept, whereby thermal mass is used around stoves and fireplaces, or in combination with under-floor heating.

Note, however, that the benefits of thermal mass are probably greater in summer than in the winter (George, 2008), particularly in the climate of SW France with its hot summers. The advantages of thermal mass in winter depend on the type and frequency of heating and the amount of solar gain. George (2008) shows that thermal mass can increase the heating load in winter, especially in a leaky and intermittently heated building. When space heating largely consists of electric convection radiators, as is the case for more than 7 million households in France, it may be easier to heat a light-weight building (Ademe, 2009). In buildings with a lot of thermal mass which are slow to heat, materials with a low effusivity, e.g. cork (Ef=0.14 kJ/m^{2}S.K), can be a good solution for rooms that need to heat up quickly (Oliva, 2009).

Despite the excellent overall result of wall M20 (woodfibre board and old daub), the spider diagram (Fig.24) has a flattened plot on the right side of the diagram, caused by the modest score for embodied carbon (11.3). This is due to the fact that this wall 'only' stores 20 kg of carbon. Of the 31kg CO_2eq/m^2 stored by the woodfibre board, 11 kg is 'emitted' by the renders. The lower score for EC is partly due to the arbitrary range of the scale for EC in Cocon, which means that even a 'carbon neutral' wall gets a rather low score of 10 (*see* Appendix III.i). For all wall types the average score for EC is only 9.4 !

Fig.24 *Comparison of six scores for M20*



Clockwise from the top: embodied energy (with RNE), embodied carbon (climate change), resource depletion, thermal resistance, decrement delay, thermal inertia.

May (2005) says another advantage of woodfibre board is its hygroscopicity (9%)[32] and the fact that it is vapour-open (μ=3). It absorbs moisture quickly and, due to its higher density than most other insulation materials, it has a reasonably high hygroscopic capacity of 18kg/m^3, which means it can buffer humidity (May, 2005). When woodfibre board is used for interior insulation it therefore reduces the risk of interstitial and surface condensation (May, 2005).

Compared to expanded polystyrene (EPS) as exterior insulation, woodfibre board has a much better environmental record. The wall with polystyrene insulation (M17) has the lowest overall score of the wall types with exterior insulation (Table 5.1). This is mainly due to its high EE and EC and low decrement delay (*see* Tables 4.4 and Appendix IV.ii). However, 10 cm of woodfibre board insulation costs 110€/m^2, including labour, compared to 70€/m^2 for polystyrene (Floissac et al., 2008).

Polystyrene is not vapour-open (r=150; μ =30) and therefore traps the moisture in the wall (May, 2005)[33]. Whereas the walls (M19 and M20) with woodfibre board on the outside 'breathe' and let the old daub or clay blocks do the hygroscopic buffering (*see* 2.4.3). Vapour permeable is an important factor, particularly in older buildings without damp courses and ventilation systems (May, 2005).

Fig. 25 *Exterior insulation with woodfibre board* (Floissac et al., 2008)

Despite its advantages exterior insulation has to be weighed against aesthetic and conservation criteria. Almost all respondents (*see* 5.2) said that keeping the historic timber-frame facade was an absolute priority. If an old timber-frame facade with Toulousian style bricks is in a repairable state, the choice for exterior insulation is unlikely, especially if the building is in a conservation area, a so-called ZPPAUP[34]. However, for a back yard wall, or a side street, exterior insulation might be appropriate, especially if it is north facing. And in areas where timber-frame houses were

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[32] Hygroscopicity is the increase in moisture/mass at 20°C from a RH of 50% to 85% (May, 2005).

[33] In the UK vapour resistance (r) is measured in MNs/gm. On the continent vapour resistivity is measured as a ratio of still air (μ=1). To get the European unit μ one has to divide the UK unit r by 5 (May, 2005).

[34] ZPPAUP Zone de Protection du Patrimoine Architecturale, Urbaine et Paysager. The enforcement of the conservation zone can be slack, however, and depends on the mayor, not on the Architect des Bâtiments de France (ABF).

traditionally cladded with slates, wall type M18 might provide a good opportunity for exterior insulation with a material that adheres to the vernacular style (*see* Appendix IV.ii). Other constraints for exterior insulation are the position of eaves and door and window sills that may need to be adapted.

5.2.2 The benefits of old daub and earth&straw

If exterior insulation of timber-frame walls is not an option, than there are three appropriate solutions for interior insulation: wall M10 (woodfibre board), and M12 and M15 (earth&straw). All three are considered to be breathable walls, assuming air lime or clay is used for the exterior renders (*see* Ch.2). Perhaps the woodfibre board wall will be more 'accessible' for most builders and architects, because it is a common industrial product that can be used in many types of renovation. Earth&straw will be cheaper material wise, but more labour intensive and might therefore work out more expensive. Therefore, if the old daub (or brick) infill is still in good condition, instead of 30cm of earth&straw (M12) one might opt for 22cm of earth&straw onto old daub (M15).

The assessment shows that it does not make sense to take out the old daub if not necessary. Traditional infill panels in timber-framed buildings can perform extremely well if properly constructed and maintained (Pritchett, 2001). Repairing the daub and adding a lighter earth&straw mix (density 300kg/m^3) gives M15 the same thermal performance as M12, with less materials and therefore a shorter drying time and less work (see Appendix IV.ii). According to Marcom (2009) a density of 300 to 400 kg/m^3 is a good compromise between thermal resistance and thermal mass and appropriate for the climate in SW France. In colder climates lower densities would give a better thermal resistance, but one would lose in terms of thermal mass and 'summer comfort' (Marcom, 2009).

'Plant fibre and binder' wall types in category 3 are amongst the ones with the highest scores for decrement delay, but generally have a mediocre thermal inertia (*see* 4.3.6). Increasing the densities of these materials, by adding more binder or sand, will increase the thermal inertia, but will lower the thermal resistance (Table 5.2). Therefore it is important to find a balance between the thermal performance parameters, as more thermal mass might decrease the thermal resistance but increase the overall thermal performance (*see* Ch.2). This is also applies to the infill of new timber-frame buildings.

Table 5.2 *Changing R-values for different densities earth&straw* (Volhard F. in Oliva, 2008)

Density (kg/m^3)	**Thermal conductivity (W/mK)**	**R-value (m^{2}K/W)**		
		10 cm	***20cm***	***30cm***
300	0.10	1.00	2.00	3.00
400	0.12	0.83	1.67	2.50
600	0.17	0.59	1.18	1.76
800	0.25	0.40	0.80	1.20
1000	0.35	0.29	0.57	0.86
1200	0.47	0.21	0.43	0.64

The assessment confirms that earth&straw is a very good matreial for the insulation of timber-frame walls (Oliva, 2008), whether in new build or renovation. However, it is still not officially recognised in France and at present there is no building regulation for earth&straw (Asterre, 2009). The main disadvantage of earth&straw is that it is labour intensive and time consuming. If a ready mix could be delivered, as is the case for 'light earth' in Germany and Holland and new daub in parts of France, this would save a considerable amount of time (Marcom, 2002). The method itself, i.e. filling into shuttering, does not take any longer than for hempcrete, which is becoming a competitive technique in France. One disadvantage is that the drying time of a 30 cm earth&straw wall is 2 to 4 months, depending on the density and the weather (Oliva, 2008). It would be interesting to study the wider applications of earth&straw in thermal renovations and retrofits of existing buildings, as Le Doujet (2009) has done for straw bale in the UK.

Fig. 26 *Preparation of earth&straw mix in SW France (Marcom, 2002)*

Floissac et al. (2009) introduce the *labour intensity indicator* that they would like see included as a socio-economic indicator in the EPDs. The indicator is the ratio between the hours of labour per GJ (or kWh) of embodied energy per functional unit. The authors compare an earth&straw filled timber-frame house with two common buildings types: a standard house of breeze blocks and a fashionable 'ecohouse' built with insulation clay blocks (Floissac et al., 2009). Though the labour intensity of the 'local materials' (straw&earth) house is 70% and 80% higher than for the standard and the 'ecohouse', the price is only 13% higher than the standard house and 20% lower than the 'ecohouse' (Table 5.3, p.60). Note that it is harder to give price indications for renovation.

Table 5.3 *Comparison of ratios between 3 houses, 'local' house indexed at 100%* (Floissac et al. 2009)

	'Local materials' house *reference*	**Standard house**	**Fashionable 'ecohouse'**
Embodied Energy (GJ)	100%	160%	240%
Embodied carbon (CO_2eq)	100%	170%	180%
Labor intensity (h/GJ)	100%	30%	20%
Price (€/m^2)	100%	87%	120%

5.2.3 'Ecological' wall types that do not perform as well

Striking in the assessment is the bad performance of the hempcrete wall, which has the lowest score of all ecological wall types, due to its high EE and low thermal inertia. Many ecobuilders in France use hempcrete though, mostly in new build, often combined with timber-frame. And many construction experts highlight the environmental qualities of this material. Bevan and Woolley (2008) claim that using hempcrete is a good means of storing carbon. A hempcrete wall of 26cm wide, with a density of 420kg/m^3, can store 35 kgCO_2eq/m^2 (Boutin et al, 2006). However, in the assessment the carbon storage is almost outweighed by the CO_2 emissions caused by the lime renders (26 kgCO_2eq/m^2), for which Grecau (2009) does not take recarbonation into account (*see* 2.3.4).

The best way to improve the environmental performance of hempcrete is to change the binder from lime to clay. With a clay binder the carbon storage of a hempcrete wall will be almost double (Rhydwen, 2009)[35]. Further research is necessary to see if a clay binder has the same physical and thermal properties as lime (Rhydwen, 2009). Another advantage of hemp&clay would be that it's 100% recyclable and nicer to work with. One builder said he had experimented with hemp&clay (Douze, 2009). The problem is that builders can not give a guarantee as long as there are no building regulations for this technique[36].

With more accurate data that take recarbonation into account the hempcrete wall (M11) would score slightly better, though this is the case for most wall types in the assessment. The data for lime renders in Grecau are not based on an official EPD, but are an extrapolation (*see* Appendix III.ii). However, the data used for the lime binder in the hempcrete itself are official LCA data and based on Tradical-70, which has a particularly high EE because it comes all the way from Spain (Boutin et al., 2006). It is not entirely clear how much recarbonation Boutin et al. (2006) have taken into account. It is also notable that the woodchip&lime wall (M13) has the second highest EE, but the lowest EC, because it stores the most 'carbon' of all wall types. The explanation for this could be that the data or the lime binder in M13 are based on air lime and include a high ratio for recarbonation. Note that the data for woodchip&lime are not as reliable as those for hempcrete for which there is a full LCA (Grecau, 2009).

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[35] I.e.around 180 kg/m3, which is almost 55 kgCO_2eq per m^2 (Rhydwen, 2009)

[36] There are two stages of product certification by the CSTB: innovative products first need an Avis Technique and a European Product Authorisation; for conventional products and building techniques there is the DTU (Document Technique Unifié), which is the basis for the French product norm and building regs (Conteville and Den Hartigh, 2008). As a first step to certification the industry can issue a Règles Professionelle, e.g. for hempcrete (www.construction-chanvre.asso.fr).

Fig. 27 *Hempcrete infill in timberframe (source: www.limetechnology.co.uk)*

Fig. 28 *The properties of hydraulic limes in the lime cycle (Holmes, 2009)*

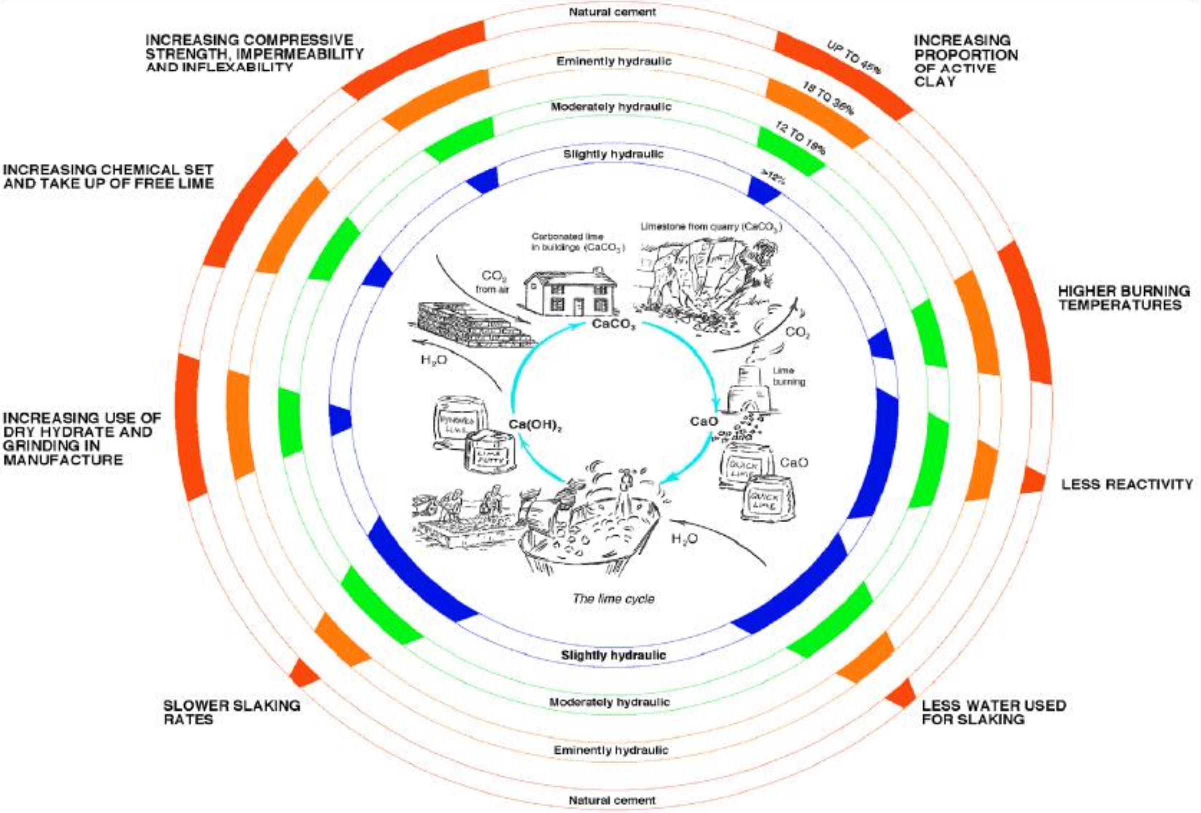

Fig. 28 The outer ring are cement binders (in red), the inner ring are air limes (blue) and in between are the hydraulic limes, from eminently hydraulic to moderately hydraulic. The purer or less hydraulic the lime the higher the recarbonation ratio, by reabsorbing the CO_2 during the drying process.

Another notable result from the assessment is the bad score for the *monomur* (M6) with insulation blocks. Despite its high EE and EC it is often advertised as an environmental product, because of its good thermal resistance and high thermal mass. The industry claims it provides a good solution for thermal bridges and reduces the risk of condensation (Briques de France, 2006). Oliva (2008) says the *monomur* functions as a natural acclimatiser that regulates peaks in temperature and humidity. However, despite the maximum score for decrement delay it has a surprisingly low score for thermal inertia of 4.9 (Table 4.4). Because it requires solid foundations it is considered more appropriate for new buildings, though not as an environmental option. Also Floissac et al. (2009) show that in new build it is 20% more expensive than earth&straw (Table 5.3).

Fig. 29 *Monomur behind timber-frame (H.Valkhoff)*

5.2.4 An appropriate 'conventional' solution for thermal insulation

If for cost or other reasons, e.g. skills and availability, a builder or architect does not want to choose any of the mentioned ecological renovation techniques and materials, the most acceptable conventional option is an old daub wall insulated with glasswool, and doubled with clay blocks instead of plasterboard (M3-b, *see* Appendix IV.ii). Changing the plasterboard for a 5cm clay block improves the thermal mass but increases the EE, resulting in an overall score of 11.8. Using clay blocks is a slightly more expensive solution, usually done by the builders themselves.

However, the most commonly applied insulation technique is interior 'doubling' with plasterboard and mineral wool, mostly done by a 'plasterboarder' (*plaquiste*). The preferred style is the exposed timber with red brick infill which, after the *monomur*, is the wall type with the lowest score in the assessment (Table 5.1). The walls with fired bricks have a high EE, mainly due to the EE of the bricks (108 kWh/m^2, including the mortar). Taking reused bricks reduces the impact considerably and increases e.g. the overall score of M4 from 9.4 to 12 points (M4-b, *see* Appendix IV.ii).

The reason why the daub wall with no insulation (M5) gets a higher score than most of the other conventional wall types is because it has a very low EE and a reasonably good thermal mass. Obviously it would not meet the insulation standard, and it is therefore not considered an appropriate solution. Adding an insulation render, which Cuquel (2009) calls 'thermal improvement', does not increase the thermal resistance much. For example 7 cm of hemp&lime render onto old daub (M5-b), gives a R-value of 0.82 (m^{2}K/W), but diminishes the thermal mass (*see* Appendix IV.ii).

Due to its low density (11kg/m^3) and high recycling content, glasswool has a reasonably low EE of 10 kWh/m^2 (for 8cm). In France glasswool represents 53% of the 5 billion euro market for insulation products, followed by polystyrene (28%) and rockwool (15%) (Oliva, 2008). However, when health hazards and indoor air quality are taken into account, mineral wool insulation may not be appropriate at all. Denmark and Germany have already banned glasswool in public buildings (Oliva, 2008). Though there is much conflicting research on whether glasswool fibres are carcinogenic or not, Berge (2009), Woolley et al. (1997) and Oliva (2008) suspect the fibres and the off gassing of phenol formaldehyde used in the glue can be a health hazard. Garbut (2006) and other insulation industry representatives believe there is no risk, based on research by the IARC[37]. The EPD for glasswool only says that mineral fibres are exempted from the carcinogenic classification by the EU directive 97/69/CE (INIES, 2009).

One of the builders said there is much progress to be made regards insulation products, because there is not much choice amongst 'healthy' materials with a CSTB certificate[38](Alexandrov, 2009). Conteville and Den Hartigh (2008) show how producers of ecological building products have a hard time getting the certification. This applies to new build and renovation. To avoid glasswool some builders use reflective multi-layered insulation products, although they know that these are not an optimal solution in renovation of historic buildings (Interviews, 2009).

Using woodwool instead of glasswool puts up the score of wall M3-b (old daub, glasswool, clay block) from 11.8 to 13.6 (*see* Appendix IV.ii). This is comparable with M7 (new daub, woodwool and clay block). The advantage is that woodwool, like most natural fibre insulation materials, is hygroscopic, which makes it more compatible to the building and allows the whole wall section to work as one unit (May, 2005). At present woodwool would probably be the most competitive way of combining conventional insulation techniques with a widely available ecological material.

Because woodwool has a higher density and thermal conductivity than glasswool, one has to add 1cm to get the same R-value of 2.7 m^{2}K/W. Materials with a low density, e.g. mineral wool, tend to score well in impact assessments, simply because they use less material (May and Newman, 2008). However, in Cocon the thermal mass parameters compensate for this, giving denser insulation materials better scores for decrement delay and inertia. Also, renewable materials with a higher density tend to store more carbon and therefore get a better score for climate change. This applies to new build and renovation.

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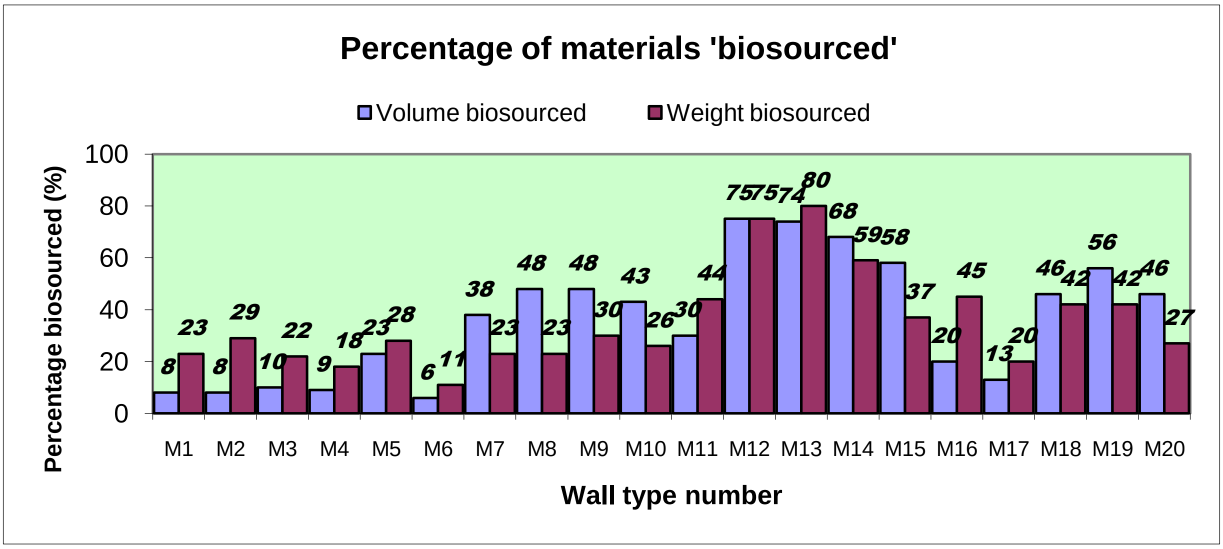
[37] International Agency for Research on Cancer, www.iarc.org

[38] *See* footnote 36.

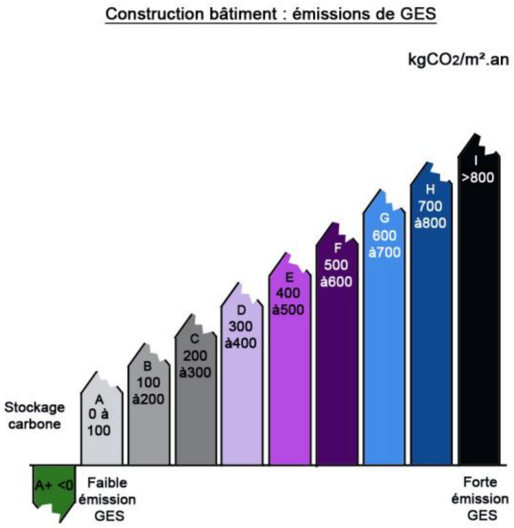
Fig. 30 shows how much of the wall sections is ‘biosourced’, i.e. materials derived from renewable plant-based sources. The plant fibre filled walls of category 3 clearly have the highest percentages. The walls with just woodwool insulation (M7, M18) also have a reasonable percentage (38 and 46%). Again these figures would also apply to new timber-frame buildings.

Fig. 30 *Percentage of ‘biosourced’ materials per wall type*



Another innovative tool in Cocon is the certificate for embodied energy and embodied carbon. Following the principle of the energy certificates these divide a building’s energy consumption into categories from A to I, where A has the smallest and I the biggest impact (Fig. 31). Note that these are only indicative and do not represent official certificates. In the case of the embodied carbon certificate the A category represents buildings that store carbon and have a negative EC. Because the certificates are for whole buildings they were not used in this assessment.

Fig. 31 *Carbon storage certificate in Cocon*



5.2.5.Vapour control and breathability

In most conventional wall types in the assessment there is a high risk of interstitial condensation. One in two builders said they did not use a vapour control layer (VCL) when applying mineral wool insulation. Problems with condensation can cause a considerable decline in insulation capacities (Oliva, 2008). Often VCLs are badly fitted and therefore increase damp problems instead of avoiding them (May, 2005; Oliva, 2008). Cuquel (2009) said that to avoid problems with condensation sometimes it would be better not to insulate historic buildings at all.

Fig. 32 *The Sterling bar graph for RH and indoor air quality (CAUT, 2009)*

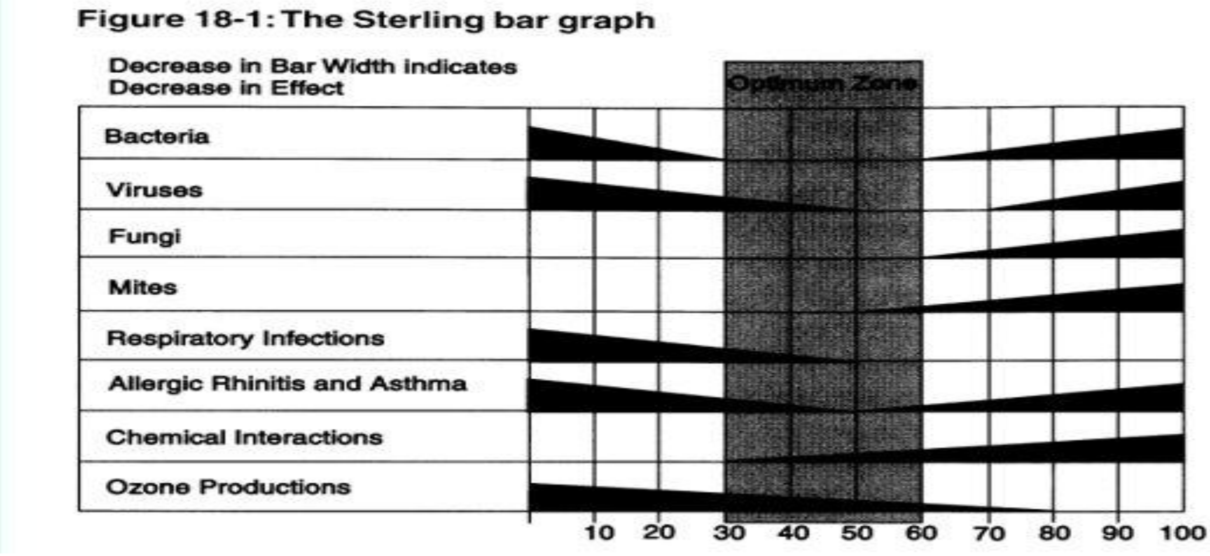


Fig. 32 shows how important the control of relative humidity (RH) is for a healthy indoor environment. The optimum zone is between 30 and 60% RH, where most moulds, mites, bacteria and viruses will not survive. May (2005) puts the safe zone between 40 and 60%. Note that VOCs[39] are also more active with increasing RH (May, 2005).

For humidity control most builders interviewed leave an air gap of 4cm or 5cm between the outside wall and the insulation material. When fully ventilated this has a negative impact on the thermal resistance, as cold air leaking around the insulation will drastically reduce its effectiveness (Harris and Borer, 2005). The CIBSE Guide to building services for historic buildings shows that without some degree of airtightness insulation is pointless (May, 2005)[40]. Therefore Oliva (2008) advises seperating the insulation from the cavity by woodfibre board. If the air gap is not fully ventilated, which is often the case, then there will potentially be interstitial condensation from the inside, rainwater penetration from the outside and rising damp from the ground floor (May, 2005).

A simple simulation of the number of dew points per year, based on regional climate data, using the software Parois Respirantes (Floissac, 2009/d)[41], shows for wall M1 (brick, cavity, glasswool, plasterboard) almost 4.000 dew points per year, mostly situated in the insulation layer. Putting in a breathable VCL reduces these to around 30 dew points per year. According to Floissac (2009-b) the

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[39] VOCs, Volatile Organic Compounds.

[40] Unfortunately this CIBSE guide (2002) costs 84£ for non-members!

[41] Parois respirantes means breathing walls.

remaining ones could also be points of exterior surface condensation, but the simulation does not include capillarity. The simulation shows that a cavity does not address the risk of interstitial condensation if it is not fully ventilated. However, in SW France condensation is less of a problem than in NW Europe because in all seasons there are long dry spells during which the walls dry out (Floissac, 2009-b).

It would be interesting to include an indicator with a score for 'breathability' in Cocon. Some argue that it is not necessary to add a VCL to daub walls that are insulated with vapour-open and hygroscopic materials. However, it is not always obvious to achieve breathable walls that follow the 1:5 rule. Only the walls M9, M19 and M20 would be considered 'breathable', if a vapour-open render was used on the outside. Vapour resistance coefficients of the interior and exterior lime renders used in the assessment are crucial (μ=7, for a density of 1500kg/m^3)[42]. Most builders said they use air limes (CL), which are more vapour-open than hydraulic limes (NHL). When it is difficult to follow the 1:5 rule in renovation, Oliva (2008) recommends a breathable VCL that has the right vapour resistance.

For an example of a 'breathing' cellulose wall (M9) *see* Appendix IV.ii. Note that despite its hygroscopic qualities the cellulose wall does not achieve a high score in the assessment. From an environmental point of view it might be better to insulate with woodwool, though cellulose is still one of the cheapest and most widely used 'ecological' insulation materials. At 20€ per m^2 (ex.VAT, incl. labour), it is hardly any more expensive than glasswool insulation (Floissac et al., 2008).

Fig. 33 *Spraying of cellulose (source: Warmcel, UK)*

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[42] For 3 cm of render this gives a vapour resistance (Sd) of 0.21m (metres of still air). On the continent vapour resistivity is measured as a ratio of still air (μ=1). In the UK vapour resistance (r) is measured in MNs/gm. To get the European unit, μ, one has to divide the UK unit, r, by 5 (May, 2005).

5.2.6 Qualitative aspects

LCA provides a purely quantitative impact assessment, while neglecting more qualitative aspects such as indoor air quality and the effect of building materials on people's health (Haas, 2002). Building-related health problems and indoor air quality become increasingly important in more airtight buildings (Woolley, 2006). Greater focus on the indoor environment could therefore lead to an increased use of natural materials (Broome, 2006). As seen for glasswool, the EPDs in INIES (2009) provide an information sheet on health risks. However, in most cases this information is not very precise and largely used as marketing (Floissac, 2009-b).

Other health risks relevant to the assessment are related to the use of plasterboard and paints, wood treatments and other finishes (VOCs). Plasterboard is commonly made of gypsum from industrial waste products, of which phosphorous gypsum often includes radioactive substances (Berge, 2009). Some years ago Criirad (2009) showed that low radioactive waste was 'recycled' into building products such as metals and plaster board. How successful industry has been in keeping hazardous products on the market was demonstrated by Ruers and Schouten (2005) in the study on asbestos producer Eternit, still a leading multinational in building products. However, it is not in the scope of this study to give a comprehensive assessment of environmental pollutants and health hazards.

Table 5.4 *Parameters and indicators not fully quantified in the assessment*

Parameters / indicators	*Remarks / examples*
Health, toxicity and indoor air quality	Difficult to assess; much conflicting information
Breathability	Assess the 1:5 rule for different wall types
Cost of materials (per m^2)	Economies of scale will make ecological materials more competitive
Carbon tax (per m^2)	France and EU : 17 € per ton CO_2eq
Availability of 'eco'materials (local or not)	Problems of certification for ecomaterials Create local production and economy
Carbon storage (per m^2)	COCON carbon storage certificate (*see* 5.2.3) Can have a positive effect on biodiversity
Labour intensity (per m^2)	LI indicator : ratio of kWh per unit EE (*see* 5.2.3)
Availability of skills	Disappearing traditional techniques New ecological materials
Recyclability	E.g. glasswool is recycled but not recyclable
Reuse	E.g. bricks and old daub can easily be reused
Impact on biodiversity	Should be included in LCA and building assessment
Heritage and conservation	The priority for the majority of interviewees

Table 5.4 gives a list of indicators and parameters that are perhaps harder to quantify in LCA, yet equally important to take into account. Building assessment tools, e.g. Milieuclassificatie Bouwproducten (NIBE, 2009) and HQE (Association HQE 2009)[43] already include indicators for health and indoor air quality. And Berge (2009), Oliva (2008) and Woolley et al. (1997) have tried to

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[43] The American LEED (2009), the French HQE, Haute Qualité Environnementale (2009), and the Dutch Milieuclassificatie Bouwproducten (NIBE, 2009).

estimate the importance of some of the qualitative parameters, reflected in an approximate score per building material. In a further study it would be interesting to assess the 20 wall types accordingly. For now Table 5.4 just lists the issues that need further research in relation to the environmental assessment of renovation techniques.

Cocon allows for the inclusion of pricing and labour intensity (*see* 5.2.3), but this is rather difficult to estimate in renovation projects, where every wall is different and jobs are done on a case by case basis. Another cost indicator in Cocon is the carbon tax, which is based on the French tax proposal and a price of 17€ per ton CO_2eq (Pouthier, 2009). Recycling and reuse are often good solutions, but there are a number of barriers related to extra costs for labour, energy and water for reprocessing, transport and cleaning (Harris, 1999).

Reuse can be complicated when inappropriate materials have been used, i.e. cement mortar for bricks or cement render onto old daub. Wattle and daub is without doubt one of the oldest known construction techniques and nowadays a great deal of research and experimentation is done to rediscover the skills of former craftsmen (Houben and Guillaud, 1994). Though wattle and daub can be quickly and cheaply repaired, it is often discarded during works (Bouwens, 1997). When the daub is beyond repair it still is an excellent building material that can easily be reused, simply by adding water, straw and earth (or clay and sand). The new mix can contain more straw to achieve the appropriate density for thermal insulation.

Fig. 34 *Old wattle and daub in need of repair (H.Valkhoff)*

Some of these traditional techniques are already reappearing, e.g. the use of air lime (Interviews, 2009). Several small brick producers in the region, together with the regional council of Midi-Pyrenees and Areso (2009), are working on a LCA study to show the environmental benefits of unfired clay bricks. CAPEB (2009)[44] organises ‘eco-training’ schemes for thermal insulation and

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[44] Eco Artisan programme (CAPEB).

energy saving, and Maisons Paysannes de France (2009) promote the use of traditional techniques and materials. In the Transition Town approach ‘re-skilling’ is one of the main tasks in the transition to a fossil fuel-free society (Hopkins, 2008).

The builders interviewed said they need better information and training programmes to become familiar with traditional and ecological materials. This confirms the outcome of a study by CAPEB (2008) which shows that 62% of French builders give lack of knowledge as the main reason for not using ecological products, whereas 20% say they are too expensive, and only 1% say insurance is the reason. The same study shows that only 10% of CAPEB members “often” use ecological materials, versus 60% “never” and 30% “sometimes”. It is of note that ecological materials are more used in renovation than in new build (CAPEB, 2008).

Chapter 6 (Conclusion) considers the wider implications of the assessment and the way renovation of period timber-frame buildings can also teach us about modern building techniques. The vast majority of these historic buildings are not protected in France, although all but one interviewee said that keeping the aesthetic qualities of timber-frame is the absolute priority. The challenge is to find insulation techniques that do not compromise historic buildings and the principles of good conservation. When trying to achieve higher levels of thermal insulation and airtightness, inappropriate materials that do not ‘breathe’ can bring huge perils to both the health of the building and the occupant (May, 2006). This has been long understood by building conservationists, but this knowledge must be extended to all renovation projects (May, 2006). Builders and architects are aware of this and name humidity control as the main problem in old houses (Interviews, 2009). However, the study shows that the solutions they provide for thermal insulation are often inappropriate.

Fig. 35 *Reparation of wattle and daub (Marcom, 2002)*

Chapter 6 Conclusion

6.1 No one optimum solution

The aim of the study was to find out what the most appropriate techniques are for the renovation of period timber-frame houses. The research question was: how to renovate historic timber-frame buildings in SW France up to modern insulation standards, while preserving the environment and the vernacular qualities of the building, and reducing the embodied energy (EE) and embodied carbon (EC)?

To find out what the current renovation techniques are, interviews were held with builders and building experts. Though the results from the interviews are not representative, they give a good indication of the current context. The outcome was used to select a relevant number of wall types for the assessment, representing a wide range of materials and techniques. These were divided into four main categories: ‘conventional’ walls, ‘ecological’ walls with interior insulation, walls with ‘plant fibre and binder’, and walls with exterior insulation. The interviews confirmed that the most current renovation technique is interior insulation with mineral wool and plasterboard.

To answer the research question 20 timber-frame wall types were compared for their environmental impact and thermal performance. The building assessment tool Cocon (2009) allowed for a comprehensive impact assessment based on LCA data from two French databases, INIES (2009) and Grecau (2009). Despite the limitations of LCA and the lack of LCA data for ecological materials, these databases provide reliable figures which have been checked and compared with other sources, during the course of this study. The cross-checking was done in cooperation with Floissac (2009-a) and has contributed to the continuous updating process of Grecau (2009) and Cocon (2009).

The main focus of the study is the assessment of thermal performance and environmental impact of period timber-frame walls. However, the aim is to find a solution for thermal improvement that does not have a negative impact on the building itself, whether from an aesthetic or structural viewpoint. The assessment shows that there is no one optimum solution which is satisfactory for all these criteria. Though some wall types may be satisfactory from an energy-saving viewpoint, they are not considered appropriate solutions when they have a negative impact on the environment or the building itself.

6.2 Lack of knowledge about appropriate materials

It is clear that the ‘conventional’ wall types have the worst scores in the assessment. This is not only due to their environmental impact, but also because interior insulation completely cancels out the benefits of thermal mass. Furthermore these materials do not let the timber-frame ‘breathe’ and therefore change the natural hygroscopic qualities of the building. Building experts have demonstrated the risk of interstitial condensation, which is a real danger when inappropriate insulation materials are used (Oliva, 2008; May, 2005; Cuquel, 2009; Floissac, 2009).

The interviews (2009) show that one in two builders do not put in a VCL when insulating with mineral wool. They leave a cavity, which often is not fully ventilated and therefore does not eliminate the condensation risk. A quick simulation with Cocon-compatible software showed a great number of dew points in wall M1 (Floissac, 2009-d). In a further study a more in depth assessment of the condensation risk could be done for all the wall types, using more sophisticated similation software, e.g. Wufi (2009).

There is a consensus amongst building and conservation experts that lack of knowledge about materials amongst builders can put timber-frame buildings at risk, to the point of ruining the building (Marchal, 2009; Cuquel, 2009; Taylor, 1998). Although most builders recognise the importance of breathability, they only seem to apply this to the use of natural lime renders and not to the use of appropriate insulation materials (Interviews, 2009). The same is true for the proper use of thermal mass, which they all consider important, though few tend to put this into practice. In most cases exterior insulation is out of the question for aesthetic reasons. Builders believe there is not much choice amongst insulation materials available on the market (Interviews, 2009). They all said they need more information on ecological materials and training programmes to become familiar with both traditional and 'new' techniques that are more appropriate for renovation.

Fig. 36 *Typical timber-frame street in SW France, in Sarrant (Wikipedia)*

6.3 Woodfibre board and earth&straw are the most appropriate

The three wall types with the highest overall scores all have exterior insulation, which gives much better scores for thermal inertia. The walls with woodfibre board on the outside give the best overall results, whereas more conventional wall types with exterior insulation, e.g. polystyrene, do not achieve a satisfactory overall score, due to their high environmental impact.

Due to its thermal resistance, vapour-openness and low embodied energy, woodfibre board is an appropriate insulation material for the renovation of period timber-frame and many other renovation projects. It is an industrial ecoproduct that builders easily get used to using, though it is still about 35% more expensive than conventional insulation materials (Floissac et al., 2008). However, most woodfibre board (Pavatex and Gutex) has to come from Switzerland or Germany.

When exterior insulation is out of the question the earth&straw walls give the best overall results. They are probably more compatible to historic timber-frame than woodfibre board, especially in the case of wattle and daub. Beside their hygroscopic qualities and vapour-openness, timber-frame walls with plant fibre and binder provide an excellent decrement delay and are a good solution for thermal bridging and achieving airtightness in leaky timber-frame buildings (Oliva, 2008; Bevan and Woolley, 2008). The disadvantage of earth&straw is that it is labour intensive and takes several months to dry.

Amongst French builders earth&straw is less well-known than hempcrete. However, hempcrete does not get a satisfactory score in the assessment due to its high EE. Changing the lime binder for clay would lower its environmental impact, though hemp&clay is still at an experimental stage and needs more research (Rhydwen, 2009). Another advantage of earth&straw over hempcrete is that the materials can be found cheaply and locally. Though earth&straw is still waiting for official certification in France (Oliva, 2008; Marcom 2009). At present it is mainly used for the infill of new timber-frame buildings, though it can be an excellent solution for renovation, especially in combination with the repair or reuseof old daub.

The hempcrete wall is not the only ‘ecological’ wall that gets a mediocre score in the assessment. The cellulose wall and the *monomur* do not get satisfactory results either, despite the fact that these are often portrayed as ‘environmentally friendly’. Blown cellulose is still one of the cheapest and widely used ‘ecological’ insulation materials, also in renovation. However, it has very little thermal mass, which brings down the overall score in Cocon. The *monomur* has a very high EE and EC, but is not often used in renovation anyhow, though it is very popular in new build in France, and advertised by the brick industry as an ecological product (Briques de France, 2006).

Furthermore, the assessment shows that conventional interior insulation techniques could still be acceptable if glasswool was replaced by woodwool, which is more hygroscopic and therefore more compatible with ‘breathing’ timber-frame constructions. When used in combination with clay blocks it still achieves a reasonable decrement delay and overall score. Woodwool is becoming a common industrial product and is probably the most competitive way of combining conventional insulation techniques with a widely available ‘renewable’ material.

Fig. 37 *Timber-frame house with hempcrete infill in the UK (www.limetechnology.co.uk)*

6.4 Wider applications and further research

A lot of the results from the assessment are also applicable to new timber-frame buildings or to other renovation projects that take the vernacular qualities of old buildings into account. Cocon can be used for all types of construction and is normally used to assess a whole building, including its operational energy. In a further case study on historic timber-frame buildings it would be interesting to look at whole buildings, testing several wall types from this assessment. Comparing several case studies could give an indication of which techniques are more appropriate for particular walls and situations. Comparison could also be made with renovation techniques used in other regions and countries with a lot of timber-frame buildings, e.g. Normandy, the Alsace, Germany and the UK.

Taking into account climatic parameters (e.g. orientation, solar gain, wind and weather) and the different use of certain parts of the building, would make some techniques and materials more apt than others. For example, a north facing wall that does not have its façade exposed to the street can be suitable for exterior insulation. It would also be interesting to take interior walls and floors into account and see e.g. if the loss of thermal mass can be compensated for elsewhere in the fabric. Note that in the climate of SW France thermal mass is beneficial in summer, but can be a disadvantage in winter in leaky and intermittently heated buildings (George, 2008).

A further case study could also take the cost of labour and materials into account, and estimate the number of building miles for imported materials. The labour intensity factor proposed by Floissac et al. (2009) deserves further study and is an interesting socio-economic concept for the development of a locally sourced and sustainable construction industry.

6.5 Lack of scientific data on the benefits of ecoproducts

The study shows that there is a general lack of scientific data on ecological building materials. This concerns their environmental impact as well as the building physics, e.g. the benefits of thermal mass and 'breathability'. Several studies, e.g. Evrard and Herde (2005), show how the dynamic thermal performance of insulation materials can be very different from the 'steady state' situations used for thermal regulations. For example hemp walls perform better than one may expect from simple R-values, due to the benefits of thermal mass, hygroscopicity and reduction of thermal bridging (Bevan and Woolley, 2008).

Although it is a new field of study, there is strong evidence that natural materials which are vapour-open and hygroscopic can reduce the necessity for other means of humidity control such as VCLs and mechanical ventilation (May, 2005). Humidity control is not only vital for buildings, but also for the control of moulds that affect human health (May, 2006). German building regulations already acknowledge that vapour-open and hygroscopic materials protect the timber-frame through natural humidity control, which reduces the need for wood treatment (May and Newman, 2008). This applies to both new build and renovation.

In a further study it would be interesting to add an indicator for 'breathable' walls to the assessment and find out how many wall sections follow the 1:5 rule of thumb, whereby the exterior layer is 5 times more vapour-open than the interior layer (Borer and Harris, 2005; Oliva, 2008). Other insulation materials, e.g. hemp and flax batts could be taken into account. Sheepswool is generally not suitable for walls, because it is not rigid enough, and was therefore left out of the assessment.

More research needs to go into the production and application of natural building materials from plant fibres (Van Dam, 2005). The assessment shows that the walls with 'plant fibre and binder' store considerable amounts of carbon. There are many claims for the environmental benefits of using renewable building materials that store carbon (Berge, 2009; Harris, 2009; Bevan and Woolley, 2008; Cornillier and Vial, 2008). However, there is no scientific consensus in the LCA community on carbon storage. Some authors maintain that the inclusion of carbon sequestration only makes sense in a wholly sustainable state of production and consumption. Furthermore, carbon sequestration by building materials is only temporary and depends on what happens at the 'end-of-life' of a product.

Renowned LCA databases, e.g. Ecoinvest (2009), now take carbon storage into account. And so does Grecau (2009), which was used in the assessment. Cocon gives an indication of the amount of renewable materials that are 'biosourced' and allows the calculation of carbon storage certificates. Perhaps Cocon is slightly biased against building elements that do not store carbon, because even walls that are 'carbon neutral' get a mediocre score of 10 out of 20 (50%) for EC. Though this is true for all the walls in the assessment.

Carbon storage in building materials has a great GHG mitigation potential, which applies to both renovation and new build. However, further research and scientific consensus on calculation methods are needed. We know that carbon storage in historic buildings can last from some decennia up to over a thousand years (Cornillier and Vial, 2008). A several hundred years old timber-frame houses is probably one of the best examples of a quasi-permanent carbon store. And at the 'end-of-life' of a building the timbers can be reused to prolong their carbon store (Harris, 2009).

6.6 Limitations of LCA data

The Literature Review (section 2.3.2) shows that there is no consensus on the French LCA methodology for calculating the EE of renewable materials. The latest EPDs for construction timber still include feedstock energy, which unjustly puts up the EE (Cornillier and Vial, 2008). Therefore the data for sawmill wood products in Grecau (2009), which are an extrapolation of the EPDs, increase the EE of all the wall types that include wood cladding, studs or frames.

A similar problem arises with the lime render data in Grecau (2009), that do not take recarbonation into account, and therefore show a high EC. According to Berge (2009) recarbonation in natural lime renders is 80%. Taking this into account would give most walls in the assessment a much better score for EC or climate change.

One of the main limitations of the assessment is the lack of reliable, comparable and independent LCA data, both for conventional and ecological materials. Section 2.3.1 has pointed out that the problems with LCA are the different weighting methods and system boundaries which can lead to rather different results. All LCA based building assessment tools have this problem. The advantage of Cocon, e.g. compared to Envest-2 which is based on data from the Green Guide (BRE, 2009-b), is that the EPDs in INIES (2009) and the overall scores in Cocon are a lot more transparent. Future European harmonisation of LCA procedures might resolve some of these problems, e.g. the controversial energy calculations in the French EPDs (Cornillier and Vial, 2008).

Another limitation of LCA is that it provides a purely quantitive approach. It does not include some important factors and parameters that are difficult to quantify, e.g. health, indoor air quality, biodiversity, re-use, labour intensity, 'reskilling', conservation issues, etc. This is a vast area for further research that concerns the construction sector as a whole, not just the renovation of historic timber-frame buildings.

6.7 Thermal insulation and good principles of conservation

The French refurbishment programme will have a big impact on the renovation of period timber-frame buildings (Gironnet, 2009). Therefore it is vital to have more reliable figures on the number of period timber-frame houses in France. For towns and villages in the south-west which historically had a lot of timber-frame, probably around a third of the buildings in the old town centres are still timber-frame. However, this a broad extrapolation from a small survey in twelve towns and villages in the Tarn (Béa, 2006). Hopefully the ongoing national BATAN survey on energy consumption in houses before 1948 will give more representative figures (CETE, 2009).

From the mistakes made in the past we know how much damage inappropriate renovation can do to timber-frame houses. The problem with thermal regulations is they are not adapted to historic buildings (Cuquel, 2009). It is essential to understand the physical characteristics of old buildings, and we need more scientific studies that explain their vernacular qualities (Marchal, 2009).

The study shows that insulation with natural and 'breathable' materials is better for the environment, the building and the occupant. However, all insulation needs to be carefully applied to avoid any damage to the building fabric (May, 2006). The study shows that the main reason why natural materials are not used is lack of knowledge. At present, most of these materials are more expensive, or the techniques are labour intensive. Though all respondents agreed that the market is evolving rapidly.

The answer to the renovation problem seems to be training and education and better access to appropriate materials. Most builders that work on renovations are not specialised in restoration (Cuquel, 2009). Restoration skills are rapidly disappearing, yet urgently sought after (CAPEB, 2007). Clearly we are only at the beginning of (re)learning about natural and traditional materials and techniques, and their contribution to the energy-efficiency of historic buildings (May, 2006). That is why traditional building technology is not about the past but about the future of buildings (May, 2006).

There may not be much time to learn, however, in the current drive for better insulated buildings most old buildings will soon be boarded up with mineral wool and plasterboard. This does not only concern timber-frame, but all historical buildings that need to meet modern insulation standards. Paradoxally this drive for sustainable development may well go against the principles of good conservation (Marchal, 2009). The study clearly shows there are appropriate techniques that follow good conservation principles, however, it is the task of builders, 'renovators' and conservationists to put these into practice before it is too late.

Fig.38 *Old renovation made timber-frame house look like stone (H.Valkhoff)*

Appendix III.i Cocon for building assessment

The two Excel workbooks used for the assessment are on the CD

Scenario (of the assessment)

In the *scenario* sheet one can chose construction (new build), renovation, rehab or restoration. However, this is only for visibility in graph and figure titles and does not have any consequences for the calculations. In the *scenario* sheet one can also chose the thermal insulation norm or energy label, the altitude (200m in this study), and the climate coefficient (0.9 for SW France).

Options (in Cocon)

Linear method When the lifetime of a building is 100 years and the lifetime of a window is 30 years, it needs 3.3 replacements. When the lifetime of a building is 70 years and the lifetime of a window is 30 years, it needs 2.3 replacements. This is the method that was used in the assessment.
Rounded method When the lifetime of a building is 100 years and the lifetime of a window is 30 years, it needs 4 replacements. When the lifetime of a building is 70 years and the lifetime of a window is 30 years, it needs 3 replacements.

There is the *option* with or without renewable energy (RNE). Despite the controversy over the primary energy (E_p) calculations, it is more appropriate to chose with RNE, because all the EPDs in INIES (2009) include RNE. And for a lot of the data in Grecau (2009) there is only the total E_p available, no while the RNE is not specified.

Calculation of scores for six parameters

Thermal Resistance For a R-value that equals the lower level of the chosen insulation standard or energy label, the Cocon score is 10; for a R that equals the upper level, the Cocon score is 15. On either side of the lower or upper level the score will be lower than 10 or higher than 15.

This calculation also takes the climate zone and the altitude into account, and R-values of boundary layers are included by a default value of 0.2 for interior and exterior layers together, which is a standard French approach (Bernstein et.al, 2007).

For each of the remaining 5 parameters Cocon gives an overall score (1-20) which is a simple linear interpolation on a somewhat arbitrary scale with an upper and lower limit, taking the real values from the LCA or other source data. Below the lower limit gives a zero score, above the upper limit a maximum score of 20 (Table III.i).

Table III.1 *Upper and lower limits for the 6 parameters in Cocon (2009)*

INDICATOR	Unit	Norm	Lower limit	Upper limit
Thermal résistance (R)	m²°k/W	RT-2005	2.0	2.9
		RT-2007	2.3	2.8
		BBC-reno	2.1	2.9
Embodied energy	kWh/m²		0	300
Embodied carbon	kg CO2eq/m²		-150	150
Decrement delay	h (hours)		0	12
Thermal Inertia (admittance)	kJ/m²K		0	250
*Resource depletion**	Kea		-	-

Embodied energy (with RNE) The primary energy (E_p) calculation in a LCA is divided into process energy (used during the production) and feedstock energy (the combustion energy that is stored in the material). Both these types of energy can than be divided into renewable energy (RNE) and non-renewable energy. In an ideal situation it would be better to use the EE or E_p without the ambivalent calculation of RNE (*see* 3.2).

Embodied carbon The score for climate change is based on the somewhat arbitrary scale with upper and lower limits of +150 and -150 kgCO2eq (Table III.1). For a zero carbon wall (i.e. no emissions, no storage) the score is 10, which is rather low. Therefore only walls that store carbon can achieve scores above 10. Changing the range of the scale, with a lower limit of 100 kgCO2eq, an upper limit of 150 kgCO2eq, and a score of 12 for zero carbon, would have been more balanced perhaps.

*Resource depletion** The unit is kilogram equivalent of antimony (kea), a rather rare element that is used as in indicator of scarcity and resource depletion in most LCA. There are no upper an lower limits (the formula for the score in Cocon is: -log.kea.20/3). The values vary to such an extent that it is hard to interpret the impact score.

Decrement delay ('summer comfort') the number of hours between the highest outdoor and the highest indoor temperature (*see* 2.4.1).

Thermal inertia In an earlier version of Cocon thermal inertia had a rather high upper limit of 350 kJ/m²K. With the new upper limit Cocon gives better scores for inertia. The complex calculation for inertia is based on ISO 13786 (2006-b) for thermal performance of building components and takes the position and dynamic characteristics of all the layers into account.

Appendix III.ii Extrapolation of data

At present INIES barely covers very common building materials, such as fired bricks (plain and hollow), natural lime mortars, wood cladding, etc. Simply because the industry has not provided EPDs on these products yet. The next section will compare the data of some of these materials used in the assessment with data from other sources. Note that the figures in the Tables *in blue* are the data used in the assessment. Some of the limitations regards data from LCA and other sources are explained in chapter 2.3 and discussed in chapter 5.2.

Bricks

So far there are only two types of fired clay bricks in the database, both hollow bricks (clay blocks) which are most common in France. There is no information on plain fired bricks. Therefore Grecau and Cocon use an extrapolation based on the EPD for clay blocks (Floissac 2009-a). There are also no data for 10cm hollow bricks, often used as infill in timber-frame, so in Cocon one has to chose 5cm hollow bricks from the INIES database and double the thickness (Table III.2).

Table III.2 *Comparison of EE and EC data for fired bricks and clay blocks (10cm)*

	Density kg/m^3	*EE* MJ/kg	*EE* kWh/m^2	*EC* gCO_2eq/kg	*EC* kgCO_2eq/m^2
Grecau (bricks)	**1.500**		**108**		**21**
Grecau (clay blocks)			**65**		**13**
Berge (bricks)	1.700-1.900	3.00		190	
ICE (bricks)		3.00		200	
Oekobilanz (bricks)		3.03		247	

Fig. III.i *Dimensions and weights of hollow bricks (clay blocks)* (Terréal, 2007)

Code produit	Dimensions ép x h x L (cm)	Poids (kg)	Quantité/m²	Rrose [1] (dB)	Ru [1] (m²/K.w)	Coupe feu avec enduit plâtre 5 mm/face	Coupe feu avec enduit plâtre 10 mm/face
1 rangée d'alvéoles pour montage cloisons de doublage							
CL01	3,5 x 20 x 40	2,6	12	-	0,08	-	-
CL02	4 x 20 x 40	2,7	12	-	0,10	-	-
CL03	5 x 20 x 40	3,0	12	30	0,10	1h	1h30
CL04	3,5 x 25 x 40	3,2	10	-	0,08	-	-
CL05	4 x 25 x 40	3,4	10	-	0,10	-	-
CL06	5 x 25 x 40	3,6	10	30	0,10	1h	1h30
2 rangées d'alvéoles pour montage cloisons de distribution							
CL07	7 x 20 x 40	4,2	12	32	0,16	1h	1h30
BCR05	10 x 20 x 50	6,2	9,5	36	0,16	1h	1h30

(1) Valeur pour cloisons finis avec enduit plâtre 10 mm / face

A quick extrapolation shows that the Cocon data are reliable compared with figures from other sources such as the Swiss database Oekobilanzdaten (KBOB Ecobau, 2009), ICE (2009) or Berge (2009). As these give EE and EC data per kg material, one can argue to use them for hollow bricks as well. A quick calculation based on a commonly used Terréal hollow brick of 10 cm, that weighs 6.2 kg, gives an EC of 13 kgCO2eq/m^2, when using the average EC of Oekobilanzdaten and ICE. This is exactly the amount of carbon that Cocon gives when using two hollow bricks of 5cm.

Lime

The main problem with data for lime renders and mineral mortars in Grecau (2009) and INIES (2009) is that they do not take recarbonation into account. This is the amount of carbon dioxide absorbed by the lime during the drying process (*see* 2.3.4). In Cocon there is the choice between a mineral based mortar from INIES (2009), and a lime render from Grecau (2009). The first one is based on a LCA for "mineral mortars and coloured renders based on hydraulic binders" which does not specify how much lime, how much cement, pigments (resins) or other additives it contains (SNMI, 2007)[45].

Because all builders interviewed use lime renders for timber-frame walls, and not mineral mortars or coloured renders, the assessment uses natural lime render data from Grecau (Table III.3). Grecau (2009) does not specify what type of lime it is, hydraulic (NHL) or air lime (CA), and does not take recarbonation into account. The Discussion (Ch. 5) shows that therefore a substantial part of the EE and EC of most wall sections is due to the lime renders. Accounting for recarbonation should reduce the EC with roughly 80%, depending on the type of lime (Berge, 2009). According to the figures from the lime industry the reduction is even 90% (St Astier, 2006). Table III.3 also shows lime data and EE and EC from other sources, which are only illustrative. As said, despite its limitations the assessment uses the Grecau data.

Table III.3 *Comparison of EE and EC data for lime render/mortar (2cm)*

	***Density* kg/m^3**	***Embodied energy* kWh/m^2**	***Embodied Carbon* gCO_2eq/kg**	***EC* kgCO_2eq/m^2**
Grecau (INIES)	*mortier mineral* 1.600kg/m^3	23	208	7
Grecau/Cocon	***lime render*** **1550kg/m^3**	**20**	**277**	**9**
Berge	lime plaster 1.700kg/m^3	9.7	190 70 (190-120)	6.65 (ex. recarb.) 2.45 (+ recarb.)
Oekobilanz	cement render	1.78 MJ/kg	218	
Lime technology	lime render			1
St Astier	lime mortar (1:3) 117kg/tonne		39	1.2

Calculations: Berge (2009) EC : 0.02x1700=35kgx190g=6.65kgCO2eq/m2 ; EE : 1MJ/3.6=0.278kWhx35kg=9.7 kWh/m^2 ; Lime Technology, in Bevan and Woolley (2009) ; Grecau, extrapolation based on Oekoinventaire, Ofen (Floissac, 2008); St Astier (2006) (39kg/tonne) 39g/kg x 0.02m x 1.550kg/m3 = 1.209 kgCO2eq/m^2.

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[45] SNMI Syndicat National des Mortiers Industriels

Wood cladding

For wood cladding similar confusion arises. The entry *bardage bois massif* (wood cladding) in Cocon gives rather high figures for EE and EC (Table III.4), but is based on old data from CTBA (2008). Another option for cladding in Cocon is Okume plywood, based on the official EPD (INIES, 2009), which strangely enough gives better results than the first entry. However, it is not common to use plywood for cladding of period timber-frame houses, and it would not make sense to use tropical hard wood either. Therefore in the assessment the option *planches* (planks) was chosen, under the entry *bois scié* (sawn wood), which figures are based on recent EPDs for construction timber and take carbon storage into account (FCBA, 2009). These figures are based on extrapolation by Floissac (2009-a) and differ somewhat from Berge (2009) figures for air dried timber, which have a lower EC, but a higher EE (Table III.4). The reason for the higher EE may be that Berge (2009) takes more feedstock energy into account (*see* 2.3.2).

Table III.4 *Comparison of EE and EC data for wood cladding (2cm)*

	Type of wood (density)	*Thickness*	*EE kWh/m^2*	*EC kg CO_2eq/m^2*
Grecau (CTBA)	Wood cladding 500kg/m^3	2 cm	67	22
Grecau (INIES)	Plywood Okume 500kg/m^3	2 cm	94	1
Grecau (Floissac)	**Wooden planks 500kg/m^3**	**2cm**	**19**	**- 3**
Berge (2009)	Timber air dried 550kg/m^3	2cm	50	- 6

All these data include feedstock energy (see 2.3.2)

Calculations: Berge (2009) includes carbon storage (timber 300g/kg - 850 = -550g/kg); EC = 11kg x -550g = -6 kgCO2eq/m^2; EE = 16.5MJ/kg = 16.5/ 3.6 x 11kg = 50.4 kWh/m^2. *Note*: Berge (2009) feedstock energy = 16MJ/kg for 16.5MJ/kg primary energy.

Cork

Looking at different sources with data on EE and EC for expanded cork insulation boards again gives a wide range of figures (Table III.v). In Grecau (2009) alone the data vary to such an extent that using one or another material and source for expanded cork can put up the overall score of the wall section (M8) by one to two points. To find a balance between the data the choice was made for 'pure' cork at 125kg/m3 density, even though this comes in pellets and not in boards. Despite its higher thermal conductivity (λ=0.049) this gives a more advantageous result for EE and EC, compared with the cork boards (λ=0.040) in Grecau and the figures from Berge (2009) and Oekobilanzdaten (KBOB Ecobau, 2009). At present INIES (2009) does not give data for cork insulation.

Table III.5 *Comparison ofEE and EC for cork boards*

	10cm cork (expanded)	*Density* kg/m^3	*Embodied energy kWh/m^2*	*Embodied Carbon* kgCO_2eq/m^2
Grecau/Cocon	Boards	120	88	16
Grecau/Cocon	“Light”	125	9	-71
Grecau/Cocon	**“Pure”**	**125**	**9**	**-23**
Berge	Boards	130	100	-2.9
Oekobilanzdaten	Boards	N/A	172	15.2
Oliva	Boards	120	9	N/A

Calculations and sources : **Berge** (2009) : EE = 12kg x 30MJ/3.6 = 100 kWh/m2 ; EC = 600 gCO2eq/kg - 825 gCO2eq/kg = -225gCO2eq/kg x 12kg = -2.9 kgCO2eq/m2 **Oekobilanzdaten** (2009) : EE = 12kg x 51.6 MJ/3.6 = 172 kWh/m2 ; EC = 1270g gCO2eq/kg x 12kg = 15.2 kgCO2eq/m2 ; Grecau (16) extrapolation Floissac (2008) from Oekobilanzdaten ; Grecau (58) Office Federal de l'Energie, Switserland (OFEN, 2008) ; Oliva (2009) nor Berge (2009) specify where their primary cork data come from, though Berge gives a long list of sources for his Table 1.4 (p.26) and Table 2.8 (p.46).

Lack of transparency in Green Guide

In the Green Guide for specification (BRE, 2009) a potentially 'ecological' exterior wall section, e.g. timber-frame clad with clay tiles, will get the same maximum A+ rating per functional unit as a PVC clad timber-frame wall. The PVC performs even better than the clay tiles and has only two impact category A-ratings, the rest is all A+. Whereas the clay tile shows some category A and B-ratings, amongst seven A+ratings. For some reason - weighting of the impact categories perhaps ? – the clay tiles still receive an overall A+ rating. Furthermore, for both wall sections the insulation material is not even specified, neither are the type of OSB or plasterboard. This example shows a complete lack of transparency, which makes it impossible to use the Green Guide data for cross-referencing.

Appendix IV.i Interview results

1. Interview coding tables and english summary of transcripts

(*See next section for questionnaire*)

A.Renovation techniques

Table IV.1 *Coding of interview questions 1-4*

1 Problems and Diagnostic	3' Techniques *Infill*	3'' Techniques *Insulation*	4. Type of insulation
Humidity A1a,B1a,C1a,E1a,F1a,G1a	*Bricks (exposed)* A3'a, B3'a, C3'a, G3'a, H3'a	*Interior: plaster board and insulation* A3''a, B3''a, C3''a, D3''a, H3''a	*Glasswool* A4a, B4a, C4a, H4a
Structural (modifications) G1b, D1b, H1b	*Hollow bricks (render)* A3b, B3'b, C3'b, D3'b, G3'b	*Interior: hollow brick and insulation* A3''b, C3''b	*Rockwool* A4b, B4b, C4a, D4b
Daub in bad shape A3c, G1c, D1c	*Take out daub* A3c, B3'c, C3'c, D3'c	*Interior: hempcrete* E3''c, G3''c	*Hempcrete* G4c
Cement renders D1d	*Render old daub* B3'd, C3'a, D3'c	*Interior : earth and wood shavings* G3''d	*Sheepswool* G4d
Termites B1e	*Remake daub(cob)* G3'e, H3'e	*Exterior: wood cladding* E3''e, F3''e	*Woodwool* D4e, H4e
	Reuse old floortiles B3'f	*Monomur* A8f, B24f	*Cork (pallets)* G4f, F4f
	Unfired Bricks G3'g, H'3g		*Wood shavings* F4f
	Hempcrete (lime) G3'h		*Straw (bale)* F4f
	Earth and straw G3'i, H3'i		
	Earth and shavings F3'j, G3'j		
	Strawbale F3'j		

Table IV.2 *Coding of interview questions 5-9*

5. Timber exposed	6. Type of exterior render	8. Preferred technique	9. Most difficult
YES, aesthetics A5a, C5a, D5a, G5a, H5a	*Lime (NHL)* A6a, D6a, F6a, H6a	*Timber and bricks exposed* A8a, B8a, C8a, G8a	*Humidity* F9a, G9a
YES, let the timber continue to work B5b	*Lime (CL)* A6a, B6b, E6*b, G6b, H6b	Earth& straw H8b	*Restore the old timber structure* A9b, B9b C9b, D9b, H9b
		Rammed earth E8c	*Choice of insulation* E9c
NO, infiltration of water and air F5c	*Ready Mix (CL-NHL)* C6c	*Monomur* A8d	
	Earth F6d, H6d	*Hempcrete* D8e, G8e	
		Strawbale F8f	

Interviews renovation techniques

1. Most respondents name humidity as the main problem, mostly due to rising damp from cellars and ground floor walls. This can cause structural problems of course and can also lead to serious insect infestation, e.g. by Capricorn beetles and termites who thrive on humidity. According to one of the builders, Bonnet (2009), termites can even eat through the heart of century old oak timbers.

3 *a. Infill* The fact that hollow bricks are the most frequently mentioned, doesn't mean this is *the* most common technique. Most respondents give this as an alternative for normal fired bricks when these are too expensive, or when the client and the builder decide not to leave the façade exposed. One of the builders, Bonnet (2009), reuses old floor tiles (often on site), which he cuts into strips of 10cm and which he uses as 'new' brick infill. All interviewees seem to agree that the original daub is often in too bad a state to restore. This would take too long. The daub is mostly knocked out straight away and put in a skip. Especially when the outdoor render was cement based it is hard to keep it, because it all comes apart when the cement is taken off. The architect has done one project where new daub was made. This took 7 hours per m2, which normally is not economically feasible (Collart, 2009).

When the daub is in reasonable condition, however, it is often repaired (not restored!) by filling the holes and fixing the wattles, and then re-rendered. When the timbers are exposed on the outside (in most cases), they attach chicken wire mesh between the timbers to reinforce the old daub and the new lime render. This is a common technique, which often gives a slightly rounded and bulky effect. "Not very pretty", according to Collart (2009). Originally, a lot of these houses were not built to have their facades exposed (Collart, 2009). This was only the case for the 16th and 17th century Toulousian style houses with more expensive brick infill (Béa 2009). From the 18th century onwards most timber-frame houses were rendered on the outside (Bea, 2009). Nowadays, however, clients often ask for the Toulousian style, with the red bricks and oak timber exposed on the outside (Bonnet 2009).

b. Insulation The most common renovation technique in the region is definitely interior insulation by means of doubling the timber-frame wall with plaster board and mineral wool, frequently done by a 'plaquiste', not the builder himself. The plasterboard is fixed onto a metal frame, with insulation behind it and an air gap of 4 or 5 cm between the outside wall and the insulation. As we will see later (14.), most builders don't put in any form of vapour control layer. Humidity is ventilated through the air gap. Another common technique is doubling on the inside with slim hollow bricks (5 cm) and mineral wool behind it. This is slightly more expensive than the plaster board option.

Two of the interviewed builders have also used insulation clay blocks, known as 'monomur', to double walls on the inside. This can only be done on a proper foundation or stone wall, as these bricks are much heavier and wider (30 cm) than the traditional timber-frame infill. The architect and ecomaterials supplier prefer an infill and insulation with hempcrete (30 cm). Or a light earth mix of clay (earth) and wood shavings, lightly rammed into an extra wooden frame, using reed mats as shuttering, which can be rendered with lime or clay (earth). The ecobuilding expert, Floissac, proposes a similar technique. Marcom proposes a sort of cob mix (*bauge*) with earth and hemp, or otherwise earth&straw.

4 The most commonly used insulation product is mineral wool, which is used by all four builders that were interviewed, whether it's glass or rock wool. Only the architect, the expert, and the materials supplier give alternatives. The supplier, Drouilleau (2009), calls the use of mineral wool and plasterboard "a heresy". And the architect, Collart (2009), says that we are witnessing "a massacre" of these types of buildings. One of the builders, Alexandrov (2009), rightly points out that there is "a lot of progress to be made regards insulation products", because there is not a lot of choice of non-polluting materials with a CSTB certification. To avoid glass and rock wool builders also use reflective multi-layered insulation products, knowing these are not a optimal solution either (Alexandrov, 2009).

5 Keeping and improving the aesthetic qualities seems to be the priority for most respondents. Except for the building expert, they all want to keep the wood and brick (or daub) exposed, if possible. The majority prefers a Toulousian style brick infill.

6 They all use lime, because it allows the building to breathe. Cement renders are out of the question now, due to the damage these have done in the past. All interviewed builders are familiar with the traditional techniques and know the different qualities of different types of lime. They all seem to be aware that the walls need to breathe, in order for humidity to escape. Surprisingly the majority uses 'air lime', which is the purest form of natural slated lime. This is the most suited to these type of brick and daub filled buildings, not only because it lets the building breathe, but also because it is very flexible and less likely to crack. It takes longer to dry, however, and is more friable than hydraulic lime. To avoid micro fissures some masons add polyester fibre to the exterior render.

7 The preferred renovation techniques and materials have already been discussed under 3. and 5. The majority prefers Toulousian style brick and timber-frame walls. It is clear from Table IV.2. that none of the interviewees gives much attention to the maintenance or restoration of the daub, which still seems to be considered an inferior material. Also because it takes "ridiculously long" to restore or rebuild it properly (Collart, 2009).

8 The most difficult thing in timber-frame renovation for most respondents is the maintenance of the old wooden structure and its aesthetic qualities. Collart (2009): "Despite the deformations and the fact that a timber-frame building is a house of cards, it has a great flexibility and capacity to endure the centuries and resist the elements, even earth quakes".

B.Insulation techniques

Table IV.3 *Coding of interview questions 10-13*

10.Thickness	11.Abiding norms (RT-2005)	12 Au fay with BBC	13.Consider thermal bridges
8 – 10 cm ; A10a, C10a, D10a, G10a, H10a	*YES ;* A11a, C11a, D11a, F11a, G11a, H11a	*YES ;* E12a, F12a, G12a	*YES ;* A13a, B13a, C13a, D13a, F13a, G13a, H13a
6 cm ; E10*b	*NO ;* E11*b	*Hear say ;* A12b, D12b, H12b	*NO ;*
≥ 10 cm ; F10c	*Don't know ;* B11d	*NO ;* B12c, C12c	*Don't know ;* E13*c
Don't know ; B10d			

Table IV.4 *Coding of interview questions 13-18*

14. Damp screen	15. Breathing walls	17. Exterior insulation	18. Consider thermal mass
YES ; D14a, E14*a	*YES ;* B15a, D15a, F15a, G15a, H15a	*YES ;* D17a, E17a, F17a,	*YES, if possible;* D18a, F18a, G18a, H18a
NO ; A14b, C14b, H14b	*YES, essential in old buildings ;* A15b, C15b, E15b	*Good idea, but not for timber-frame facades* A17b, C17b, G16b, H17b	*NO ;* C18b, E18*b
YES, freine vapeur ; F14c, G14c	*NO ;*	*NO;*	*Don't know ;* A18c, B18a
Don't know ; B14d		*Don't know ;* B17d	

Interviews insulation techniques

10-12. All the interviewees seem to abide to the insulation norms as defined in the Réglementation Thermique (RT, 2005). One of the builders didn't want to answer the questions on insulation, because it's not him that applies it but his colleague, the 'plaquiste'. The materials supplier is quite sceptical about the builders saying they abide to the insulation norms. Drouilleau (2009) reckons they often "cheat" on the thicknesses, to save money: "instead of 8 or 10cm, they often put in 4 or 6cm. Once it's behind the plasterboard no-one verifies it." In the first section on renovation techniques we already saw that most builders use mineral wool for insulation. The BBC label for renovation (Effinergie, 2009) is not much stricter than the RT-2005, but most builders have not heard of it, or do not know what it actually implies.

13. Interesting is the fact that all the respondents are aware of thermal bridging and seem to have some understanding of how this works. Remarkable is that some builders mention that the air gap between the wall and the insulation will sufficiently stop thermal bridging. Collart architect says that nowadays builders and architects pay a lot more attention to thermal bridges than in the past.

14. It is surprising that two of the four builders interviewed do not apply vapour control layers (VCLs), and do not see the purpose of these in the renovation of timber-frame. They refer to the air gap between the wall and the insulation for humidity control. Collart (2009) and Floissac (2009-b) advise a breathable damp screen (*frein vapeur*) when using mineral wool, because this is a building regulation. They both stress the fact that it is a big debate in the (eco)building sector, whether to put up a damp screen or not (*see* 2.4.3). The material supplier reckons that even a breathable damp screen stops the building from breathing (Drouilleau, 2009). Floissac (2009-b) says that the air gap does not do much, because it's neither airtight nor ventilated, so their will always be convection (above 1.5cm width). There also is a big risk of condensation onto the interior of the timber-frame wall which is the first cold surface (*see* Ch. 2 and 5).

15. All interviewees are aware of the fact that a period timber-frame building needs to breathe in order for humidity to be able to escape. Several builders say that this is the main reason why they work with lime. And some again mention the role of the air gap in the natural ventilation and humidity control of the envelope. There is always rising damp in these houses, says Alexandrov (2009). If the walls do not breathe, the humidity can creep up by capillary action as high as 1.5 or 2m (Alexandrov, 2009).

17. The builders recognise the advantages of exterior insulation, but think it is a shame to apply this to period timber-frame, for aesthetic reasons. From the answers to question 16 it is clear that cladding is not common in this region. Wood cladding was sometimes applied on NW walls that were exposed to bad weather. Nowadays the renders are better and masons often add a breathable water proof layer or hydrofuge (Parro, 2009).

18. The question about thermal mass and summer comfort often lead to some hesitation, especially on the part of the builders. Some say they take it into account, if possible. E.g. when insulating with the 'monomur' that has a high thermal mass. However, we know that in most renovations timber-frame houses are insulated from the inside with plasterboard and mineral wool, which means they lose a lot of thermal mass.

C.Ecobuilding and renovation

Table IV.5 *Coding of interview questions 19-22*

19. Ecobuilding	20. Impact of Grenelle	21. Au fay with HQE	22. HQE and renovation
Develops quickly ; A19a, C19a, E19a, G19a, H19a	*YES, a lot of talk about it ;* A20a, H20a	*YES ;* E21a, F21a, G21a, H21a	*Possible ;* C22a, F22a, G22a
All for it ; C19b, F19b	*YES, but not enough*; C20b, E20b, F20b, G20b	*Hear say ;* A21b, D21b,	*Difficult ;* A22b,
Don't believe in it ; B19c	*No, not significant ;* C20c	*No, don't know ;* B21c, C21c	*Not possible ;*
	Don't know ; B20d		*Depends ;* E22b
			Don't know ; B22d, C22d, H22d

Table IV.6 *Coding interview questions 22-24*

24. Who proposes use of eco materials	26. Awareness of embodied energy	27. Know the origin of materials	28. Willingness to use eco materials
The client asks for it ; C24a	*YES* ; A26a, D26a, E26a, F26a, G26a, H26a	*YES, mostly* ; A27a, B27a, E27a, H27a	*YES, certainly* ; A28a, D28a, E27*a, F27a, G28a, H28a
We propose it ; F24b	*NO, not really* ; C26b	*YES, some* ; C27b, D27b, F27b, G27b	*YES, why not* ; B28b, C28b,
Either way ; A24c, D24c, E24c, G24c, H24c	*Don't know* ; B26c	*NO* ;	*NO* ;
Neither way ; B24d			

Interviews ecobuilding and renovation

19. Most interviewees say the market for ecobuilding develops rapidly. The majority says that the mentalities have changed in the last few years, both of builders (and architects) and clients. There is only one builder who does not believe in eco building or eco renovation, saying that 100% eco products do not exist.

20. The majority has heard of the Grenelle de l'Environnement, but not necessarily of the recently voted first Grenelle Act with the Plan Bâtiment, which includes the 'eco loans' and tax breaks for insulation materials and renewables. Some reckon it is not enough, and say it is mainly focussed on new buildings. Others think that once these incentives stop, it will all fall to pieces again, just like in the seventies (Drouilleau, 2009).

21-22. The 'conventional' builders interviewed do not really know what HQE means. So it is hard to find out what they think it could do for renovation projects. Collart (2009), Marcom (2009) and Drouilleau (2009) are very sceptical about HQE and say it is just a voluntary engagement, not necessarily a good reference for eco projects. You can get the HQE label easy enough with breeze blocks and polystyrene (Collart, 2009). Drouilleau (2009) reckons it is a political programme that only works in the public sector, "though it does not stop them using glasswool everywhere". Marcom (2009) calls it a scam, used by the industry for green washing.

24-25. Several times interviewees have said that house owners especially, are creating a demand for eco materials. They ask for natural and healthy materials and do not want us to use glass wool or other toxic materials (Alexandrov, 2009). Some are willing to pay more, but it depends on their budget and the availability of techniques and materials. Products like the Monomur might be 30% more expensive, but money is saved on insulation and plasterboard, so it works out cheaper in the end (Bonnet, 2009). A lot of clients also use eco products themselves, and sometimes do part of a renovation project themselves to save money (Parro, 2009).

The materials supplier sees a big increase in the demand for eco products, especially from house owners and self builders. However, the building companies do not take any risks, they are the ones that slow things down (Drouilleau, 2009). Builders tend to stick to the materials and techniques they know. Alexandrov (2009) agrees with this, and says it's the older generation that does not want to change. The younger builders are more open minded and, to survive, they are obliged to adapt to new markets and techniques. The CAPEB (2009-b) has started the programme ECO Artisan, but most interviewees have not heard of it, or have not shown a particular interest.

26. There is quite an awareness of the embodied energy of building materials amongst the interviewees. One of the builders says he gets his bricks from Imerys, e.g., because he knows they're made locally. Alexandrov (2009): "The more we use local building materials, the less we create transport and CO2. At the end of a project this can result in one or two lorries less on the road for several hundred kilometres."
Despite his awareness of 'building miles' and embodied energy, Alexandrov is still a great defender of the Monomur, which has a very high EE (*see* Ch.4). This is the reason why Collart (2009) has stopped using this product, though a lot of builders have only just discovered it. Partly because the industry advertises it as an eco product. Two of the interviewed masons are member of the Monomur Club of the brick maker Imerys. A lot of people still believe the Monomur is ecologically sound, which it is not (Floissac, 2009).

27. For a lot of products the builders know where they come from. Most of the bricks, the lime and the sand are local or regional. The clay and earth products, such as renders, are still imported from Germany, says Collart (2009), although they are abundant in the region. The materials supplier says that five years ago almost all ecoproducts came from Germany. Nowadays we have a regional production of hemp, flax and sheepswool (Drouilleau, 2009).

28. All the interviewed builders are willing to use more eco friendly materials, especially if they see that the clients start demanding this. Some have already worked with hempcrete or the Monomur. Douze (2009), says that his ecobuilding company is experimenting with hemp and clay - as a binder instead of lime -, to cut the cost and the EE. Alexandrov (2009) says there is a big improvement to be made on the part of insulation products. However, all respondents say they need better information and training programmes to become familiar with eco products. CAPEB is now proposing these kind of training schemes.

2. Questionnaire (September 2009)

Name :
Company :
Main activity :
Number of employees :
Place :

A. Renovation Techniques

1.Which problems do you come across during the renovation of period timber-frame houses?
E.g. structural problems, decay, infestation, humidity, cement renders, etc.

2. What are the current techniques for renovation of old timber-frame walls?

3.Which techniques do you use most in the renovation of walls?
a.infill: e.g.daub, brick, clay blocks, lime/cement renders, etc;
b.insulation: e.g.interior doubling with insulation and plaster board,
or clay blocks, or other techniques?

4.Which insulation products do you use?
a.conventional: e.g.mineral wool, Kingspan, polystyrene;
b.ecological: e.g. sheepswool, woodwool, cellulose, cork, woodfibre board;

5. Do you leave the timbers exposed on the outside?
YES, why? NO, why not?

6. Which type of render do you use?
E.g. natural hydraulic lime (NHL), air lime (CL) earth,
mineral and coloured renders (crepi), cement, , etc.

7. What do you think of traditional materials and techniques?
E.g.natural lime, daub, etc.

8. What is your preferred technique for renovating timber-frame walls, say if it was your own house?

9. What do you find the most difficult in renovating timber-frame walls? What have you come across in different renovation jobs?

B. Insulation

10.How much insulation do you generally use for exterior timber-frame walls?
E.g.. 0cm, 4cm, 6cm, 8cm, 10cm, 12cm, > more

11.Do you always respect the current thermal insulation norms?
YES, NO, don't know

12. Do you know the BBC label, or other energy efficiency labels?
YES, NO

13. Do you take thermal bridging into account?
YES, NO, don't know

14. Do you systematically use a vapour control layer?
YES, why? NO, why not?

15. Do you believe it is important for timber-frame walls to 'breathe'?
YES, why? NO, why not?

16. Do you sometimes use cladding for exterior timber-frame walls?
NO. If YES, *which materials: e.g. wood, boards, metal, PVC…*

17. What do you think of exterior insulation?
E.g. advantages, constraints.

18. Do you pay attention to thermal mass, e.g. for 'summer comfort'?
If YES, why? If NO, why not?

C. Ecoconstruction and renovation

19. What do you think of 'ecobuilding' and 'ecorenovation'?

20. Do you think the Grenelle de l'Environnement has an important impact on the renovation sector?
E.g. the eco loans, tax breaks, etc.
YES, NO

21. Do you know the HQE label?
    Haute Qualité Environnementale
    YES, Yes but only hear say, NO

22. Do you think one can attain HQE standards in renovation of period timber-frame?
    YES, NO

23. Have you heard of the training programme ECO Artisan of the CAPEB?
    YES, NO

24. Do your clients ask you to use ecological materials? Or do you propose these yourself?
    More often the clients, More often us

25. Are clients willing to pay more for ecological materials?
    YES, NO, it depends, don't know

26. Are you aware of the embodied energy of building materials?
    I.e. the total energy used during the whole production process, distribution, use and final disposal of a product.
    YES, NO, don't know

27. Do you know where the materials that you use come from?
    E.g. local resources, regional, (inter)national
    YES, NO, sometimes

28. Are you willing to use more ecological materials?
    E.g.hempcrete, earth&straw, daub, Monomur, woodfibre board
    If YES, which ones? If NO, why not?

3. Interview sur les maisons en pan de bois (CAUE du Tarn)

Adeline Béa (AB) et Lucie Cuquel (LC) du CAUE du Tarn, Albi 12/10/09

1.Avez vous une idée du nombre de maisons, dites *a colombage* ou *en pan de bois,* dans le Tarn ou en Midi-Pyrenees?

AB: Non, ce n'est pas possible actuellement. Les inventaires etait fait que sur 12 communes du Tarn. Conclusion: environ un tiers du bati ancien des centres villes des villes et villages du Tarn sont encore en pan de bois (colombage). C'est le cas a Labruiguiere, et a Soreze il reste meme un peu plus. C'etait beaucoup plus avant, mais une grande partie du parc a ete detruit dans le 19e/20e siecle.

Ce patrimoine fragile, emblématique de la ville et du département du Tarn, a connu de grands dommages. Il ne concerne actuellement que le tiers du bâti intra muros alors que les élévations et vues du 19e siècle et de la première moitié du 20e siècle révèlent qu'il était encore majoritaire au début du 20e siècle (Béa, 2006) En façade, le remplissage est pour l'essentiel un hourdis de brique. Quelques rares maisons, plus modestes, ont un remplissage en torchis. La maison en pan de bois, construite en milieu urbain, est alignée sur la rue. Les étages en pan de bois peuvent avoir le premier étage en encorbellement, quelques fois le deuxième étage pour les maisons les plus anciennes, ou à l'aplomb pour les constructions du 18e siècle
(L'inventaire: sur www.patrimoine-mp.fr).

AB (telephone 22/09/09) : *Il y a un inventaire du patrimoine bati pour 12 communes de la Mt.Noir, dont Soreze, Dourgne, Labruguiere, St Amancet, qui donne une indication du nombre des maisons en pan de bois dans le Tarn. Mais on ne peut pas extrapoler. Il n'y a pas de chiffres ou des estimations pour tout le Tarn ou les MP. C'est vrai, il y a beaucoup de maisons en pan de bois parmi les maisons existentes, mais on ne sait pas exactement combien. Ca demande une etude approfondi. Souvent ca se voit pas d'exterieur.*

2.Quel est la specificité architecturale (régionale et locale) de ce type d'habitat?

AB: Construite en pan de bois, pas le colombage comme dans le Nord et dans l'Est de la France. Due a des toitures et charpentes plus legeres dans le Sud (toits a faible pente et en tuiles, pas en lauze/ardoise). Tandis que le colombage est une piece de bois qui va du rdc au toit et fait partie de la charpente. Les maisons en colombage ont leur pignon vers la rue, tandis que les maisons en pan de bois ont leur façade vers la rue, avec le courbellement qui est typique.
Il ya quelques etudes sur ce patrimoine dans le Nord de la France (Orleans, recent!), mais il reste beaucoup a faire. Une etude/inventaire du debut de siecle dernier etait menee a Rouen, qui reste une reference (Gueueley?).
LC: Mais on a besoin des etudes comme la votre, qui font le lien entre le patrimoine et la performance thermique.

3.Ces maisons datent de quelle période, en gros? Les premières et les dernières sont construites quand à peu près? Y a t'il beaucoup de différences entre elles?

AB: Surtout en 15eme et 16 siecle, c'est la grande periode. Dans le style de la brique apparante (le houlis). Le torchis etait plutot pour les cloisons, les murs de fend et pour les maisons plus modestes. Le courbellement c'est jusqu'au 17eme. En 18eme le style change, les enduits se sont generalises *(donc ne plus le bois apparent, HV) et l'ornementation et les courbellements disparaissent. Souvent les anciennes maisons sont modifiees avec les memes bois (de recup, HV). La construction de ce type de maison continue jusqu'au 19eme.*

4.Ces maisons font partie d'un patrimoine important, mais sont elles toujours protégées? Problèmes des vélux, des fenêtres et volets en PVC, etc.

AB: Non, pas protégé ! Ex. à Albi il y a que 2 maisons protegees. Mais il y a le ZPPAUP (Zone de Protection du Patrimoine Architecturale, Urbaine et Paysager). C'est une forme de conservation des rues entieres, pas des maisons individuelles. C'est une longue demarche entame par la mairie, qui emmene une nouvelle conscience et volontee de la part de la mairie. Souvent la protection par les ZPPAUP reussi bien, le moment qu'elle est entierement operationelle. Finalement c'est le maire qui est responsible pour le sanctionnement des facades denaturees (volets roulants, huisseries en PVC, bois exotique etc, HV), ne pas les Architects de France (ABF).
LC: Dans les communes ou il n'y a pas de ZPPAUP, il est tres difficile de maintenir une protection, et d'eviter des denaturisations. Quand il y a un ZPPAUP, les gens (proprietaires et habitants) sont souvent mieux informes, et prennent conscience de leur patrimoine. Mais il reste beaucoup de travail a faire.

5.Quel est l'état général de ce patrimoine? Par exemple, avez-vous une idée des dégats liés aux enduits au ciment des annees 60/70?

AB: Difficile a dire, on ne sait pas. Mais il est sur que les enduits en ciment ont fait beaucoup de degats. C'est un gros probleme: ca pourri le bois. Et c'etait largement employe jusqu'en 80.
LC: On traite ces maisons pareils que des maisons neuves, avec les memes materiaux. Surtout dans les annees 60,70, il y a eu une grande denaturation du patrimoine, jusqu'en 80. Dans les annees 90 les mentalites ont changes. Maintenant c'est rare que les artisans font ces erreurs, mais ca arrive encore.

6.Comment et par qui ces maisons sont renovées généralement, d'après vous?

AB: La plupart par des macons, qui ne sont pas specialise dans la restauration. Il font de la renovation, ce n'est pas pareil. LC: Et il y a les autoconstructeurs qui, eux aussi, souvent ne connaissent pas les bonnes techniques de la restauration. C'est tres delicat. Le probleme majeure, c'est la meconnaissance. Dans le nord du departement il y a des intitiatives comme le reseaux Clé (chambre de metiers), qui regroupent des artisans de la restauration.

7.Comment faut-il se prendre à la tâche énorme de mettre ces maisons aux exigences d'isolation thermique d'aujourd'hui?

LC: Bonne question, mais on n'a pas vraiment la reponse. Comment isoler les murs en pan de bois? On ne sait pas! Du point de vue thermique, le mieux est d'isoler a l'exterieur. Mais cela pose un probleme du point de vue du patrimoine.

8.Que pensez vous des améliorations thermiques? Et les risques éventuels?

> Ex: condensation dans les parois à cause de l'isolation par l'interieur – placoplâtre et laine minerale sans pare-vapeur (assez courant!).

LC: Est-ce qu'on doit vraiment isoler ces murs? Souvent on risque d'entrainer plus de degats que d'en tirer les avantages. L'isolation thermique n'est qu'un des parametres. Les gens (ex. les thermiciens) se *focalise souvent sur une approche seulement. Chaque parois doit avoir sa solution specifique, il n'y a pas de solution unique. C'est le probleme des reglementations (RT 2007 Batiments existants) et des DTUs. La RT n'est pas adaptee a des maisons en pan de bois.*

LC ne s'exprime pas sur le pare-vapeur, mais dit qu'ils preconisent toujours une lame d'air ventile pour que l'humidite puisse sortir. LC: Ça va a l'encontre de l'isolation thermique, car une lame d'air isole seulement quand elle est etanche, donc pas ventilee. Il faut trouver l' equilibre entre les differents parois (toit, murs, sol) et compenser (thermiquement) ou ça ne pose pas de problemes majeurs. La solution ldv/placo est une aberration qui mets ces maisons en danger (verifie citation). Nous preconisons plutot une "correction thermique", genre un enduit de chanvre comme une des solutions. Mais c'est notre avis du CAUE du Tarn, pas celui de tous les CAUEs. On est tres mefiant de l'isolation des murs en pan de bois. Souvent on dit aux gens, il ne vaut mieux rien faire que denaturer la maison. C'est tellement delicat. Les murs ne sont pas la priorite, c'est le toit. Actuellement on n'a pas de solution pour les murs. LC et AB sont d'accord que l'isolation en ldv/placo (sans pare vapeur) entraine un gros risque de dégats (par la condensation, si la lame d'air n'est pas bien ventilee), comme celui du ciment des annees apres guerre.

LC dit que le principe de la parois respirante est tres bien, mais tout depends de la mise en oeuvre, si c'est bien fait ou non. Souvent on applique le contraire, en disant que c'est une parrois respirante;. ça veut dire des enduits plus serrés a l'exterieur, au lieu de les faire a l'interieur (donc moins de porosité, qui empecherait la migration de l'humidite).

9.Dans votre inventaire patrimoine, étudiez-vous également la performance énergétique?

AB: NON, c'est une autre demarche.

10.Quelles sont les contraintes et priorités par rapport à d'autres réhabilitations des maisons plus modernes?

LC: Pas une solution unique. La restauration c'est du cas par cas. Il y a aussi le probleme de l'assurance des materiaux. Pour beaucoup de materiaux ecologiques il n'y a pas de DTU. Les artisans se basent sur les DTU pour la garantie decennale.

11.Qui s'occupe du bilan Habitat Patrimoine et les Estimations Performance Energetique (EPE) dans le département?

Ne connaissent pas.

12.Connaissez-vous des examples réussis de réhabilitation des maison en pan de bois?

LC: Pas vraiment. AB: Certaines choses peuvent etre plus ou moins reussies, mais jamais entierement. C'est l'objectif, le depart (d'une nouvelle approche…,HV). Avec la crise actuelle dans le batiment, le marche du demain, c'est la rehabilitation et la restauration.

Appendix IV.ii Wall sections and results per wall type

1. ‘conventional’ wall types with interior insulation

M1 Brick, glasswool, plasterboard	Source	Width	State
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Bricks (1450 -1500 kg/m^3) λ=0,550	GRECAU	10	
Lime render (1550 kg/m^3) λ=0,700	GRECAU	3	
Cavity 40 mm λ=0,230	GRECAU	4	
Glasswool batt IBR NU 80 mm (11 kg/m^3) λ=0,040	INIES	8	
Plasterboard Placodur BA13 (990 kg/m^3) λ=0,250	INIES	1.3	
Wall paint AQUARYL SATIN (1360 kg/m^3) λ=1,600	INIES	1 u	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130	GRECAU	3	existing
Metal frame for plaster board (19 kg/m^3) λ=0,141	GRECAU	1 u	

Summary Table *M 1*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Weight 'bio sourced'
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
8.5	177.5	8.2	39.7	7.4	0.0281	10.3	47.4	207.6	23
Carbon tax	Thermal resistance		Decrement delay		Thermal Inertia		Volume 'bio sourced'	Volume	Volume 'bio sourced'
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^3/m²*	*m^3/m²*	*%*
0.67 €	2.65	13.6	5.7	9.5	24	1.9	0.030	0.355	8

M-1 With 8cm of glass wool the wall has a R of 2.65, which is largely within the norms for existing buildings (RT-2007). However, with an overall score of 8.5 this is one of the worst performing wall types from an environmental point of view. This is largely due to its high embodied energy (EE) and embodied carbon (EC), and its extremely low thermal inertia (24 kJ/m2K) and decrement delay (5.7 h).

The high EE (177.5 kWh/m2) is mainly due to the use of fired bricks (108 kWh/m2 - including mortar). Reusing the old bricks would give this wall a much better overall score of 11.4 (similar to M4b). This would also be reflected in a better score for resource depletion (19.4 instead of 10.3). Glasswool has a relatively low EE, which in this wall (10 kWh/m2) is even lower than that of the plaster board (15 kWh/m2). Note that the metal structure that holds up the plasterboard and the insulation material is accounted for in the environmental impact assessment, but not in the thermal performance because this would require sophisticated thermal simulation.

Using rockwool instead does not change the overall note. It has a higher density (75 kg/m3), and therefore a higher EE, but due to a better thermal resistance and thermal mass the overall performance of the wall stays the same.

M2 Clay block, glasswool, plasterboard	**Source**	**Width**	**State**
Layers from outside to inside (for 1 m^2)	INIES/GRECAU	cm / unit (u)	new / existing
Lime render (1550 kg/m^3) λ=0,700	GRECAU	2	
Clay block - 5 cm (871 kg\m^3) λ:0,417	INIES	10	
Lime render (1550 kg/m^3) λ=0,700	GRECAU	2	
Cavity 40 mm λ=0,230	GRECAU	4	
Glasswool batt IBR NU 80 mm (11 kg/m^3) λ=0,040	INIES	8	
Plasterboard Placodur BA13 (990 kg/m^3) λ=0,250	INIES	1.3	
Wall paint AQUARYL SATIN (1360 kg/m^3) λ=1,600	INIES	1 u	
Accessories not included in thermal calculations (for 1 m^2)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130	GRECAU	3	existing
Metal frame for plaster board (19 kg/m^3) λ=0,141	GRECAU	1 u	

Summary Table *M 2*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**		**Weight 'bio sourced'**	**Weight**	**Weight 'bio sourced'**
Overall Score	*kWh /m^2*	*Score*	*kg eq CO2/m^2*	*Score*	*kea*	*Score*	*kg/m^2*	*kg/m^2*	*%*
9.7	**144.4**	**10.4**	**35.7**	**7.6**	**0.0053**	**15.2**	**47.4**	**165.2**	**29**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Volume 'bio sourced'**
€ / m^2	(m^{2}K/ W)	*Score*	h	*Score*	(kJ/ m^{2}K)	*Score*	*m^3/m^2*	*m^3/m^2*	%
0.61 €	**2.72**	**14.0**	**5.6**	**9.3**	**24**	**1.9**	**0.030**	**0.365**	**8**

M-2 When the client does not want, or can not afford, to have exposed timber and ‘new’ red brick infill, builders often use clay blocks (hollow bricks). These are rendered on both the outside and inside. M2 has a much better overall score than M1. This is mainly due to the lower EE of clay blocks, compared to plain fired bricks (65 in stead of 108 kWh/m2). It still performs very badly on thermal inertia and mediocre for decrement delay.

M3 Old daub, glasswool, plasterboard	**Source**	**Width**	**State**
Layers from outside to inside (for 1 m^2)	INIES/GRECAU	cm / unit (u)	new / existing
Lime render (1550 kg/m^3) λ=0,700	GRECAU	3	
Daub (1600 kg/m3) λ:0,650	GRECAU	10	existing
Lime render (1550 kg/m^3) λ=0,700	GRECAU	3	
Cavity 40 mm λ=0,230	GRECAU	4	
Glasswool batt IBR NU 80 mm (11 kg/m^3) λ=0,040	INIES	8	
Plasterboard Placodur BA13 (990 kg/m^3) λ=0,250	INIES	1.3	
Wall paint AQUARYL SATIN (1360 kg/m^3) λ=1,600	INIES	1 u	
Accessories not included in thermal calculations (for 1 m^2)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130	GRECAU	3	existing
Metal frame for plaster board (19 kg/m^3) λ=0,141	GRECAU	1 u	

Summary Table *M 3*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Weight 'bio sourced'
Overall Score	*kWh /m^2*	*Score*	*kg eq CO2/m^2*	*Score*	*kea*	*Score*	*kg/m^2*	*kg/m^2*	*%*
11.2	99.7	13.4	31.9	7.9	0.0012	19.4	58.6	269.1	22
Carbon tax	Thermal resistance		Decrement delay		Thermal Inertia		Volume 'bio sourced'	Volume	Volume 'bio sourced'
€ / m^2	(m^2K/ W)	*Score*	h	*Score*	(kJ/ m^2K)	*Score*	*m^3/m^2*	*m^3/m^2*	%
0.54 €	2.67	13.7	6.5	10.9	24	1.9	0.037	0.385	10

M-3 When the old daub is in reasonable state the client and the builder often agree to keep it, repair the holes and reinforce it with chicken wire on the outside. The lime render on the outside still leaves the possibility of having the timbers exposed when these are still in good shape. Otherwise the wall will be rendered without the timbers exposed. M3 has a much better overall score (11.1) than M1 and M2, due to a lower EE because it does not contain fired bricks anymore. This is also reflected in a better score for resource depletion. It has similar low scores, however, for decrement delay and thermal inertia.

***Wall M3b** - Old daub, glasswool, clay block*

Summary Table *M 3b*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Weight 'bio sourced'
Overall Score	*kWh /m^2*	*Score*	*kg eq CO2/m^2*	*Score*	*kea*	*Score*	*kg/m^2*	*kg/m^2*	*%*
11.8	123.6	11.8	42.4	7.2	0.0027	17.1	58.6	328.5	18
Carbon tax	Thermal resistance		Decrement delay		Thermal Inertia		Volume 'bio sourced'	Volume	Volume 'bio sourced'
€ / m^2	(m^2K/ W)	*Score*	h	*Score*	(kJ/ m^2K)	*Score*	*m^3/m^2*	*m^3/m^2*	%
0.72 €	2.76	14.2	8.8	14.6	71	5.7	0.037	0.380	10

M3-b Changing the plasterboard for a 5cm clay block or hollow brick improves the thermal mass (decrement delay and inertia), but increases the EE. Therefore the overall score only goes up from 11.2 to 11.8. Note that the plasterboard data are based on an EPD, whereas the clay block data are an extrapolation from a general EPD for fired bricks (Floissac, 2009-a), *see* Appendix III.ii.

M4 Brick, glasswool, clay block	**Source**	**Width**	**State**
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Bricks (1450 -1500 kg/m^3) λ=0,550	GRECAU	10	
Lime render (1550 kg/m^3) λ=0,700	GRECAU	3	
Cavity 40 mm λ=0,230	GRECAU	4	
Glasswool batt IBR NU 80 mm (11 kg/m^3) λ=0,040	INIES	8	
Clay block - 5 cm (871 kg\m3) λ:0,417	INIES	5	
Lime render (1550 kg/m^3) λ=0,700	GRECAU	2	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130	GRECAU	3	existing

Summary Table *M 4*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**		**Weight 'bio sourced'**	**Weight**	**Weight 'bio sourced'**
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
9.4	**201.3**	**6.6**	**50.1**	**6.7**	**0.0296**	**10.2**	**47.4**	**267.0**	**18**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Volume 'bio sourced'**
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^3/m²*	*m^3/m²*	*%*
0.85 €	**2.75**	**14.2**	**7.9**	**13.2**	**71**	**5.7**	**0.030**	**0.350**	**9**

M-4 is a commonly applied variation of M-1, with the bricks and timber exposed on the outside and a clay block wall (5cm) with lime render on the inside. Compared to a plasterboard wall this has a better decrement delay and thermal mass, which is reflected by a slightly better overall score (9.4).

***Wall M4b** – Bricks (re-use), glasswool, clay blocks*

Summary Table *M 4b*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**		**Weight 'bio sourced'**	**Weight**	**Weight 'bio sourced'**
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
12.0	**93.1**	**13.8**	**29.3**	**8.0**	**0.0027**	**17.1**	**47.4**	**267.0**	**18**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Volume 'bio sourced'**
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^3/m²*	*m^3/m²*	*%*
0.50 €	**2.75**	**14.2**	**7.9**	**13.2**	**71**	**5.7**	**0.030**	**0.350**	**9**

M-4b Reusing old bricks as infill gives a much better overall score (12) compared with the same wall section with new bricks (M4), due to a much lower EE (93 instead of 202 kWh/m2). On the other hand, both the score for EC and thermal mass are still below average.

M5 Old daub, no insulation	**Source**	**Width**	**State**
Layers from outside to inside (for 1 m^2)	INIES/GRECAU	cm / unit (u)	new / existing
Daub (1600 kg/m^3) λ:0,650 Lime render (1550 kg/m^3) λ=0,700	GRECAU GRECAU	10 3	existing
Accessories not included in thermal calculations (for 1 m^2)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130	GRECAU	3	existing

Summary Table *M 5*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**		**Weight 'bio sourced'**	**Weight**	**Percentage 'bio sourced'**
Overall Score	*kWh /m^2*	*Score*	*kg eq CO2/m^2*	*Score*	*kea*	*Score*	*kg/m^2*	*kg/m^2*	*%*
10.2	**30.4**	**18.0**	**13.1**	**9.1**	**0.0000**	**20.0**	**58.6**	**206.5**	**28**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Percentage 'bio sourced'**
€ / m^2	(m^{2}K/ W)	*Score*	h	*Score*	(kJ/ m^{2}K)	*Score*	*m^3/m^2*	*m^3/m^2*	*%*
0.22 €	**0.40**	**1.1**	**4.6**	**7.6**	**70**	**5.6**	**0.037**	**0.160**	**23**

M-5 This is more a reference wall than anything else. Cuquel (2009) of CAUE, said that sometimes it is better for some historic buildings not to insulate at all, to avoid problems with condensation and other damages. Despite the extremely low thermal resistance (R=0.40), the overall score is not as bad as expected, which is mainly due to the low EE and the fact that it gets a better score for thermal inertia (5.6) compared with a similar daub wall (M3) with interior insulation (1.6).

Wall M5b *Old daub, 'thermal improvement*

Summary Table *M 5b*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**		**Weight 'bio sourced'**	**Weight**	**Weight 'bio sourced'**
Overall Score	*kWh /m^2*	*Score*	*kg eq CO2/m^2*	*Score*	*kea*	*Score*	*kg/m^2*	*kg/m^2*	*%*
10.7	**4.7**	**19.7**	**-8.5**	**10.6**	**0.0000**	**20.0**	**60.9**	**183.1**	**33**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Volume 'bio sourced'**
€ / m^2	(m^{2}K/ W)	*Score*	h	*Score*	(kJ/ m^{2}K)	*Score*	*m^3/m^2*	*m^3/m^2*	*%*
-0.14 €	**0.82**	**3.4**	**5.2**	**8.7**	**23**	**1.8**	**0.044**	**0.200**	**22**

M-5b Cuquel (2009) said that CAUE sometimes advises people to opt for 'thermal improvement' in the form of an *insulation* render, e.g. hemp and lime onto old daub. However, when using 7 cm of hemp&lime, this does not put up the overall score by much (10.7). Despite a better thermal resistance (R=0.82), a remarkably lower EE (4.7) and better EC (-8.5), it loses a lot on thermal inertia.

2. Wall types with ‘ecological’ materials and interior insulation

M6 Brick and 'monomur'	Source	Width	State
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Bricks (1450 -1500 kg/m^3) λ=0,550	GRECAU	10	
Lime render (1550 kg/m^3) λ=0,700	GRECAU	3	
Cavity 40 mm λ=0,230	GRECAU	4	
Monomur insulation blocks - 30cm (740 kg\m3) λ=0,120	INIES	30	
Lime render (1550 kg/m^3) λ=0,700	INIES	2	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130	GRECAU	3	existing

Summary Table *M 6*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Percentage 'bio sourced'
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
8.1	354.8	0.0	135.0	1.0	0.1034	6.6	47.4	444.6	11
Carbon tax	Thermal resistance		Decrement delay		Thermal Inertia		Volume 'bio sourced'	Volume	Percentage 'bio sourced'
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^3/m²*	*m^3/m²*	*%*
2.29 €	3.13	16.3	22.5	20.0	61	4.9	0.030	0.520	6

M-6 The *monomur* wall section with exposed plain bricks on the outside and 30cm thick insulating bricks on the inside has the highest EE (355 kWh/m2) and EC of (135 kgCO2eq/m2) all wall types. It even gets a zero score for EE, because it is above the upper limit set in Cocon (*See* Appendix 3.i). Despite its very high decrement delay and hygroscopic qualities the wall section gets a very low overall score in Cocon (8.0). Even after deducing the EE of the plain fired bricks, assuming they are reused, the overall score with the insulation blocks on the inside is still very low (9.1).

M7 New daub, woodwool, clay block	**Source**	**Width**	**State**
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Earth render (2000 kg\m^{3}) λ=1,200	GRECAU	3	
Daub (1600 kg/m^{3}) λ:0,650	GRECAU	10	
Earth render (2000 kg\m^{3}) λ=1,200	GRECAU	3	
Woodwool batts (140 kg\m^{3}) λ=0,042	GRECAU	9	
Clay block - 5 cm (871 kg\m^{3}) λ:0,417	INIES	5	
Lime render (1550 kg/m^{3}) λ=0,700	GRECAU	2	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^{3}) λ=0,130	GRECAU	3	existing

Summary Table *M 7*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**		**Weight 'bio sourced'**	**Weight**	**Percentage 'bio sourced'**
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
13.9	**71.5**	**15.2**	**-2.8**	**10.2**	**0.0020**	**18.0**	**83.2**	**367.1**	**23**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Percentage 'bio sourced'**
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^{3}/m^{2}*	*m^{3}/m^{2}*	*%*
-0.05 €	**2.70**	**13.9**	**12.4**	**20.0**	**77**	**6.2**	**0.133**	**0.350**	**38**

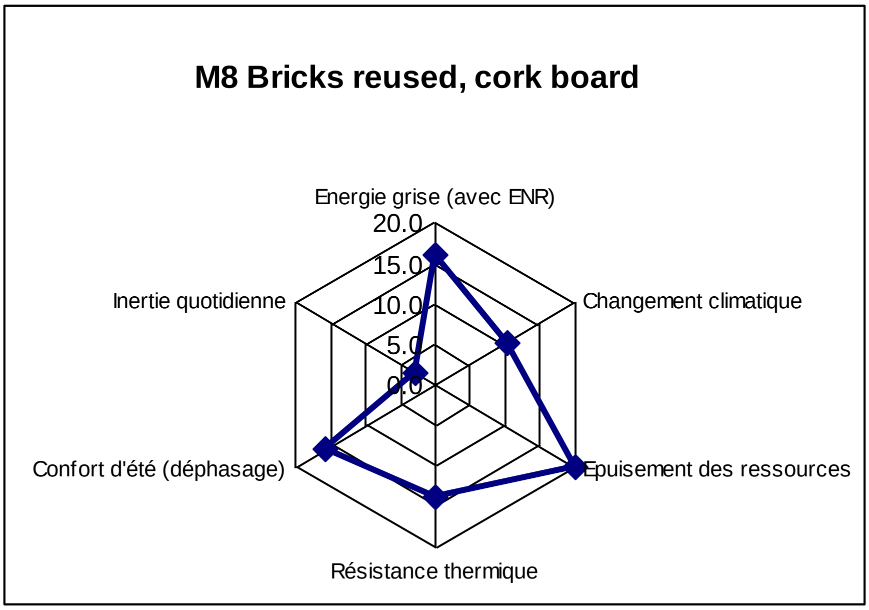
M-7 The overall score (13.9) is good, when using 9cm of woodwool insulation onto an infill of new daub, with a hollow brick wall on the inside. It has an acceptable thermal resistance and a good decrement delay (12.4 hrs). The environmental impact of the new wattle and daub infill (10cm) is so low (EE=11 kWh/m2) that it does not change the overall score much if one switches between new daub and old daub. The overall score only goes up by 0.2 points to 14.1 due to a slightly better EE and EC.

M8 Bricks (re-used), cork board	**Source**	**Width**	**State**
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Bricks (1450 -1500 kg/m^{3}) λ=0,550	GRECAU	10	existing
Lime render (1550 kg/m^{3}) λ=0,700	GRECAU	3	
Expanded cork - NF EN 13170 (125 kg\m3) λ=0,049	GRECAU	11	
Lime render (1550 kg/m^{3}) λ=0,700	GRECAU	2	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^{3}) λ=0,130	GRECAU	3	existing

Summary Table *M 8*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**		**Weight 'bio sourced'**	**Weight**	**Percentage 'bio sourced'**
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
13.1	**60.1**	**16.0**	**-3.3**	**10.2**	**0.0000**	**20.0**	**61.2**	**236.3**	**23**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Percentage 'bio sourced'**
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m³/m²*	*m³/m²*	*%*
-0.06 €	**2.70**	**13.9**	**9.4**	**15.7**	**36**	**2.8**	**0.140**	**0.290**	**48**

M-8 Note that 11cm of expanded cork gives the brick wall an acceptable thermal resistance, but one of the lowest scores for thermal inertia (2.8), hence the flat plot in the spider diagram (Fig.IV.1). It has a reasonable score for EE (16.0), also because the bricks for the infill of the wall are re-used. The average score for EC (10.2) is due to the fact that the carbon 'stored' by the cork (-25 kgCO2eq) is evened out by the carbon 'emitted' by the lime renders (22 kgCO2eq), while recarbonation is not taken into account (*see* Ch.3). Over 48% of its wall volume is 'biosourced' and 27% of its weight. Cork has a very low effusivity (0.14 kJ/m^{2}S.K) and can be a good solution for rooms that need to heat up quickly (Oliva, 2008).

Fig. IV.1 *Six scores for M8*



M8-b *Bricks (reused), cork board*

Summary Table *M 8b*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Weight 'bio sourced'
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
12.0	129.6	11.4	36.3	7.6	0.0000	20.0	58.2	233.3	25
Carbon tax	Thermal resistance		Decrement delay		Thermal Inertia		Volume 'bio sourced'	Volume	Volume 'bio sourced'
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^3/m²*	*m^3/m²*	*%*
0.62 €	2.70	13.9	9.8	16.3	36	2.9	0.120	0.270	44

M-8b Using a different type of expanded cork with a better thermal conductivity (λ=0.040) gives the same thermal resistance (R=2.7), when only using 9 cm instead of 11cm. However this cork board is very high in EE and EC (*see* Table below), which leads to a much lower overall score of 12. For a more detailed comparison between the different cork products in Grecau (2009) and their EE and EC, *see* Appendix 3.ii.

M9 Old daub, cellulose, Fermacell	Source	Width	State
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Lime render (1550 kg/m^3) λ=0,700 Daub (1600 kg/m3) λ:0,650 Earth render (2000 kg\m^3) λ=1,200 Blown cellulose insulation (23 kg\m^3) λ=0,040 Vapour control layer - Sd=1m (130 kg\m^3) λ=2,30 Fermacell board (1125 kg\m^3) λ=0,320 Lime render (1550 kg/m^3) λ=0,700	GRECAU GRECAU GRECAU GRECAU GRECAU GRECAU GRECAU	3 10 3 9 1u 1 2	existing
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130 Wood frame studs 32 x 150 mm (474 kg\m3) λ=0,130	GRECAU GRECAU	3 5	existing

Summary Table *M 9*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Percentage 'bio sourced'
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
11.8	143.9	10.4	18.5	8.8	0.0001	20.0	88.0	290.9	30
Carbon tax	Thermal resistance		Decrement delay		Thermal Inertia		Volume 'bio sourced'	Volume	Percentage 'bio sourced'
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^3/m²*	*m^3/m²*	*%*
0.31 €	2.69	13.9	8.3	13.8	45	3.6	0.160	0.334	48

M-9 Interior insulation with cellulose gives a considerably lower overall score (11.8), compared with other ecological wall types with interior insulation. The thermal resistance of the wall with 9 cm of cellulose is acceptable (R=2.69), but due to its lack of thermal mass it has a very low inertia (45 kJ/m2K) and a low decrement delay (8.3 hrs), which brings down the overall score. The relatively high EE (144 kWh/m2) is largely due to the wood frame (69 kWh/m2) and the lime renders (50 kWh/m2). The cellulose insulation itself has a low EE (4 kWh/m2), but apparently is not considered to store carbon, which gives this wall section a lower score for EC (8.8). Almost 48% of its wall volume is 'biosourced', and over 30% of its weight.

Compared to a similar 'conventional' wall type (M3) it has only a slightly better overall score (11.8 instead of 11.2).However, in the comparison one should take into account other parameters, such as health, toxicity and indoor air quality, which are not included in the LCA. *Note* that the data for Cellisol 500 wall insulation are not based on an EPD. They are based on general data on EE and EC from the Swiss database Oekobilanzdaten (KBOB Ecobau, 2009).

Note that the cellulose insulated wall (M9) would not need a vapour control layer (VCL) when this is a truly 'breathing' wall (May, 2005; Oliva, 2008). Cellulose is a hygroscopic material and vapour open (μ=2), and so are the clay renders and the exterior daub wall. This means that any excess moisture will be absorbed by the wall and released later. The Fermacell board (μ=13) in M9 acts as a first more vapour resistant layer and should be as airtight as possible. The exterior lime render must have a very low vapour resistance to make the wall follow the 1:5 rule for vapour resistance (*see* Ch.2).In the case of a brick wall the hygroscopicity of the wall would be quite different, due to the high vapour resistance of fired bricks (μ=13). In this case a VCL or a ventilated cavity would be recommended. Note that cellulose insulation is hygroscopic (9%) and takes up moisture fast, but it has not got a great hygroscopic capacity (4 kg/m3), due to its low density (May, 2005)[46].

M10 Old daub, woodfibre board	**Source**	**Width**	**State**
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Lime render (1550 kg/m³) λ=0,700 Daub (1600 kg/m3) λ:0,650 Earth render (2000 kg\m³) λ=1,200 Cavity 10 mm λ=0,071 Woodfibre board PAVATEX Diffutherm (168 kg\m3) λ=0,044 Earth render (2000 kg\m³) λ=1,200	GRECAU GRECAU GRECAU GRECAU GRECAU GRECAU	3 10 3 1 9 2	existing
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m³) λ=0,130	GRECAU	3	existing

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[46] Note that these figures are based on cellulose insulation with a 45kg/m3 density, instead of the one used in M9 which is 23kg/m3 (May, 2005).

Summary Table *M 10*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**		**Weight 'bio sourced'**	**Weight**	**Percentage 'bio sourced'**
Overall Score	*kWh /m^2*	*Score*	*kg eq CO2/m^2*	*Score*	*kea*	*Score*	*kg/m^2*	*kg/m^2*	*%*
14.3	**37.1**	**17.5**	**-12.9**	**10.9**	**0.0000**	**20.0**	**83.7**	**321.6**	**26**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Percentage 'bio sourced'**
€ / m^2	(m^2K/ W)	*Score*	h	*Score*	(kJ/ m^2K)	*Score*	*m^3/m^2*	*m^3/m^2*	*%*
-0.22 €	**2.62**	**13.5**	**11.8**	**19.6**	**54**	**4.3**	**0.132**	**0.310**	**43**

M-10 Of all the wall types with interior insulation the old daub wall with 9cm of woodfibre board (Pavatex) on the inside has the best overall score (14.3). For an existing wall in plain brick the score with woodfibre board on the inside will be roughly the same. Note that for the wall types with exterior insulation, woodfibre board onto old an old daub wall (M20) is the best solution as well (16.6). The better overall score of M20 compared to M10 is partly caused by a slightly higher R-value (2.7), but mainly due to a much better use of thermal mass, with a score for inertia of 16.1 in the case of exterior insulation.

M10 has a good decrement delay (11.8 hrs), an acceptable thermal resistance (R=2.62), but a rather low inertia (54 kJ/M2K). The EE and EC are mainly caused by the renders. The Pavatex woodfibre board (9cm) itself has got a very low EE (1 kWh/m2) and stores 28 kgCO2eq of carbon per m2. Almost half of its wall volume (43%) is ‘biosourced’ and 27% of its weight. *Note* that the data for wood fibre board are extrapolations (Floissac, 2009), based on figures from Oliva (2008).

3.Wall types with plant fibre and binder

M11 Hempcrete	Source	Width	State
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Lime render (1550 kg/m^3) λ=0,700 Hempcrete - wall (420 kg\m^3) λ=0,100 Lime render (1550 kg/m^3) λ=0,700	GRECAU GRECAU GRECAU	3 25 3	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130 Wood frame studs 32 x 150 mm (474 kg\m^3) λ=0,130	GRECAU GRECAU	3 3	existing

Summary Table *M 11*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Percentage 'bio sourced'
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
11.2	152.1	9.9	-3.5	10.2	0.0325	9.9	87.6	198.0	44
Carbon tax	Thermal resistance		Decrement delay		Thermal Inertia		Volume 'bio sourced'	Volume	Percentage 'bio sourced'
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^3/m²*	*m^3/m²*	*%*
-0.06 €	2.79	14.4	10.8	17.9	58	4.6	0.106	0.357	30

M-11 The overall score (11.2) of the hempcrete wall is one of the lowest of all ecological wall types. The wall has got a high EE of 152 kWh/m2, of which 92 kWh/m2 is caused by the hempcrete itself and the other 60 kWh/m2 by the lime renders. This is also the reason for its mediocre score on resource depletion. Therefore, changing the interior lime render in the hempcrete wall (M11) for a clay render would make a fairer comparison with the earth&straw wall (M12). However, this only puts up the overall score of M11 by 0.6 point. Also because the lime render has a lower thermal conductivity, λ=0.70 instead of 1.20 for the earth render. The hempcrete wall still has a much higher EE and a lower thermal mass than M12 for roughly the same density of 400 kg/m3.
A large proportion of the EE of the hempcrete is due to the lime binder, which in the case of Tradical-70 comes from Spain (Boutin et al, 2005). The Tradical-70 binder for the hempcrete used in the product declaration contains 75% pure air lime (CA), 15% hydraulic lime (NHL) and 10% pouzzolane (Oliva, 2009). The hempcrete wall has a good decrement delay (10.8 hrs), but a low thermal inertia (58 kJ/m2K). Almost 30% of its volume is biosourced, and 46 % of its weight. Note that the wood for the framework is already included in the LCA (Boutin et al, 2005). Therefore we added the framework on as “existing”, which means it is not calculated again in the impact assessment.

M12 Earth and straw	Source	Width	State
Layers from outside to inside (for 1 m^2)	INIES/GRECAU	cm / unit (u)	new / existing
Lime render (1550 kg/m^3) λ=0,700 Earth and strawcrete (400kg/m^3) λ=0,120 Earth render (2000 kg\m^3) λ=1,200	GRECAU GRECAU GRECAU	3 30 3	
Accessories not included in thermal calculations (for 1 m^2)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130 Wood frame studs 32 x 150 mm (474 kg\m^3) λ=0,130	GRECAU GRECAU	3 3	existing

Summary Table *M 12*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**		**Weight 'bio sourced'**	**Weight**	**Percentage 'bio sourced'**
Overall Score	*kWh /m^2*	*Score*	*kg eq CO2/m^2*	*Score*	*kea*	*Score*	*kg/m^2*	*kg/m^2*	*%*
14.7	**85.2**	**14.3**	**-38.9**	**12.6**	**0.0001**	**20.0**	**170.6**	**226.5**	**75**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Percentage 'bio sourced'**
€ / m^2	(m^2K/ W)	*Score*	h	*Score*	(kJ/ m^2K)	*Score*	*m^3/m^2*	*m^3/m^2*	*%*
-0.66 €	**2.77**	**14.3**	**16.0**	**20.0**	**86**	**6.9**	**0.305**	**0.407**	**75**

M-12 Compared to the hempcrete, an earth&straw wall of similar density gives a much better overall score (14.7). For each square meter of wall (30 cm wide) the earth and straw mix 'stores' 39 kgCO2eq of carbon for the lifetime of the building. Note that 13 kg/m2 is 'emitted' by the lime render and 7kg/m2 stored by the wooden frame. Almost 75% of the wall volume is 'biosourced' and 77% of its weight.

At the 'end of life' the earth&straw mix can be reused or composted. The EE of 30 cm of straw and earth is extremely low (3 kWh/m2). Most of the wall's total EE (85.2 kWh/m2) is caused by the exterior lime render (30 kWh/m2) and the wood frame (48 kWh/m2) . Despite the maximum score for decrement delay the score for thermal inertia (6.9) is rather low, as is the case for most of the category plant fibre filled walls.

M13 Woodchip and lime	Source	Width	State
Layers from outside to inside (for 1 m^2)	INIES/GRECAU	cm / unit (u)	new / existing
Lime render (1550 kg/m^3) λ=0,700 Woodchip and limecrete (550 kg\m^3) λ=0,160 Lime render (1550 kg/m^3) λ=0,700	GRECAU GRECAU GRECAU	3 40 2	
Accessories not included in thermal calculations (for 1 m^2)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130 Wood frame studs 32 x 150 mm (474 kg\m^3) λ=0,130	GRECAU GRECAU	3 3	existing

Summary Table *M 13*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Percentage 'bio sourced'
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
10.1	**290.0**	**0.7**	**-47.0**	**13.1**	**0.0682**	**7.8**	**238.6**	**297.5**	**80**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Percentage 'bio sourced'**
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m³/m²*	*m³/m²*	*%*
-0.80 €	**2.77**	**14.3**	**18.6**	**20.0**	**62**	**5.0**	**0.367**	**0.497**	**74**

M-13 Another form of 'limecrete' mixed with a plant based fibre is what the French call *béton de copeaux* (limecrete with woodchip). In the Grecau database there is only one density available (500 kg/m3) which has relatively high thermal conductivity (λ=0.16). One needs 40cm of this woodchip mix to get a R-value of 2.77. The main reason for the low overall score (10.1) is the high EE : 290 kWh/m2, of which 191 kWh/m2 is caused by the lime&wood chip mix. Using a clay binder, instead of lime, would considerably lower the environmental impact of this material. Also, using a lower density, e.g. 400kg/m3, comparable to the hempcrete and earth and straw, would increase the thermal resistance while lowering the EE.

M14 Earth&straw, woodwool, Fermacell	Source	Width	State
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Lime render (1550 kg/m³) λ=0,700	GRECAU	3	
Earth and strawcrete (400kg/m³) λ=0,120	GRECAU	10	
Earth render (2000 kg\m³) λ=1,200	GRECAU	3	
Woodwool batts (140 kg\m³) λ=0,042	GRECAU	6	
Fermacell board (1125 kg\m³) λ=0,320	GRECAU	1	
Earth render (2000 kg\m³) λ=1,200	GRECAU	2	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m³) λ=0,130	GRECAU	3	existing
Battens - 27 x 40 mm (474 kg\m³) λ=0,130	GRECAU	5	

Summary Table *M 14*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Percentage 'bio sourced'
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
13.9	**69.5**	**15.4**	**-15.1**	**11.0**	**0.0000**	**20.0**	**115.1**	**196.2**	**59**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Percentage 'bio sourced'**
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m³/m²*	*m³/m²*	*%*
-0.26 €	**2.74**	**14.1**	**10.6**	**17.6**	**63**	**5.0**	**0.193**	**0.285**	**68**

M-14 Another environmental option is the infill of the timber-frame with a lower density earth&straw mix (300kg/m3), and interior insulation with woodwool behind a Fermacell board wall. To keep the R-value comparable with other wall types in the assessment, 6 cm of woodwool was used (R_{wall}=2.74). Putting in 8cm of woodwool (same thickness as in the case of mineral wool in conventional wall types), would have given an excellent R-value of 3.22 and an overall score of 14.7. This is comparable to M12, with 30 cm earth&straw. However, wall section M14 demands less interior space than M12 (27cm instead of 36cm) and will be quicker to apply. It has a reasonable EE (70 kWh/m2), though with -15 kgCO2eq it does not stock half as much carbon as M12. Still, almost 68% of its wall volume is 'biosourced' and 61% of its weight.

M15 Old daub, earth and straw	**Source**	**Width**	**State**
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Lime render (1550 kg/m^3) λ=0,700	GRECAU	3	existing
Daub (1600 kg/m^3) λ:0,650	GRECAU	10	
Earth and strawcrete (400kg/m^3) λ=0,120	GRECAU	22	
Earth render (2000 kg\m^3) λ=1,200	GRECAU	3	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130	GRECAU	3	existing

Summary Table *M 15*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**		**Weight 'bio sourced'**	**Weight**	**Percentage 'bio sourced'**
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
14.8	**35.3**	**17.6**	**-22.2**	**11.5**	**0.0000**	**20.0**	**124.0**	**332.5**	**37**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Percentage 'bio sourced'**
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^3/m²*	*m^3/m²*	*%*
-0.38 €	**2.62**	**13.5**	**15.3**	**20.0**	**81**	**6.5**	**0.238**	**0.410**	**58**

M-15 Earth&straw can also be applied to a timber-frame wall with existing daub or brick infill. Like M14 the mix has a density of 300 kg/m3(λ=0.10). With 22cm of earth& straw onto an old daub wall, the overall score (14.8) is still very good. It's a less material and labour intensive variation of M12, with an even better score.

4. Wall types with exterior insulation

M16 Wood cladding, glasswool, old daub	Source	Width	State
Layers from outside to inside (for 1 m^2)	INIES/GRECAU	cm / unit (u)	new / existing
Wood cladding - planks 27 x 125 mm (474 kg\m3) λ=0,130	GRECAU	2	
Ventilated cavity λ=0,192	GRECAU	3	
Rain screen - Sd=0,1 (333 kg\m^3) λ=2,300	GRECAU	1 u	
Glasswool batt IBR NU 80 mm (11 kg/m^3) λ=0,040	INIES	8	
Lime render (1550 kg/m^3) λ=0,700	GRECAU	3	
Daub (1600 kg/m3) λ:0,650	GRECAU	10	existing
Lime render (1550 kg/m^3) λ=0,700	GRECAU	3	
Accessories not included in thermal calculations (for 1 m^2)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130	GRECAU	3	existing
Wood frame studs - 60 X 80 mm (474 kg\m^3) λ=0,130	GRECAU	3	
Battens - 27 x 40 mm (474 kg\m^3) λ=0,130	GRECAU	5	

Summary Table *M 16*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Percentage 'bio sourced'
Overall Score	*kWh /m^2*	*Score*	*kg eq CO2/m^2*	*Score*	*kea*	*Score*	*kg/m^2*	*kg/m^2*	*%*
13.6	**146.7**	**10.2**	**17.1**	**8.9**	**0.0008**	**20.0**	**118.8**	**266.7**	**45**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Percentage 'bio sourced'**
€ / m^2	(m^{2}K/ W)	*Score*	h	*Score*	(kJ/ m^{2}K)	*Score*	*m^3/m^2*	*m^3/m^2*	*%*
0.29 €	**2.80**	**14.5**	**8.4**	**14.0**	**177**	**14.1**	**0.064**	**0.327**	**20**

M-16 This is the first of several wall types with exterior insulation, of wood cladding with mineral wool onto an old daub wall. The overall score of 13.6 is much higher than the other conventional wall types with glasswool (M1-M4). This is largely due to the better use of thermal mass, reflected by a score of 14.1 for thermal inertia, even though the decrement delay (8.4 h) is average.

Of the overall EE (147 kWh/m2) half is due to the wood cladding and the wooden frame (75 kWh/m2) and 60 kWh/m2 is caused by the lime renders. The carbon storage by the wood (-11 kgCO2eq in total), is evened out by the total EC of the lime renders (26 kgCO2eq). Using air lime, and taking into account recarbonation, would certainly give a lower impact for climate change and a better overall score. By using wood cladding, 47% of the wall's weight is 'biosourced' against only 20% of its volume.

M17 Polystyrene, old daub	Source	Width	State
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Mineral render (1600 kg\m^3) λ=0,700	INIES	2	existing
Expanded polystyrene KNAUF ITEx Th38 SE 80mm (17 kg\m^3) λ=0,038	INIES	8	
Lime render (1550 kg/m^3) λ=0,700	GRECAU	3	
Daub (1600 kg/m^3) λ:0,650	GRECAU	10	
Lime render (1550 kg/m^3) λ=0,700	GRECAU	3	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130	GRECAU	3	existing

Summary Table *M 17*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Percentage 'bio sourced'
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
12.2	**124.0**	**11.7**	**38.7**	**7.4**	**0.0052**	**15.2**	**58.6**	**286.3**	**20**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Percentage 'bio sourced'**
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^3/m²*	*m^3/m²*	*%*
0.66 €	**2.57**	**13.2**	**7.0**	**11.6**	**175**	**14.0**	**0.037**	**0.290**	**13**

M-17 Expanded polystyrene is a commonly used and cheap material for exterior insulation. Although it is not common in renovation of old timber-frame walls, builders said it could be used for this type of renovation as well. This wall has a high EE of 124 kWh/m2, of which 40 kWh/m2 is caused by the polystyrene and 63 kWh/m2 by the renders. Of all the wall types with exterior insulation it has the lowest overall score (12.2). This low score is partly due to its high impact on climate change. However, like most walls with exterior insulation it makes good use of the thermal mass. It has a good score for thermal inertia but average for decrement delay. To achieve a better thermal resistance one should use 10cm of polystyrene, which puts the R-value of the wall up from 2.57 to 3.09 m2K/W.

M18 Slate cladding, woodwool, old daub	Source	Width	State
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Natural slate - 4,5 mm (4675 kg\m^3) λ=0,550	INIES	1	
Ventilated cavity λ=0,192	GRECAU	2	
Rain screen - Sd=0,1 (333 kg\m^3) λ=2,300	GRECAU	1 u	
Woodwool batts (140 kg\m^3) λ=0,042	GRECAU	9	
Lime render (1550 kg/m^3) λ=0,700	GRECAU	3	
Daub (1600 kg/m^3) λ:0,650	GRECAU	10	existing
Earth render (2000 kg\m^3) λ=1,200	GRECAU	3	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130	GRECAU	3	existing
Wood frame studs - 60 X 80 mm (474 kg\m^3) λ=0,130	GRECAU	3	
Battens - 27 x 40 mm (474 kg\m^3) λ=0,130	GRECAU	5	

Summary Table *M 18*	Embodied Energy		Embodied Carbon		Resource Depletion		Weight 'bio sourced'	Weight	Percentage 'bio sourced'
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
15.0	119.6	12.0	-9.6	10.6	0.0003	20.0	124.6	300.2	42
Carbon tax	Thermal resistance		Decrement delay		Thermal Inertia		Volume 'bio sourced'	Volume	Percentage 'bio sourced'
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^3/m²*	*m^3/m²*	*%*
-0.16 €	2.68	13.8	10.6	17.7	198	15.9	0.150	0.324	46

M-18 In this example the wall is cladded with thin slate (4.5mm) and insulated with 9cm woodwool, onto an existing daub wall. This gives a good overall score of 15.0, with a reasonable thermal resistance (R=2.68), an average EE (12), but a good score both for thermal inertia (15.9) and decrement delay (17.7). The score for EC is rather low (10.6), mainly due to the fact that this wall does not store much carbon (-9.6 kg CO2eq per m2). From the EPD it is not exactly clear how much of the EE and EC of the slates is due to transport. Through reusing slates on-site one can reduce the EE by 28 kWh/m2. This will put up the overall score of the wall section to 15.4 points.

M19 Woodfibre board, unfired bricks	Source	Width	State
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Lime render (1550 kg/m^3) λ=0,700	GRECAU	2	
Woodfibre board PAVATEX Diffutherm (168 kg\m^3) λ=0,044	GRECAU	10	
Earth render (2000 kg\m^3) λ=1,200	GRECAU	3	
Unfired bricks CLAYTEC (1500 kg\m^3) λ=0,660	GRECAU	10	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^3) λ=0,130	GRECAU	3	existing

Summary Table *M 19*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**		**Weight 'bio sourced'**	**Weight**	**Percentage 'bio sourced'**
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
15.9	**35.8**	**17.6**	**-17.7**	**11.2**	**0.0000**	**20.0**	**107.7**	**257.8**	**42**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Percentage 'bio sourced'**
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^{3}/m²*	*m^{3}/m²*	*%*
-0.30 €	**2.65**	**13.7**	**11.4**	**19.0**	**176**	**14.1**	**0.158**	**0.280**	**56**

M-19 When the timbers are not very pretty anymore, and the old daub or brick infill is in bad condition and therefore difficult to repair, a solution might be to replace the daub by unfired clay bricks which have a similar high thermal mass (density 1.500kg/m3). The use of woodfibre board as exterior insulation gives an excellent overall score of 15.5, with an acceptable insulation, a low EE, a good decrement delay (11.4 h) and a good score for thermal inertia (14.1). The score for EC is relatively low, due to the fact that this wall type does not store much carbon (-17.7 kgCO2eq).

M20 Woodfibre board, old daub	**Source**	**Width**	**State**
Layers from outside to inside (for 1 m²)	INIES/GRECAU	cm / unit (u)	new / existing
Lime render (1550 kg/m^{3}) λ=0,700	GRECAU	2	existing
Woodfibre board PAVATEX Diffutherm (168 kg\m^{3}) λ=0,044	GRECAU	10	
Earth render (2000 kg\m^{3}) λ=1,200	GRECAU	3	
Daub (1600 kg/m^{3}) λ:0,650	GRECAU	10	
Earth render (2000 kg\m^{3}) λ=1,200	GRECAU	3	
Accessories not included in thermal calculations (for 1 m²)	INIES/GRECAU	m / unit (u)	new / existing
Studs 100 x 100 mm (474 kg/m^{3}) λ=0,130	GRECAU	3	existing

Summary Table *M 20*	**Embodied Energy**		**Embodied Carbon**		**Resource Depletion**		**Weight 'bio sourced'**	**Weight**	**Percentage 'bio sourced'**
Overall Score	*kWh /m²*	*Score*	*kg eq CO2/m²*	*Score*	*kea*	*Score*	*kg/m²*	*kg/m²*	*%*
16.6	**28.1**	**18.1**	**-20.0**	**11.3**	**0.0000**	**20.0**	**87.4**	**327.8**	**27**
Carbon tax	**Thermal resistance**		**Decrement delay**		**Thermal Inertia**		**Volume 'bio sourced'**	**Volume**	**Percentage 'bio sourced'**
€ / m²	(m²K/ W)	*Score*	h	*Score*	(kJ/ m²K)	*Score*	*m^{3}/m²*	*m^{3}/m²*	*%*
-0.34 €	**2.71**	**13.9**	**12.3**	**20.0**	**202**	**16.1**	**0.143**	**0.310**	**46**

M-20 This is the wall type with the highest overall score of 16.6. Exterior insulation with woodfibre board gives very good scores for thermal inertia (16.1) and decrement delay (20). Much better than e.g. M16 (wood cladding and glasswool). It has a very low EE and stocks a reasonable amount of carbon (20 kgCO2eq/m2).

References

Ademe (2006) Agence de l´Environnement et de la Maitrise de l´Energie *Stratégie Utilisation Rationnelle de l'Energie dans le bâtiment* [online] Available from: http://www2.ademe.fr/servlet/KBaseShow?sort=1&cid=96&m=3&catid=12624 (Accessed 5 November 2009)

Ademe (2007) Agence de l´Environnement et de la Maitrise de l´Energie *Les chiffres clés du bâtiment, 2007* [online] Available from: http://www2.ademe.fr/servlet/KBaseShow?sort=-1&cid=96&m=3&catid=12612 (Accessed 15 December 2009)

Ademe (2008) Agence de l´Environnement et de la Maitrise de l´Energie *Bilan Produit* (users guide), Ademe and Université de Cergy Pontoise, 2008.

Ademe (2009) Agence de l´Environnement et de la Maitrise de l´Energie *Energy Efficient Buildings Info sheet no.2* [online] Available from: http://www2.ademe.fr/servlet/KBaseShow?sort=-1&cid=96&m=3&catid=17778 (Accessed 1 December 2009)

Alexandrov A. (2009) *Interviews about renovation of period timber-frame* Ten interviews with building professionals in Midi-Pyrénées - Hans Valkhoff Thesis MSc AEES, Graduate School of the Environment CAT/UEL 2009.

ANVPAH (2009) Association Nationale Villes et Pays d´Art et d´Histoire
Journée de formation Bâti ancien et développement durable : recherche d'une méthodologie partagée ANVPAH, Paris 16 juin 2009. Available from : http://www.an-patrimoine.org/index-module-orki-page-view-id-652.html (Accessed 27 December 2009).

Areso (2009) Association Régionale d´Ecoconstruction du Sud-Ouest 'Meeting October 2009'.

Association HQE (2009) *Haute Qualité Environnementale* [online] Available from: http://www.assohqe.org/index.php (Accessed 9 December 2009).

Asterre (2008) Association nationale des professionels de la terre crue *Techniques de mise en œuvre de la terre crue dans la formation initiale et continue* Available from : http://www.asterre.org/spip.php?article119 (Accessed 22 December 2009).

Béa (2006) *Inventaire général Région Midi/Pyrénées 2006* : *Maisons en Pan de bois Pays d´Autan* [online] Patrimoines en Midi-Pyrénées. Available from : http://patrimoines.midipyrenees.fr/fr/connaitre/recherche-documentaire/resultats-de-la-recherche/index.html (Accessed 27 December 2009).

Béa A.(2009) *Interviews about renovation of period timber-frame* Ten interviews with building professionals in Midi-Pyrénées - Hans Valkhoff Thesis MSc AEES, Graduate School of the Environment CAT/UEL 2009.

Berge B. (2009) *The Ecology of Building Materials*, 2nd ed. Architectural Press.

Bernstein D. et al. (2007) *Traité de construction durable* Ed. Le Moniteur.

Bevan R., Woolley T. (2008) *Hemp lime construction ; a guide to building with hemp lime composites* IHS BRE Press.

Bonnet F. (2009) *Interviews about renovation of period timber-frame* Ten interviews with building professionals in Midi-Pyrénées - Hans Valkhoff Thesis MSc AEES, Graduate School of the Environment CAT/UEL 2009.

Borjesson P, Gustavsson L. (2000) 'Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives' *Energy Policy* No.28.

Bourru L. (2009) 'Les qualites thermiques du bâtiment ancien' *Journée de formation ANVPAH, Patrimoine Bâti et Developpement Durable*, Paris 16 juin 2006

Boutin M.P., Flamin C., Quinton S., Gosse G. (2006) *Etude des characteristiques environnementales du chanvre par l'analyse de son cycle de vie* INRA, Ministère de l'Agriculture et de la Pêche.

Bouwens D. (1997) *Earth buildings and their repair* [online] Building Conservation Directory, Cathedral Publications Ltd. Available from: www.buildingconservation.com (Accessed 1 December 2009).

BRE, Building Research Establishment (2009-a) *The Green Guide to specification* [online] Available from : http://www.bre.co.uk/greenguide/podpage.jsp?id=2126 (Accessed 27 December 2009).

BRE, Building Research Establishment (2009-b) *Envest 2 : Environmental impact assessment and whole life cost analysis for buildings* Available from : http://envestv2.bre.co.uk/account.jsp (Accessed 6 December 2009).

Briques de France (2006) FDES [online] Available from : http://www.inies.fr/fic_prod.asp?id_prod=444&mode=Fam (Accessed 28 December 2009).

Broome J. (2006) *A Code for Sustainable Homes* The Green Building Bible, Vol.1, 3rd ed. 2006

BS 5250 (2002) *Code of practice for control of condensation in buildings* Available from: http://www.standardsdirect.org/standards/standards4/StandardsCatalogue24_view_3566.html (Accessed 17 December 2009).

BSI, British Standards Institute (2008) *PAS 2050:2008 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services* BSI, October 2008.

CAUT, College & University Technicians of the piano technicians guild (2009) *How does this effect hygroscopic materials* Austin, Texas (U.S). Available from: http://www.ptg.org/caut/Kissmann.htm (Accessed 3 December 2009).

CAPEB (2007) La Conféderation de l'Artisanat et des Petites Entreprises de Bâtiment *Les Artisans du bâtiment sur le marché du patrimoine*, décembre 2007.

CAPEB (2008) ‘L’utilisation des éco-matériaux dans les entreprises artisanales du bâtiment’ *Lettre trimestrielle d’informations de l’Artisanat du Bâtiment* – 1er trimestre, avril 2008.

CAPEB (2009) *Eco Artisan, la nouvelle énergie du bâtiment* Available from: http://www.capeb.fr/INTERNETCAPEBWeb/National/Publication/accueil/accueil.jsp (Accessed 7 December 2009).

Cateret C. (2009) ‘Personal communication’ *Cerqual Sud* Telephone conversation, 9 October 2009.

Céquami, Certification Qualité en Maisons Individuelles (2009) *La qualité globale certifiée maintenant accessible aux maisons individuelles du parc existant avec la certification NF Maison Rénovée* Dossier de presse, 1 October 2009. Available from: http://www.mamaisonrenoveecertifiee.com/-Actus-presse-.html (Accessed 10 December 2009).

CETE de l´Est (2009), Centre d´Etudes Techniques d ´Equipement Est *Operation BATAN (Bâtiment Ancien) 2010* [online] Available from http://www.maisons-paysannes.org/images/stories/pdf/comportement_thermique_du_bati_ancien_ecobat_20_mars_2009_version_light.pdf (Accessed 30 December 2009).

Cocon (2009) *Logiciel de Comparaison de solutions Constructives, de Confort et d'émissions de* CO_2 Developed by Luc Floissac (Grecau), ed. Eosphère, Toulouse. Available from : http://www.citemaison.fr/COCON-comparaison-solutions-constructives-confort.html (Accessed 10 December 2009)

Collart J.F. (2009) *Interviews about renovation of period timber-frame* Ten interviews with building professionals in Midi-Pyrénées - Hans Valkhoff Thesis MSc AEES, Graduate School of the Environment CAT/UEL 2009.

Conteville and Den Hartigh (2008) *Les Ecomatériaux dans la rénovation thermique des logements en France* Amis de la Terre, Novembre 2008.

Cornillier C., Vial E. (2008) ‘L’Analyse de Cycle de Vie (ACV) appliquée aux produits bois : bilan énergétique et prise en compte du carbone biomasse’ *IXème Colloque Sciences et Industrie du Bois*, 20 & 21 novembre 2008.

Courgey S., Oliva J.P. (2007) *La conception bioclimatique; des maisons confortables et économes* Terre Vivante 2006, 2007.

Criirad (2009) Commission de Recherche et d'Information Indépendantes sur la Radioactivité *Mobilisation contre l’ajout de substances radioactives dans les biens deconsommation et les matériaux de construction* [online] Available from: www.criirad.org (Accessed 12 December 2009).

CSTB (2008) *Elodie : Evaluation à L'échelle de l'Ouvrage Des Impacts Environnementaux* [online] Available from : http://ese.cstb.fr/elodie/ (Le Progiciel). (Accessed 1 December 2009)

Cuquel L. (2009) *Interviews about renovation of period timber-frame* Ten interviews with building professionals in Midi-Pyrénées - Hans Valkhoff Thesis MSc AEES, Graduate School of the Environment CAT/UEL 2009.

Douze M. (2009) *Interviews about renovation of period timber-frame* Ten interviews with building professionals in Midi-Pyrénées - Hans Valkhoff Thesis MSc AEES, Graduate School of the Environment CAT/UEL 2009.

Drouilleau (2009) *Interviews about renovation of period timber-frame* Ten interviews with building professionals in Midi-Pyrénées - Hans Valkhoff Thesis MSc AEES, Graduate School of the Environment CAT/UEL 2009.

Ecobilan (2009) *TEAM Bâtiment: Tool for Environmental Analysis and Management* PriceWaterhouseCoopers (PWC).

Ecoinvent (2009) *Ecoinvent Data V-2.1* Swiss [online] Centre for Lifecycle Inventories. Available from: http://www.ecoinvent.org/database/ (Accessed 21 December 2009).

Effinergie (2009) *BBC Rénovation: le label Bâtiment Basse Consommation pour la rénovation des bâtiments existants* [online] Effinergie, septembre 2009. Available from: http://www.effinergie.org/site/Effinergie/ (Accessed 27 December 2009).

EST, Energy Saving Trust (2009) *Envest for housing, users guide* August 2009.

FFB, Féderation Française du Bâtiment (2009-a) *Le défi de l´énergie dans les bâtiments existants* [online] Available from: http://www.ffbatiment.fr/entreprises-batiment-dossiers/31-metiers_energie.htm (Accessed 21 December 2009).

FFB, Féderation Française du Bâtiment (2009-b) *FDES Charpente bois traditionelle (chêne et résineux)* [online] Available from : http://www.inies.fr/fic_prod.asp?id_prod=444&mode=Fam (Accessed 28 December 2009).

Floissac L., Collart J.F, Pouget A., Tornay N., Fernandez L., Loisel P., Chatelet A. (2008) *Rénovation Architecturale Patrimoniale et Performance Energétique, le projet RAPPE, rapport final*, Ademe, Sophia-Antipolis.

Floissac L., Bui Q.B., Colas A.S., Marcom A., Morel J.C. (2009) ‘How to assess the sustainability of construction processes’ *Fifth Urban Research Symposium, Cities and Climate Change*, 28-30 June 2009, Marseille.

Floissac L. (2009-a) *Personal communications from August to December 2009* Meetings, telephone and e-mail.

Floissac L. (2009-b) *Interviews about renovation of period timber-frame*
Ten interviews with building professionals in Midi-Pyrénées - Hans Valkhoff Thesis MSc AEES, Graduate School of the Environment CAT/UEL 2009.

Floissac L. (2009-c) ‘Bilans Environnementaux de Bâtiments’ *Environnement et ville durable,* Emourgeon (éd.), WEKA Paris.

Floissac L. (2009-d) ‘Parois Respirantes 2.02’ Excel-based tool for ´breathable walls´.

George M. (2008) 'Modelling to assess the benefits of thermal mass in a range of wall types' *The Green Building Bible*, Vol.2, 4th ed.

Gielen D.J. (1997) *Building materials and CO2; Western European emission reduction strategies* Energie Centrum Nederland (ECN). Avaible from: http://www.ecn.nl/docs/library/report/1997/c97065.pdf (Accessed 21 December 2009).

Gillham B. (2005) *Research Interviewing; the range of techniques* Open University Press, ed. 2008.

Gironnet (2009) 'Personal communication' *Architect des Bâtiments de France du Tarn* Telephone interview, November 2009.

Grecau (2009) Groupe de Recherche Environnement et Conception en Architecture et Urbanisme *Bibliotheque de matériaux de construction (V3.4.4)* [online] Laboratoire de l'Ecole Nationale Supérieure d'Architecture de Toulouse et de Bordeaux. Available from : http://www.citemaison.fr/scripts/bibliotheque-materiaux.php (Accessed 21 December 2009).

Haas M. (2002) *Milieuclassificatie Bouw* Duurzaam en Gezond Bouwen, NIBE Research.

Hamilton L., et al.(2007) *Creating environmental weighting for construction products*
BRE Press 2007

Hammond G., Jones C. (2008) *Inventory of Carbon&Energy (ICE)* [online] Sustainable Energy Research Team, Department of Mechanical Engineering, University of Bath. (Accessed 2 December 2009).

Harris C. and Borer P. (2005) *The Whole House Book; ecological building design and materials* 2nd ed. CAT publications.

Harris D.J. (1999) 'A quantitative approach to the assessment of the environmental impact of building materials' *Building and Environment*, No.34

Harris R. (2009) 'Is Timber a sustainable building material?' *Lecture notes* AEES Module C-3 study book, Graduate School of the Environment, CAT/UEL May 2009.

Holmes S. (2009) 'Building limes and cement' *Lecture notes* (and presentation), AEES Module C-3 study book, Graduate School of the Environment, CAT/UEL May 2009.

Hopkins R. (2008) *The Transition Handbook; from oil dependency to local resilience* Green books.

Houben H. and Guillaud H. (1994) *Earth construction; A comprehensive guide* Practical Action Publishing, ed.2008.

Inforenovateur (2009) *Les Chiffres clé de la rénovation énergétique* [online] Inforénovateur, 15 April 2009 Available from : http://www.inforenovateur.com/document/lire/1_les-chiffres-cles-de-la-renovation-energetique (Accessed 22 December 2009).

INIES (2009) *La base de données française de référence sur les caractéristiques environnementales et sanitaires des produits de construction* [online] CSTB, Paris. Available from: http://www.inies.fr/ (Accessed 27 December 2009).

Interviews (2009) *Interviews about renovation of period timber-frame* Ten interviews with building professionals in Midi-Pyrénées - Hans Valkhoff Thesis MSc AEES, Graduate School of the Environment CAT/UEL 2009.

IPCC, Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: Synthesis report* Fourth Assessment Report IPCC, Geneva.

ISO 14040-44 (2006-a) International Organisation for Standardisation *Environmental Management and Life cycle Assessment - Principles and framework (ISO 14040), Requirements and guidelines (ISO 14044)* Available from: http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=37456 (Accessed 21 November 2009).

ISO 13786 (2006-b) International Organisation for Standardisation *Thermal performance of building components - Dynamic thermal characteristics - Calculation methods* ISO, 2006.

JO, Journal Officiel (2009) 'LOI n° 2009-967 du 3 août 2009 de programmation relative à la mise en œuvre du Grenelle de l'environnement (1)' *Journal Officiel* Available from: http://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000020949548 (Accessed 21 December 2009).

KBOB Ecobau (2009-1) Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren *Oekobilanzdaten im Baubereich, detail 2009* [online] Bundesamt für Bauten und Logistik (BBL) Available from: http://www.bbl.admin.ch/kbob/00493/00495/index.html?lang=fr (Accessed 19 October 2009)

Le Doujet, K. (2008) *Opportunities for the large scale implementation of straw based external insulation as a retrofit solution of existing UK buildings* MA Thesis, ECSD, Downing College, University of Cambridge.

Marcom A. (2009) *Interviews about renovation of period timber-frame* Ten interviews with building professionals in Midi-Pyrénées - Hans Valkhoff Thesis MSc AEES, Graduate School of the Environment CAT/UEL 2009.

Marcom A. (2008) *Des indicateurs pour l'écoconstruction* [online] Available from : www.areso.asso.fr (Accessed 19 November 2009).

Marcom A. (2002) *Enquête sur la mesure de la productivité dans les techniques de construction en terre* Thesis DPEA, Ecole d'Architecture de Grenoble.

Marchal T. (2009) 'Les enjeux du patrimoine bâti ancien au regard des économies d'énergie' *Journée de formation Bâti ancien et développement durable : recherche d'une méthodologie partagée* ANVPAH, Paris 16 juin 2009 Available from : http://www.an-patrimoine.org/index-module-orki-page-view-id-652.html (Accessed 27 December 2009).

May N. (2005) *Breathability, the key to building performance* [online] Available from: www.natural-building.co.uk (Accessed 27 October 2009).

May. N. (2006) *Traditional materials and energy efficiency* [online] Available from: www.natural-building.co.uk (Accessed 27 October 2009).

May N., Newman G. (2008) *Critique of the Green Guide to Specification* Good Homes Alliance, 5 December 2008.

McMullan R. (2007) *Environmental science in building* 6th ed., Palgrave Macmillan.

Miller A. J. (2001) 'Embodied Energy – A life cycle of transportation energy embodied in construction materials' *Cobra Conference paper*, 2001, Rics Foundation.

Morel J.C. et al. (2001) 'Building houses with local materials' *Building and Environment No.36*.

Murphy R.J. and Norton A. (2008) *Life cycle assessments of natural fibre insulation materials* Imperial College London and NNFCC.

MP, Maisons Paysannes (2004) *Connaissance des bâtiments anciens et économies d'énergie.* Rapport de synthèse. Available from:
http://www.maisonspaysannes.org/images/stories/pdf/version_simplifiee_dguhc.pdf
(Accessed 7 December 2009).

MP, Maisons Paysannes (2009) *Centre de formation et de perfectionnement de Maisons Paysannes de France* [online] Available from : http://www.maisons-paysannes.org/centre-de-formation (Accessed 7 December 2009).

NIBE, Nederlands Instituut voor Bouwbiologie en Ecologie (2008) *Basiswerk Milieuclassificaties Bouwproducten* Available from: http://www.nibe.info Need login!
(Accessed 17 December 2009).

Oliva (2008) *L'isolation écologique; conception, matériaux, mis en oeuvre* Terre Vivante 2001, 2008.

Padfield T. (1998) *The role of absorbent building materials* PhD TU Denmark Available from: www.natmus.dk/cons/tp/phd/tp_phd (Accessed 1 December 2009).

Parro (2009) *Interviews about renovation of period timber-frame* Ten interviews with building professionals in Midi-Pyrénées - Hans Valkhoff Thesis MSc AEES, Graduate School of the Environment CAT/UEL 2009.

Pouthier A. (2009) 'La taxe carbone: ce sera 17 euros la tonne' Le Moniteur, 10 Septemebr [online] Available from: http://www.lemoniteur.fr/135-planete/article/actualite/ (Accessed 10 December 2009).

PRé Consultants (2008) *Introduction to LCA with SimaPro-7* Available from:
http://www.pre.nl/download/manuals/SimaPro7IntroductionToLCA.pdf
(Accessed 11 November 2009).

Pritchett I. (2001) *Wattle and daub* [online] Building Conservation Directory, Cathedral Publications Ltd. Available from: www.buildingconservation.com (Accessed 1 December 2009).

RT (2005) *La Réglementation Thermique 2005* Available from: http://www.rt-batiment.fr/batiments-neufs/reglementation-thermique-2005/presentation.html
(Accessed 21 November 2009)

RT (2007) *La Réglementation Thermique des bâtiments existants 2007* Available from: http://www.rt-batiment.fr/batiments-existants/rt-existant-dispositif-general/presentation-generale-dispositif.html (Accessed 21 November 2009)

Réseaux Ecobâtir (2009) *Revue critique des FDES/ACV* [online] Available from: http://www.reseau-ecobatir.asso.fr/ (Accessed 11 December 2009).

Rhydwen R. (2009) 'Building with Hemp and Lime' *Lecture notes* AEES Module C-3 study book, Graduate School of the Environment, CAT/UEL May 2009.

Ruers B., Schouten N. (2005) *Het Asbestdrama* Wetenschappelijk Bureau van de Socialistische Partij, Rotterdam.

Saint-Gobain Isover (2006) *FDES Santé - Informations nécessaires à l'évaluation des risques sanitaires: Panneau de laine de verre IBR NU (80 mm)* INIES, 2006

SNMI, Syndicat National des Mortiers Industriels (2007) *FDES Mortier d'enduit minérake* [online] Available from : http://www.inies.fr/fic_prod.asp?id_prod=444&mode=Fam
(Accessed 28 December 2009).

St Astier (2006) *CO2 emissions from natural binders* [online] Available from: http://www.stastier.co.uk/nhl/testres/co2emissions.htm (Accessed 8 December 2009).

Terréal (2007) *Catalogue Deco; briques et plaquettes* [online] Available from: http://www.terreal.com/#/fr/doc/ (Accessed 10 November 2009)

Taylor J. (1998) *10 ways to ruin an old building* [online] Building Conservation Directory, Cathedral Publications Ltd. Available from: www.buildingconservation.com/articles/ten/tenways.html
(Accessed 7 December 2009).

Thormark C. (2006) 'The effect of material choice on the total energy need and recycling potential of a building' *Building and Environment* No.41.

Upton B., Miner R., Spinney M., Heath L.S. (2008) 'The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States' *Biomass and Bioenergy* No.32.

Valkhoff H. (2009) *Carbon storage in buildings* Essay MSc AEES, Graduate School of the Environment CAT/UEL, May 2009.

Van Dam J.E.G. (2005) 'Product development from renewable sources; Agro food chain entering construction market' *Sustainable Building* 1, 2005.

Woolley T., Kimmins S., Harrison P., Harrison R. (1997) *Green Building Handbook* E&FN SPON Green Building Digest.

Woolley T. (2006) *Natural Building; a guide to materials and techniques* Crowood Press, Marlborough 2006.

Wufi Pro (2009) *Software for calculating the coupled heat and moisture transfer in building components* Fraunhofer Institute for Building Physics IBP-Holzkirchen.