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Carbon storage in kitchen furniture

a lifespan analysis from forest products to people's attitudes

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Carbon Storage in Kitchen Furniture: A Lifespan Analysis from Forest Products to People's Attitudes

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Abstract

This thesis is comprised of two halves. The first half comprises a comprehensive survey of carbon stored in forest products. The manufacturing processes and energy consumption of these products is reviewed. The second half comprises an evaluation of the carbon content in kitchen furniture and a survey of public attitudes towards carbon storage in this furniture. Finally, suggestions are made for further research to develop and refine the findings.

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Author's Declaration

I declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University.

2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.

3. Where I have consulted the published work of others, this is always clearly attributed.

4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

5. Where elements of this work have been published or submitted for publication prior to submission, this is identified and references given at the end of the thesis.

6. This thesis has been prepared in accordance with Coventry University and Buckinghamshire New University regulations.

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Constanta Camelia Marinoiu

CHAPTER 1 Introduction

Climate change, one of the most significant challenges that humanity faces today, is attributed directly or indirectly to human activity that alters the composition of the atmosphere. Global atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have increased significantly since pre-industrial times (1750), due to the combustion of fossil fuels, cement production and land use conversion. An increase in levels of atmospheric CO_2 was observed in 1957, when these were measured directly and interest in the carbon cycle was consequently enhanced (Houghton et al., 1995).

After the unequivocal evidence of climate change was revealed, the first significant reactions of the international community were to establish the *World Methodological Organization* (WMO) in 1950 and to set up the *United Nations Environment Programme* (UNEP) in 1972. In order to provide decision makers with a clear, rigorous and balanced source of information on the current state of knowledge in climate change and its potential environmental and socio-economic impacts, the *Intergovernmental Panel on Climate Change* (IPCC) was established in 1988 by UNEP and WMO. The IPCC First Assessment Report was completed in 1990 and rapidly became an important point of reference.

The *United Nations Framework Convention on Climate Change* (UNFCCC) is an international environmental treaty negotiated at the Earth Summit in Rio de Janeiro in 1992. Coming into force in 1994, it has brought increasing attention to the role of forests as effective global sinks and as absorbers of carbon dioxide.

The UNFCCC was created to ensure the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". On 21st of March 1994, 195 countries (called here *Parties to the Convention*) ratified the Convention. Under UNFCCC, the Parties to the Convention signed the *Kyoto Protocol* (KP), adopted on 11th of December 1997 and entering into force in 2005, in order to put the Convention into operation. According to this protocol, industrialised countries committed to stabilising greenhouse gas emissions based on the principles of the Convention. During its first commitment period, the protocol set binding emission reduction targets for only 37 industrialised countries and the European Community. The average reduction in emissions was required to be 5% compared to 1990 levels and had to be achieved between 2008 and 2012. In 2003, the IPCC issued Good Practice Guidance for the *Land Use, Land Use Change and Forestry* (LULUCF), which included methodologies for measuring carbon in wood products. These recommendations were retrieved in the Guidelines for National Greenhouse Gas (GHG) Inventories published by the IPCC in 2006.

In December 2012, the *Doha Amendment to the Kyoto Protocol* was adopted, in Doha, Qatar. During this second commitment period, parties committed to reducing their GHG emissions to at least 18% below the 1990 levels in the eight-year period from 2013 to 2020. The composition of parties in the second commitment period was different from the first.

In the first commitment of the Kyoto Protocol, 2008-2012, the carbon stored in wood products was not accounted for, while carbon stored in forests was (Brunet-Navarro et al., 2016). Furthermore, wood products were considered as carbon pools in 2011, after the 17th Conference of the Parties, the United Nation Climate Change Conference in Durban, South Africa. Moreover, in 2015, 195 nations signed the *Paris Agreement* at the 21st UNFCCC, which had the main aim to keep a global temperature rise this century well below 2 degrees Celsius. They will also drive efforts to reduce the temperature increase even further to 1.5 degrees Celsius above the pre-industrial level.

According to Brunet-Navarro et al. (2016), wood products could be used intelligently, so they can contribute to reducing emissions fast enough to achieve the temperature goal. Furthermore, using models of wood products, the stock of carbon and fluctuation can be estimated.

1.1 Background and Context

Trees, by means of the photosynthesis process, have an important role in countering the greenhouse effect by sequestering atmospheric carbon and storing it in their biomass (Houghton, 2007). Atmospheric carbon dioxide (CO_2) is absorbed by trees and partly stored as carbon compounds in various wood components (e.g. celluloses, hemicelluloses, and lignin).

The major chemical component of a living tree is water, but on a dry-weight basis all wood cells consist of carbohydrates (cellulose and hemicellulose), amounting to 65-75%, in combination with lignin, amounting to 18-35% (Rowell, 2005). Furthermore, the hemicelluloses are branched with cellulose and play an important role in fibre (Ratnasingam, Ioras, 2007). Dry wood has an elemental composition of about 50% carbon, 6% hydrogen, 44% oxygen and trace amounts of inorganic material (Rowell, 2005).

Therefore, approximately one half of the dried biomass of natural wood is carbon (C) (IPCC, 2006). Biomass is defined as the total mass of a living organism and it may include the water in the organism, in which case it is referred to as fresh biomass. Often the tissue can be dried, and its oven-dry biomass is considered. The carbon content of the oven-dry plant biomass is typically measured to be between 36% and 61%. Usually, the dry biomass of the tree is the most useful measurement, not the fresh biomass (West, 2009).

According to West (2009), one quarter of the fresh biomass of wood that it is cut directly from the living tree is composed of the chemical element carbon. Occasionally, the amount of carbon sequestered in the biomass is reported as carbon dioxide equivalent, which the tree has absorbed from the atmosphere.

$$1 \; tonne \; of \; dried \; biomass \; = 0.5 \; tonnes \; of \; carbon \; \Rightarrow$$

$$0.5 \times \frac{44}{12} = 1.83 \; CO_2 \, e \qquad \text{(Eq. 1)}$$

Considering this proportion and the difference between the atomic mass of carbon (i.e. 12) and the molecular mass of CO_2 (i.e. 44), it can be demonstrated (by the calculation given in Eq. 1) that approximately 1.83 tonnes of CO_2 are absorbed from the atmosphere to produce one tonne of dried biomass. The carbon in forest ecosystems is stored in tree biomass (which comprises all components of the tree such as the bole, branches, leaves, flowers, fruits, and roots), in dead wood and in the forest soil. To take the example of black locust plantations, the specific carbon content of tree components (plantations and coppices) is approximately 49% for the stem, 47% for branches, 45% for roots and 48% for leaves (Ciuvat et al., 2013).

The need to address human-induced climate change has resulted in a variety of proposals to control carbon emissions and increase carbon sequestration through better forest management (Ingerson, 2010). In sustainably managed forest ecosystems, the carbon emissions (caused by removal of timber or biomass decomposition) do not exceed the carbon uptake through forest growth from one rotation to the next (Dixon et al., 1994). In other words, carbon removal in forests is offset by forest growth, which makes forest ecosystems carbon neutral. Therefore, what subsequently happens with the carbon stored in timber is of paramount importance.

Wood-based materials harvested from forests, called harvested wood products (HWP), are used to produce various products or for energy (UNECE). Harvested timber is transformed into a broad range of wood products, such as wood-based panels, furniture, paper, and paper board. Furthermore, HWP could play an important role in carbon storage, providing benefits via the sequestration of greenhouse gas (FRA, 2015). Carbon storage in wood products moves through various levels throughout their lifecycle. Furthermore, after their utilisation, wood products are sometimes recycled, burned, or sent to landfills, where they slowly decay. Therefore, carbon initially captured from the atmosphere and stored in wood is released back into the atmosphere (UNECE).

The most important terrestrial stock of organic carbon is the forest ecosystem. Therefore, a crucial role in the correction of the concentration of atmospheric CO_2 is played by the management of forests and various uses of harvested wood. Considering that more than 40% of the terrestrial surface of the EU is covered by forests and that all of these are managed, the role of forestry in the mitigation of climate change cannot be contested (FCC, 2018).

A way to significantly reduce carbon dioxide emissions is to substitute fossil fuels with wood-based fuels and energy-intensive materials with wood-based products (UNECE). The Kyoto Protocol recommends an increase in the use of HWP. Therefore, in the Protocol’s second commitment period (2013-2020) more information about land use, land-use change and forestry (LULUCF) is included. In May 2018, the LULUCF Regulation was adopted, which considers managing the forest land and HWP as a carbon pool and as the two categories that absorb and store CO_2 from the atmosphere (FCC, 2018).

One important case study is Taiwan. The main forestry policies of the Taiwanese government are afforestation and the reduction of CO_2 emissions (Lin et al., 2012). By means of a mail survey sent out to the domestic public, data were obtained regarding their attitudes and behavioural intentions towards afforestation and carbon reduction. The study found that older people were willing to participate in related activities and had a positive attitude towards the concept of afforestation for carbon reduction. Therefore, actual participation is still determined by the level of participant's ability to control the difficulties in related activities (Lin et al., 2012).

In addition, US forests are important sources for carbon sequestration and an important carbon sink (Markowski-Lindsay et al., 2011). Privately-owned family forests represent a significant portion of the overall forest land in the US, and their preferences for participating in carbon sequestration programmes is little known. Data from a mail survey of 930 Massachusetts family forest owners showed that opinions about forest usage, their harvesting plans and beliefs about climate change all play a significant role in their decision to participate. Furthermore, the survey gathered socio-economic characteristics such as gender, age, education level, and income. While the older respondents who did not manage forests or have harvest plans for timber were less inclined to participate in carbon sequestration programmes, the younger, more highly educated group of respondents was more open to it.

The carbon sequestered within housing and furniture can have a long-term economic benefit (Han, 2006). In contrast to the carbon released directly from the use of trees for heating or pulpwood, carbon can be sequestered in housing materials and furniture for a longer period (considering that the expected lifespan of a home is 60 years). Choices which can increase sequestration of carbon in wood products include the following:

1. Increasing the production and consumption of wood products
2. Improving the processing efficiency
3. Improving the quality of wood products
4. Intensifying the reuse and recycling of wood and wood products (IPCC, 2001a)

The amount of atmospheric carbon sequestered in wood products depends on their fate (Skog and Nicholson, 1998). Wood products are divided into categories based on lifespan and final disposal. The annual carbon assimilation in forests differs depending on tree species and region, the maximum point being reached between 20 to 70 years and decreasing after 60-100 years (Richard et al., 1993). Therefore, the carbon sequestered in forest trees has a longer residence time than that sequestered in housing and furniture or other wood products (Han, 2006).

1.2 Scope of Research

After conducting an assessment of stored carbon in different wood-based materials harvested from forests and wood products, this research aimed to investigate the factors which influence the lifespan of wooden furniture in the home and how this affects the lifecycle of carbon sequestered in it. Furthermore, in order to understand what the drivers are that affect how and when individuals change their furniture, the behaviour of a sample of London residents in relation to carbon storage in home wooden furniture was investigated.

The rationale for the research is based on the fact that the more frequently home wooden furniture is changed, the shorter the lifespan of the carbon kept sequestered in biomass, with negative consequences on climate change mitigation efforts.

Therefore, the second component of this research evaluated the mass of carbon sequestered in various kitchen models and aimed to find the sources of variability in the amount of CO_2e that was retained per linear metre of this type of home wooden furniture.

1.3 Structure of Thesis

This thesis is presented in five chapters, starting with an introduction in Chapter 1.

Chapter 2 comprises the literature review. After a discussion of trees and the carbon cycle, a classification of forest products and various types of wood products is provided. Considering that medium density fibreboard (MDF) is manufactured entirely from virgin feedstock compared to chipboard which is 40% recycled, it was taken as an important example of a relevant wood product. A presentation of the MDF manufacturing process, its physical and mechanical properties, its lifespan, and its carbon sequestration is given and the chapter ends by discussing its particular application in the manufacture of kitchen furniture.

Chapter 3 shows how the research methodology was established and how the data was collected and analysed. The research is based on quantitative methods (i.e. a questionnaire), using a Likert scale for the responses whenever possible. The analysis of the data was carried out using parametric and non-parametric methods (Harpe, 2015), depending on the type of responses analysed. An evaluation of carbon content in kitchen furniture with an explanation of its variance is given at the end of this chapter.

The research results are presented in Chapter 4. Data analysis was performed using R (R Core Team, 2017), an open-source software for statistical computing. Because the data obtained from the questionnaire was categorical, non-parametric methods were used. However, for Likert scale responses parametric tests (e.g. *t*-test, F-test) were also employed if the data was normally distributed. The chapter ends by presenting various models of kitchen furniture for which the carbon content and CO_2e (expressed per linear metre) had been calculated, as well as their variance in CO_2e due to the raw materials used for doors and drawer fronts and due to furniture design.

Finally, in Chapter 5, an evaluation of the key findings of the research project is provided. This chapter reviews the research programme with reference to the intended aim and objectives and concludes by identifying the opportunities for future research.

CHAPTER 2 Literature Review

2.1 Trees and the Carbon Cycle

The forest cover in the world has decreased by some 129 million ha (hectare; x 10,000 m^2) from 4128 million ha in 1990 to 3999 million ha in 2015 (FRA, 2015). This latter value represents 30.6% of the global land area.

The forests in the world store around 296 Gt (gigatons; x 10^9 tonnes) of carbon in below- and above- ground biomass, with the bigger quantities of stored carbon being found in the forests of South America and Western/Central Africa. Moreover, the living biomass alone contains a global average of 74 tonnes of carbon per ha: South America and Western/Central Africa store 120 tonnes of carbon per ha (FRA, 2015). The carbon stocks in forest biomass have decreased by 442 million tonnes per year in the last 25 years because of degradation of forest land and the conversion of forest land to agriculture and settlements.

The carbon in forest ecosystems is stored in tree biomass (all components of the tree such as bole, branches, leaves, flowers, fruits and roots), dead wood and in the forest soil (chapter 1.1).

Between 2010 and 2015, the regions of Europe, East Asia, and North America all experienced growths in their stocks of carbon in forest biomass, with respective increases of 220 million, 80 million and 50 million tonnes of carbon per year. Meanwhile, the regions of South America, South/Southeast Asia and Western/Central Africa have seen their carbon stock in forest biomass diminish considerably, with respective reductions of approximately 190 million, 280 million and 130 million tonnes of carbon in the same period (FRA, 2015).

According to the FAO Global Forest Resources Assessment (2015), the carbon stock in forest living biomass in Europe changed from 44.4 Gt to 45.5 Gt between 2010 and 2015 (+ 1.1 Gt), and that in North/Central America changed from 35.6 Gt to 35.9 Gt (+ 0.3 Gt).

Table 1. Carbon stocks in forest living biomass by region, 1990-2015 (Source: FAO Global Forest Resources Assessment, 2015)

	Carbon (Gt)				
Regions	**1990**	**2000**	**2005**	**2010**	**2015**
Europe	41.4	42.5	43.2	44.4	45.5
Africa	66.5	63.5	62.1	60.8	59.7
Asia	38.1	37.7	37.2	36.8	36.3
North and Central America	33.9	34.9	35.3	35.6	35.9
Oceania	16.1	15.9	15.9	15.9	15.7
South America	111.5	107.8	105.5	104.0	103.1
World	**307.6**	**302.3**	**299.2**	**297.6**	**296.2**

In the period from 1990 to 2010, the net decrease in carbon associated with below- and above- ground biomass was around 0.5 Gt per year. The subsequent period from 2010 to 2015 achieved a smaller relative reduction of approximately 0.3 Gt per year, because countries in South/Central America and in Asia have managed to considerably slow their rate of forest loss.

The overall trend in the world continues to be one of decreasing carbon stocks but these losses can be balanced.

Merely focusing on the forest carbon pool, without considering the carbon storage in the resulting wood products from timber, is a misinterpretation (Lippke et al., 2010). Using timber for wood products is an important way to keep the carbon stored in biomass for a longer time. Therefore, the cumulative effect of carbon storage in wood products could make a significant contribution to lowering the prevailing concentration of greenhouse gases.

2.2 The Classification of Wood Products

In 1973, the “Classification and definitions of forest products” was published, as a result of a collaboration between the FAO and an Economic Commission for Europe (ECE) Working Party on Forest Economics and Statistics. However, due to the revisions of the Standard International Trade Classification and as a consequence of technological advances, this classification of forest products had to be updated. Subsequently, in 1982, an updated version of the “Classification and definitions of forest products” was published, which has since been used as the standard forest products classification.

According to FAO (1982), forest products are classified into the following main groups:

1. Rough wood
    1.1. Coniferous
    1.2. Non-coniferous
2. Residues of wood processing; recoverable wood products
    2.1. Coniferous
    2.2. Non-coniferous
3. Wood chips and particles
    3.1. Coniferous
    3.2. Non-coniferous
4. Wood simply worked or processed
    4.1. Coniferous
    4.2. Non-coniferous
5. Wood sawn lengthwise; veneer sheets
    5.1. Coniferous
    5.2. Non-coniferous
6. Wood-based panel (including similar panel from other lignocellulosic materials)
    6.1. Plywood
    6.2. Particle board
    6.3. Fibreboard
    6.4. Combination boards
    6.5. Other panels based on wood or other lignocellulosic materials
7. Pulp of wood, other fibrous lignocellulosic materials, and pulp of wastepaper
    7.1. Mechanical and chemo-mechanical wood pulp
    7.2. Thermo-mechanical wood pulp
    7.3. Semi-mechanical wood pulp
    7.4. Sulphate and soda wood pulp, except dissolving grades
    7.5. Sulphite wood pulp, except dissolving grades
    7.6. Dissolving pulp
    7.7. Pulp of fibrous lignocellulosic materials, other than wood, except dissolving grades
    7.8. Pulp of wastepaper
8. Paper and paperboard
    8.1. Newsprint
    8.2. Other printing and writing paper
    8.3. Household and sanitary paper

8.4. Wrapping and packaging paper and paperboard

8.5. Other paper and paperboard not elsewhere specified

9. Wastepaper

9.1. Mainly mechanical pulp containing

9.2. Mainly unbleached sulphate pulp containing

9.3. Mainly bleached chemical pulp containing

9.4. Other wastepaper including mixed waste

10. Raw, semi-processed and worked cork

10.1. Raw cork

10.2. Semi-processed cork

10.3. Worked cork

2.3 Carbon Storage in Wood Products

According to Dewar and Cannell (1992), carbon storage in wood products represents only 16% of the total carbon using their standard values (Ex. 34/215 = 0.158 t C/ha). Carbon storage was calculated in a plantation of Sitka spruce. The amount of carbon in trees is approximately 50% of their dry biomass and, therefore, the estimated carbon storage in wood products is calculated by multiplying the tree's dry weight by 50% (Huang et al., 2003).

The amount of carbon in harvested wood products is approximately constant (Technical Paper, 2013). Two parameters, the basic density and the carbon fraction, are multiplied to obtain the carbon conversion factor for each subcategory of harvested wood products. According to Birdsey (1992), wood has a composition of approximately 48-52% carbon with some variations between species. The IPCC default of 50% is very often used and has been selected for coherence with the forest model. The wood density is widely variable and harvested wood products differ considerably in terms of how much wood material is contained within a given volume (Technical Paper, 2013).

2.3.1 Carbon Storage in Rough Wood

The rough wood category contains all harvested wood which was grouped by different criteria such as (a) species, i.e. coniferous and non-coniferous, (b) form of raw material, e.g.

logs, wood in the rough other than logs and other wood and tree biomass, (c) primary purpose or intended use, e.g. for sawn wood, pulp, wood-based panel, energy (FAO, 1982).

Within the manufacturing process, the rough wood is an aggregate comprising sawlogs and veneer logs, pulpwood, round, split and other industrial roundwood. According to FAO statistics (2006), approximately 96% of coniferous timber and about 79% of the non-coniferous timber are used for the aggregated category industrial roundwood.

Table 2 shows the production of industrial roundwood across different regions in recent years. The production has increased steadily in the period from 2010 to 2017, with the biggest increase seen in Asia.

Table 2. Production of industrial roundwood (FAO, 2013, 2014, 2017)

	Production (million m^3) per year		
Region	**2010**	**2014**	**2017**
World	1500	1830	1906
Asia	270	380	407
North America	430	500	508
Europe	500	570	603
Only UK	7.50	9.30	8.80

The trade of roundwood and wood products has an important effect on the carbon stock (Eggers, 2002). In the last 20 years, the average global consumption of wood has increased on average by only 0.3% per year, with the estimated annual wood consumption being around 3.5 billion cubic metres (FAO, 2006).

The forest area in the world is more than 4 billion ha, representing about 30% of the total land area (FAO, 2013). Europe has approximately 1 billion ha, corresponding to about 45% of its land area, more than North America, Asia, or Africa, but less than South America. Furthermore, whilst the woodland area in the United Kingdom is around 3.17 million ha, corresponding to about 13% of its land area, the United States of America has approximately 310 million ha, corresponding to about 34 % of its land area (FAO, 2015).

The forestry production of roundwood is shown in Table 3, in recent years. The production has increased in the period from 2010 to 2017 apart from in China, where it has declined steadily.

Table 3. Production of roundwood (FAO 2013, 2014, 2017)

	Production (million m^3) per year		
Region	**2010**	**2014**	**2017**
World	3600	3700	3797
Asia	1130	1120	1128
North America	540	550	574
Europe	680	720	760
Africa	700	730	752
Only United States	390	400	419
Only China	350	340	327
Only UK	10	11	10.7

The biomass conversion from harvested roundwood to an end product is determined by the input-output biomass balance during the manufacturing process. Therefore, during the manufacturing process of wood products, from the forest to the end product, there are flows of biomass (Chen et al., 2013).

After cutting the forest trees, the remaining stump can reach 30% of the tree's total volume and the root represents 10-14%. Some roots can be capitalized by having them cut into aesthetic veneers (e.g. walnut) or various chemicals can be extracted. The stem is made up of the trunk and crown, whose shape is specific to each wood species. The trunk is the main wood mass of the tree and represents 50-90% of its volume, being processed into semi-finished wood materials (timber, etc.) and various other wood products. The crown represents 5-20% of the total volume of the tree. Most branches are used for chipboard and wood fibre boards. The bark, the leaves, the stump, and some waste can be the object of some industrial processing, especially of a chemical nature (Brenndorfer, Zlate, 1990).

Peeling is required for the recovery, protection, and conservation of the wood, as well as by the qualitative conditions imposed on the wood assortments. In softwoods, peeling reduces the volume to about 10-12%. For hardwoods, keeping the bark intact is necessary to maintain the moisture content of the wood. The qualitative dimensional sorting system is used in order to obtain a large quantity of valuable mixtures of wood for industry (Brenndorfer, Zlate, 1990). Approximately 5% of all harvested wood biomass is lost when logs are selected (Dramm et al., 2002). These losses are due to selection by eliminating defects, interior and exterior, establishing wood assortments by quality classes. At the same time, a sorting of the wood from the crown, the wood degraded by exploitation and a sorting of the firewood is made.

Furthermore, approximately 2.5% of harvested biomass is lost to decomposition and waste during wood transport, storage, and mill yard handling (Pulkki, 1991).

Chen et al. (2013) showed that the key factors that determine the biomass conversion from harvested tree to finished harvested wood products are:

1. the division of harvested wood among product types
2. the production process and its conversion efficiency
3. the amount of mill residue and how it is used.

The quantitative yield, i.e. the ratio between the volume of produced timber and the volume of logs used, is approximately 68% for softwood. For deciduous trees, depending on the species, the yield is 60% for beech, 51% for oak and 68-70% for various other species (Brenndofer, Zlate, 1990). Reported annual figures for the global flow and conversion of wood into forest products demonstrated that around 47% from global forests is used for industrial roundwood and around 53% for fuelwood and charcoal. In the case of industrial roundwood, 27% is used for pulpwood and 59% as sawlogs and veneer logs, of which 49% is used for sawn wood, 5% for plywood and veneer, then 24% as pulp material (FAO, 1993).

Starting from forest harvesting, through industrial processes, resulting in industrial roundwood, there is a flow of carbon from the harvested forest biomass to the finished HWPs (Chen et. al., 2013). Meanwhile, the carbon associated with the residue left behind on harvest sites is slowly released through their decomposition.

Karjalainen et al. (1994) showed the conversion effectiveness of the logs into sawn timber to be about 43%, and into plywood approximately 38%. According to Meil et al. (2009), approximately 43% of sawlogs biomass is converted to lumber, about 35% into pulp chips and the other approximately 22% remained as processing residue and landfill.

2.3.2 Carbon Storage in Wood Residues

Residues from the manufacturing process and recoverable wood products comprise the wood which has passed through some form of processing, but which also represents the raw materials of a further process. At the base for the classification of this group are the following: (a) wood species (coniferous and non-coniferous), (b) source of material (processing residues or recoverable wood products), (c) characteristics of material (for residues, solid wood or not solid wood, for recoverable wood products, contaminated or uncontaminated) and (d) end use (e.g. for pulp, particle board, etc., with a higher level distinction between material used for wood chips and material not used for that).

Table 4 shows the production of wood residues across different regions in recent years. The production has increased steadily in the period from 2010 to 2017, with the biggest increase seen in Asia.

Table 4. Production of wood residues (FAO, 2013, 2014, 2017)

	Production (million m^3) per year		
Region	**2010**	**2014**	**2017**
World	131	220	221
Asia	31	100	110
North America	22	22.5	22.57
Europe	58	72.5	60.9
Only UK	0.73	0.83	0.81

Dwivedi et al. (2013) has shown that the use of logging residues for bio-energy development would not affect traditional forest-based industries which are dependent on sawnwood, chip-n-saw, and pulp for manufacturing various wood products, such as lumber, plywood, oriented strand board and paper. Chip-n-saw is obtained through the process of cutting small logs into cants, transforming part of the exterior of the log directly into chips without making any sawdust. Cants are then sawn into lumber as part of the same operation. Modern softwood sawmilling systems are designed to produce chips of the best quality by adjusting the speed of the chipping system to control chip length and due to optimal cutting geometry.

2.3.3 Carbon Storage in Wood Chips

Wood chips and particles cover intermediate products, which may be manufactured from several sources (wood in rough and residues of wood processing or recovered wood products) and have a great variety of uses (FAO, 1982). They are classified according to these criteria: a) coniferous or non-coniferous, b) sources as wood in rough, residues or recovered wood products and c) end use, e.g. for pulp, particleboard etc.

This group of forest products includes the wood that has been reduced to small pieces but excludes wood chips made directly in the forest from roundwood, where it was counted as pulpwood, round and split (FAO, 2006). The processing consists of chopping the logs into smaller pieces of approximately 1cm-5cm. The chips are then further milled to powder, fibres, fibre bundles, or chips (Klugman et al., 2007; Zhu et al., 2010). The weight of wood particles is reflected as delivered or as an oven dry weight (all moisture removed).

The export of wood chips and particles across different regions is shown in Table 5. Although in Europe the export of wood chips has grown, in the UK it has decreased noticeably between 2014 and 2017.

Table 5. The export of wood chips and particles (FAO, 2013, 2014, 2017)

	Production (million m^3) per year		
Region	**2010**	**2014**	**2017**
World	56	67	66.6
Asia	13	23.3	19
North America	2.51	6.4	6.5
Europe	12	11.9	14.1
Only UK	0.20	0.22	0.09

Linholm (2010) found that the primary energy used to produce chips from logging residues and stumps, was approximately 2%-5% of the harvested energy in the forest fuel (0.021-0.049 MJ per MJ chips; 1 megajoules: x 10^6 joules). According to the same study, in northern Sweden the primary energy to produce 1MJ of forest fuel chips from residues was higher than in southern Sweden, mostly due to the higher energy used in transportation.

According to Tam (2013), different sized wood chips were pre-treated by steam infusion at 180°C and 200°C and then the solids were subjected to enzymatic hydrolysis. Woody biomass is resistant to breakdown due to lignin content. Mechanical size reduction of woody biomass consumes a significant amount of energy. Therefore, a hydrothermal pre-treatment and enzymatic hydrolysis were applied to varyingly sized wood chips and fine powder of aspen to determine the impact of wood size on sugar release. The results in this study showed that large wood chips could give similar enzymatic sugar yields to small chips and powder, thus saving around 75% of energy.

Zhu et al. (2010) showed that wood chip manufacturing requires an energy consumption of around 0.05 kWh/kg. Elsayed et al. (2003) showed that by combustion of wood chips on a large scale, heat and power generation are combined, so that from 0.225 tonnes oven dried wood chips approximately 278 kWh electricity, about 667 kWh steam and approximately 0.003 tonnes of ash are obtained.

The use of wood chips used in automated boilers has the greatest associated carbon dioxide emissions principally because it needs the most fossil fuel to burn and to achieve heat transfer from the fuel to the water and steam (Northern Woodheat, 2014). The same study showed that the production and use of wood chips results in the emission of 64 g of carbon dioxide for every available kWh generated from steams produced by the boiler. The carbon balance of wood chips is 2% from planting and harvesting, 17% from processing, 3% from transport and around 78% from fossil fuel to burn and supply energy to the boiler (to heat water into steam) and to the control system (to feed the boiler).

In 2017, the global production of wood pellets was around 33.3 million tonnes (FAO, 2017). In North America, this production was approximately 9.6 million tonnes, in Asia around 4.3 million tonnes and in Europe approximately 18.4 million tonnes. The production of wood pellets in the United Kingdom was of around 281 thousand tonnes.

Wood pellets are produced from sawdust and wood shavings which are dried and then milled into particles. The particles are compressed into pellets and the compression leads to an increase in temperature. Therefore, wood pellets require mechanical processing and are dried to prevent self-heating using heat generated by fossil fuels, based on gas combustion

(Northern Woodheat, 2014). Wood pellets also require the provision of electrical energy to the boiler, to heat water into steam, and to the control system, to feed the boiler.

The production and use of locally produced wood pellets result in an emission of 34 g of carbon dioxide for every available kWh generated from steam produced by the boiler The carbon balance of locally produced wood pellets is 2% from planting and harvesting, 93% from processing, 4% from transport and 1% from fossil fuel to burn and supply energy to the boiler, that heats water into steam.

Therefore, the carbon emissions from wood pellets and wood chips are very low and so have little impact on the net carbon balance of wood fuel.

2.3.4 Carbon Storage in Wood Simply Processed

According to FAO (1982), the category of wood simply worked or processed includes (a) pressure impregnated roundwood, (b) wood charcoal and other solid fuels manufactured from wood, and (c) other wood simply worked, such as staves', shingles and shakes, and wood wool. This category has three subdivisions as (a) coniferous or non-coniferous, (b) process and (c) end product.

According to the Swiss Wood wool Standard (2011), wood wool is a natural material, high-quality, in the form of uniform, fine, and up to 500 mm long, elastic, loose, wood-splinter and virtually dust free threads. It originates from debarked, air-dried trunks of the highest quality, with up to 13% wood moisture content. The wood wool is used for filling, twisting and upholstery, insulating, and to produce materials for pollution filters in countless sectors. The wood species used for the manufacture of wood wool are softwoods (Norway spruce, Scots pine, Larch) and hardwoods such as European beech, ash, and poplar.

Table 6 shows the production of wood charcoal across different regions in recent years. In Europe, the production has increased steadily in the period from 2010 to 2017.

Table 6. Production of wood charcoal (FAO, 2013, 2014, 2017)

	Production (million metric tonnes) per year		
Region	**2010**	**2014**	**2017**
World	47	53	51.2
Asia	8	8.8	9
North America	1	0.98	0.85
Europe	0.5	0.48	0.63
Only UK	0.005	0.005	0.005

In many developing countries charcoal production supplies affordable energy and thus charcoal production leads to over exploitation of forests (Mekuria et al., 2012). Rousset et al. (2011) showed the environmental impact of wood charcoal briquettes produced from eucalyptus wood in Brazil. Charcoal briquettes are produced from charcoal fines and starch. While the production of charcoal from sustainably managed eucalyptus plantations produced the charcoal fines, starch is extracted from babassu (*Attalea speciosa*) pulp, in the Amazon region. A positive balance for CO_2 equivalent is shown in the briquette production process. The production of 1kg of briquettes corresponds to around 4 kg of CO_2 equivalent sequestered, due to the use of renewable raw materials (charcoal fines). The production of starch started from the babassu coconut extraction site, subsequently used for charcoal and starch production. These systems involve the consumption of a series of fossil fuels which produce less CO_2 than the CO_2 consumption of each production chain. Therefore, along the briquettes production process, the CO_2 emissions are totally compensated for by the quality of the raw materials used (i.e. charcoal from eucalyptus plantations and starch from babassu fruits) (Rousset et al., 2011).

2.3.5 Carbon Storage in Veneer Sheets

Veneer sheets are wood products in the group of wood sawn length wise and this group covers the products of the simple processes of sawing and peeling, with the associated processes of hewing, profile chipping and slicing (FAO, 1982). Veneer is produced when the log is chucked and rotated against a stationary knife, or it is sliced, when a log is halved or quartered into flitches with a saw, with the flitch then pressed against and moved across a knife (UNECE/FAO, 2010). Sliced veneer is used for producing thinner decorative veneer (aesthetic veneers) and rotary peeled veneer is used for structural applications (technical veneers). A composite product manufactured from veneer is plywood. This is obtained by laminating sheets of veneer together into panel.

The production of veneer sheets is shown in Table 7 across different regions in recent years. The production in Asia has increased steadily in the period from 2010 to 2017.

Table 7. Production of veneer sheets (FAO, 2013, 2014, 2017)

	Production (million m^3) per year		
Region	**2010**	**2014**	**2017**
World	12	13.5	14.43
Asia	6	6.6	7.05
North America	1	1	1.16
Europe	2	2	2.5
Only China	3	3	3

Within the manufacture of rotary peeled veneer, some resulting co-products are peeler cores, green chips, dry chips, and shrinkage from finished green lumber to finished dry lumber. Heating green wood makes it become more plastic and softer. When green wood is heated, it extends tangentially and shrinks radially. Logs for rotary cutting should typically have a minimum diameter of 250 to 300 mm. Approximately 80% of all veneer is cut by the rotary method. The rotary peeled veneer method gives the maximum yield (Lutz., 1974). The peeler core constitutes the centre of the log and is sawn for use as low-quality timber or used for fuel, chips, and pulp. The timber obtained consists almost exclusively of heartwood (Sugiyanto et al., 2010). Some peeler cores are large enough to make into sawn wood.

For example, in a North American coniferous rotary plywood mill, veneer was obtained from about 60% of the log volume processed, green chips from approximately 30%, dry chips from 5%, shrinkage from 4% and peeler core from 1% of the log volume processed (Fonseca, 2005).

Laminated veneer lumber (LVL) is a composite wood material made from sheets of veneer generally 2.54 mm or 3.18 mm thick that are laminated together with their grain orientation in the same direction and then hot-pressed (Puettman et al., 2013). Furthermore, the processing of beech wood to LVL used veneers of 3.7 mm thickness, that are glued parallel to fibre direction by a phenolic adhesive (Dill-Langer, Aicher, 2014). The thickness of the panel is in the range of 40-45 mm and the lamella thickness, after planing, is in range of 37-42 mm. The mean value of the raw density of the veneer is about 680 kg/m^3 and the veneers are jointed in the longitudinal direction by glued scarf joints. The beech LVL is used for plate-like structures and can be further processed into glued laminated beams (glulam) or Parallam (Parallel Strand Lumber or PSL). Glulam is a structural engineered wood product, made of individual wood laminations positioned and selected in the timber and bonded together with a moisture-resistant adhesive. Parallam is obtained from long veneer strands (L = 2.5 m, l = 12 mm), parallel oriented, and a phenol formaldehyde resin is used to bind the strands together (Barbu, 1999).

Energy use for manufacturing LVL is controlled by the combustion of wood fuel (biomass), which is comprised of wood and bark waste obtained during veneer production. Puettman et al. (2013) has shown that, using the Bare (2011) method, approximately 212 kg CO_2 are released in the production of one cubic metre of LVL, while the same cubic metre of LVL stores around 1093 kg CO_2.

2.3.6 Carbon Storage in Wood-Based Panels

According to FAO (1982), plywood is categorised by (a) coniferous or non-coniferous raw material (b) type, as veneer, core or other and (c) by finish, interior or exterior. Particle board and fibreboard are firstly differentiated by use in the manufacture of chips or particles, and then by fibres.

In the production and trade statistics, the wood-based panel represents the sum of veneer sheets, plywood, particleboard, and fibreboard. Moreover, particleboard includes oriented strand board (OSB), and fibreboard products represent the sum of hardboard, medium density fibreboard and insulating board. All of them are reported in cubic metres.

Table 8 shows the production of wood-based panel across different regions in recent years. Production has increased steadily in the period from 2010 to 2017, with the biggest increase seen in China and Asia.

Table 8. Production of wood-based panels (FAO, 2013, 2014, 2017)

	Production (million m^3) per year		
Region	**2010**	**2014**	**2017**
World	284	380	401.5
Asia	140	230	242.7
North America	44	46	47
Europe	75	77.7	87
Only China	104	190	201
Only United States	33	34	35.17
Only UK	3.4	3	3.18

Wood-based panel production had increased in recent years and was predicted between 2000-2020 to show an average annual growth rate of 2.7% (FAO, 2014; Kouchaki, 2016).

Ingerson (2009) showed that particleboard, OSB, and MDF may reach 90% conversion of non-bark wood to panels. Furthermore, panels made of wood particles have important different properties depending on the source of wood from which they are produced. Many panel manufacturers take into account the oven-dry weight of raw material. For example, when using Norway spruce with a basic density of 380 kg/m^3 for MDF, as a raw material, the panels will be pressed to a basic density of 760 kg/m^3. Therefore, it will be necessary to utilise 2 m^3 of solid wood as raw material per m^3 of MDF panel, but if Siberian larch is used, with a basic density of 460 kg/m^3, only 1.65 m^3 would be needed (UNECE/FAO, 2010).

Accordingly, the weight of panels made from wood particles will be dependent on the density of the parent wood, the density of the wood fibre, the weight of binders and fillers, and the moisture content which is about 6%-8% (Briggs, 1994).

Particleboard has favourable characteristics in terms of carbon storage and energy use (Wilson J.B., 2010). Particleboard is produced from some industrial wood residues and fresh solid wood material. The same study showed that in US particleboard falls into two product categories: into industrial as substrate (96%) for making office furniture, kitchen, bath cabinets, door component, and into flooring (4%).

The production of particleboard is shown in Table 9 for different regions. A significant increase in production over the years is seen in Asia.

Table 9. Production of particleboard (FAO, 2013, 2014,2017)

	Production (million m^3) per year		
Region	**2010**	**2014**	**2017**
World	98	85.6	95.3
Asia	22	31	38.1
North America	22	5.8	5.8
Europe	48	41.2	43.3
Only UK	2.6	1.9	2.16

OSB panels are made from compressed flakes and arranged in layers, from three to five, that are oriented more or less at right angles to one another (Maloney, 1996). This industry can use small and irregular logs, usually coniferous or low-density non-coniferous, with a diameter around 350 mm (Barbu, 1999). Furthermore, species such as Southern-Pine, Jack Pine, Scots Pine, Spruce, Larch (small proportion) are predominately used in the manufacture of OSB panels (Maloney, 1996).

Spruce is mainly used on thin panel production, and pine on thick panel production. Due to the low bulk density of spruce, spring back would occur if used on thick panel production resulting in costly scrap. So, well managed stock rotation and scheduling is in place to avoid this (Norbord, 2012). The logs are cut to length, debarked, and processed into strands around 120 mm long and 25 mm wide. After they are dried, blended with resin binder and wax, the strands are laid in cross directional layers and form a large continuous mat, and then it is pressed in the hot press.

Kelly (1977) showed that the control of the average final density of particle board is obtained by two factors: the raw material density and the compaction of the mat in the hot press. The pressing conditions and the amount of raw material determine the average resultant density of wood-based materials (Nishimura et al., 2001). Therefore, in the OSB manufacturing process, the use of low-density wood species is advantageous for the panel to have superior mechanical properties and less density variation (Barbuta et al., 2010). Moreover, the properties of OSB are a function of density, mass ratio between surface layer and core layer and moisture content (Barbuta et al., 2012).

The same study showed that OSB is replacing plywood in various applications, is used in residential and commercial buildings for wall and roof sheathing, flooring, I-joists, and in furniture, pallets, and boxes.

Table 10 shows the production of OSB across different regions in recent years. The biggest production is in North America.

Table 10. Production of oriented strand board (FAO, 2014, 2017)

	Production (million m^3) per year	
Region	**2014**	**2017**
World	25.12	30.7
Asia	0.27	0.77
North America	18.3	20.8
Europe	5.9	9.34
Only United States	11.75	12.93
Only UK	0.32	0.35

On a survey of OSB production practices in the southeast region of the US, Kline (2005) showed that around 1.4 m^3 of roundwood logs with bark is required for a standard 0.88 m^3 production unit of OSB. During the processing operation, approximately 710 kg of wood and around 60 kg of bark resulted in approximately 570 kg of primary OSB product, giving a total wood recovery of 71%. The density for OSB is assumed to be around of 650 kg/m^3 and approximately 54% of the energy required to manufacture this product is added on-site.

Furthermore, the same study showed that for each standard OSB production unit, around 95% (396 kg) of carbon from raw wood material is utilised, and one production unit holds approximately 69% (290 kg) of total carbon input as the final manufactured product. Only 4% of carbon is held in the form of co-product, and the remainder of carbon is released back into atmosphere, 24% in the form of non-fossil CO_2 and other emissions. On the other hand, according to Egger (2010), 1 m^3 of OSB binds approximately 864 kg CO_2, namely around 236 kg C.

Producing OSB, uses fewer resources, with a lot of the energy coming from wood residues derived during the process itself, instead of fossil fuels. According to Lippke et al. (2009), those products that are dried and/or use resins, such as plywood and OSB, require more energy but much of the drying energy is supplied by biofuels (bark and mill residues). Whereas OSB requires more energy for the manufacturing process, the higher density stores more biomass and therefore more carbon, offsetting much of the energy used. As a result, the carbon stored in wood products is substantially higher than the emissions from their initial manufacture.

Medium density fibreboard (MDF) is a dry-formed panel product manufactured from lignocellulosic fibres combined with a synthetic resin or other binder (Maloney, 1996). The wood fibres are processed from industrial roundwood residues, such as shavings, sawdust, plywood trim and chips, but can be from chips of low-valued log or urban wood waste (Wilson J.B., 2010).

In Table 11, the regional productions of MDF are compared. There is a clear trend of increase in consumption, in Asia and Europe in specially.

Table 11. Production of Medium Density Fibreboard (FAO, 2013, 2014, 2017)

	Production (million m^3) per year		
Region	**2010**	**2014**	**2017**
World	70	93.5	99.9
Asia	49	69	70.1
North America	3.3	3.8	4.25
Europe	11	12.8	17.5
Only China	40	56.8	56.3
Only United States	2.5	3	3.22
Only UK	0.77	0.75	0.67

The manufacturing process of MDF is carried out at high temperature, in which urea formaldehyde as binder is used for strength properties and paraffin wax is added for protection against water spillage (Rivela et al., 2007). Isocyanate resin is also used as binder and MDF panels made with this resin system showed low formaldehyde emission and superior mechanical and physical properties (Jie, 2008). Isocyanate bonded boards demonstrated higher strength and better stability than urea-formaldehyde bonded boards (Pensook, 1990).

Accordingly, the process includes mechanical pulping of wood chips to fibres (refining), drying, blending fibres with resin and sometimes wax, forming a mat, and hot pressing. The density of medium density fibreboard is between 496 and 801 kg/m^3 with thickness varying between 1.27 cm and 1.91 cm (Rivela et al., 2007).

The same study showed that in wood preparation inventory for 1 m^3 of medium density fibreboard processing, using around 1,080 kg biomass and approximately 49 kg additives, the emissions to air contained approximately 216 kg of CO_2.

2.3.7 Carbon Storage in Wood Pulp

The group of wood products with pulp from wood, other fibrous lignocellulosic material and pulp from wastepaper is intended to cover the products of processing of the fibrous lignocellulosic raw material used principally in the manufacture of paper and paperboard (FAO, 1982). The same study showed that the bases of classification for wood pulp, other than dissolving grades, are: (a) form of process, as mechanical pulp, sulphate pulp; (b) degree processing, as bleached, unbleached; (c) coniferous or non-coniferous raw material.

The manufacturing process comprises the separation of wood fibres using mechanical or chemical means, or a combination of both approaches. Pulp is produced using mechanical grinding applied to wood, especially wood particles, and the resultant wood fibres tend to be short. Chemical pulping implies using heat and chemicals to dissolve the lignin, resulting in long and strong wood fibres.

In the case of dissolving pulp and non-wood pulp, the primary distinction is by raw material and the secondary distinction is by form of process, as sulphite or sulphate.

The production of wood pulp is shown in Table 12 for recent years. The production has increased in general apart from the UK. According to production and trade in the UK (2017), from the total softwood deliveries, 0.442 million green tonnes were used for pulp wood compared to 0.465 million green tonnes used in 2014 (green tonne is the weight measurement of timber freshly felled before any artificial or naturally drying). The increase in softwood deliveries for wood fuel from 1.5 million green tonnes in 2014 to 1.6 million green tonnes in 2017, used for heating and energy production, reflects a decrease in wood use for pulp mills.

Also, softwood deliveries in the UK have decreased in recent years from 10.9 million green tonnes in 2014 to 10.5 million green tonnes in 2017.

Table 12. Production of wood pulp (FAO, 2013, 2014, 2017)

	Production (million m^3) per year		
Region	**2010**	**2014**	**2017**
World	168	173	183.9
Asia	28	31	35.3
North America	69	65.5	66.04
Europe	45	45.8	47.8
Only UK	0.21	0.24	0.22

According to UNECE/FAO (2010), one oven dry metric tonne of wood input will yield approximately 0.95 metric tonnes of oven dry pulp (metric tonnes: x 1000 kg), because a little of the original components of the wood is lost in mechanical processing. Chemical processes are use dependent on species of wood and the desired characteristics of papers. Measured as oven dry input to oven dry output, chemical pulping results in yields in the 40%-50% range, because much of the original wood is dissolved in the chemical treatment (Briggs, 1994). To obtain a stable pulp, the lignin and extractives from the cellulose components are removed in the chemical process.

Furthermore, an air-dried metric tonne of pulp and paper is assumed to be 10% moisture content on a wet basis. Therefore, one air-dried metric tonne of pulp is assumed to be 900 kg oven dry fibre and 100 kg of contained water (UNECE/FAO, 2010). Considering forest products conversion factors for the UNECE Region, a summary of country data on wood pulp showed that the average conversion factor for wood pulp is 3.87 (UNECE/FAO, 2010).

The efficiency of wood pulp conversion to mechanical spruce pulp was estimated to be approximately 92% for product and around 7% for non-processable residue, while chemical pine pulp was estimated to be approximately 46% for product and around 54% for non-processable residue (Yearbook, 1990-1991).

2.3.8 Carbon Storage in Paper

Paper products play an important role in mitigating the CO_2 emissions (Skog, 1998). According to FAO (1982), these products are made of pulp and wastepaper, plus fillers, size, colourants, and other additives as required. Products in this category are manufactured in strips, rolls, or rectangular sheets. This does not include manufactured paper products such as boxes, cartons, books, and magazines, etc. According to Green et al. (2006), paper products are defined as paper and paper board and are measured in dry tonnes.

In Table 13, the production of paper and paper board is shown across different regions. A significant increase is in Asia.

Table 13. Production of paper and paper board (FAO, 2013, 2014,2017)

	Production (million metric tonnes) per year		
Region	**2010**	**2014**	**2017**
World	400	400.2	412.6
Asia	175	183.5	195.4
North America	88	84.2	81.6
Europe	108	105	105.48
Only UK	4	4.4	3.85

Within the paper manufacturing process, the fibres or individual wood cells are separated in a pulping process (mechanical or chemical) and then bleached. The bleached wood pulps are entrained in the water and formed into thin sheets (Weinstock et al., 1997). Pulp and paper products are the result of the complex, energy-intensive process that separates wood fibres from one another (Cote et al., 2002). The lignin that holds the fibres together is dissolved in the chemical process, to separate the fibres. Moreover, the dissolved lignin and other wood components are burned to capture heat energy and recover pulping chemical. This energy is then used in the pulping process.

According to Ashton et al. (2012), paper products contain 0.3-0.6 tonnes carbon in fossil energy used / t C for virgin paper, more than used / t C for solid wood products. In the US, recycled paper is used within the manufacture of paper with a proportion of approximately 50%. Paper manufactured from 100% recycled pulp results in around 1,800 kg/tonne of CO_2 emissions, while for the paper manufactured from virgin pulp the result is approximately

4,245 kg/tonne of CO_2 emissions (Ireland-Forest web, 2008). Within the manufacture and distribution processes, approximately 27% of total fossil carbon emitted represents the transport of wood and paper products (Ashton et al., 2012).

Considering two years as an average half-life value for paper (IPCC, 2006), the 100-year weighted average for the carbon storage in paper is 2.885 percent of the original biomass carbon (Miner, 2010). According to FAO (2007), the production of paper and paperboard in UK was 5,284,000 tonnes. Considering the imports of 7,883,000 tonnes and exports of 970,000 tonnes, the consumption of paper and paperboard in UK was:

5,284,000 + 7,883,000 – 970,000 = 12,197,000 tonnes

The amount remaining in use is:

12,197,000 x 2.885/100 = 351,883 tonnes

While the recovered paper was 8,617,000 tonnes (FAO, 2007), the amount discarded is:

12,197,000 – 8,617,000 – 351,883 = 3,228,117 tonnes

The percent of waste sent to landfill after recovery is 82% for the UK (IPCC, 2006). Therefore, the amount discarded to landfill is:

3,228,117 x 82/100 = 2,647,055 tonnes

The amount of carbon stored in landfill is estimated to be 50% of the above total, hence:

2,647,055 x 50/100 = 1,323,527 tonnes

Because biomass carbon in forest products only remains stable and non-degradable under anaerobic conditions, it is necessary to calculate the fraction of waste that was disposed in anaerobic conditions. Considering the value of 0.9 for methane (CH_4) as an applicable correction factor in the UK (IPCC, 2006), the amount of C in anaerobic zones in landfills is:

1,323,527 x 0.9 = 1,191,174 tonnes

Furthermore, assuming 50% of C in anaerobic zones is non-degradable under anaerobic conditions, the amount of C remaining is:

1,191,174 x 50/100 = 595,587 tonnes

Or in CO_2 equivalent is:

595,587 x 44/12 = 2,183,819 tonnes

Whereas in 2004 the paper and pulp industry consumed approximately 32% of all industrial roundwood produced globally (FAO, 2007), the global emissions of fossil CO_2 per year in the manufacture process of paper and pulp were around 195 Mt-205 Mt, i.e. 195,000,000-205,000,000 tonnes (Upton et al., 2007).

2.3.9 Carbon Storage in Wastepaper

According to FAO (1982), wastepaper is an important raw material for the paper, paperboard and other industries. The same study showed that using wastepaper is an indication of its end use or of the grade of pulp for which it may be substituted.

Table 14 shows the production of recovered paper across different regions in recent years. The production has increased in the period from 2010 to 2017, with the biggest increase seen in Asia.

Table 14. Production of recovered paper (FAO, 2013, 2014, 2017)

	Production (million metric tonnes) per year		
Region	**2010**	**2014**	**2017**
World	212	221	235.3
Asia	90.4	99.6	104
North America	50.3	49	50.3
Europe	56.2	56.7	62.1
Only UK	8	7.9	7.7

Lost or discarded paper is tracked to recycling, disposal in landfills or dump, or burned, emitting carbon to the atmosphere (with or without energy produced). After the material is placed in landfill, this is covered, and oxygen is stopped from entering, but when it is, the available oxygen is consumed rapidly, and anaerobic bacteria remain. These organisms cannot break down lignin, but they can break down exposed cellulose and hemicelluloses only about 20% (Wang et al., 1994).

2.3.10 Carbon Storage in Cork

Although cork is a forest product that lies outside the remit of this study, a discussion of its properties is included in this subsection for completeness.

The extraction of cork from cork trees starts when the trees approach maturity (approximately 35-40 years old) and has a periodicity of approximately 12-13 years. Therefore, during a tree's lifetime, the cork can be harvested at least 12 times (Pereira, 2007). While the cork oak tree can survive for 250-350 years, the industry limit for cork production is only 200 years. Therefore, cork is a natural raw material and a renewable resource (Rives et al., 2011). According to Lopes et al. (2011), cork is usually removed from the tree as single pieces of cork, commonly called cork slabs, which is the raw material used to make products out of solid cork. The remaining cork raw materials of virgin cork, second cork, virgin winter cork, fragments of reproduction cork, cork with defects and fired cork are granulated and then agglomerated before becoming a product. This group of cork resources is known under the generic term "cork by-products" (Boschmonart, 2011).

In the western Mediterranean region (comprising Spain, Portugal, Morocco, Algeria, Tunisia, Italy, and the south of France), cork oak exists in an area of approximately 2.13 million ha (APCOR, 2011). As a result of reforestation programs, in the last 10-15 years, 130 thousand ha have been planted in Portugal and Spain (APCOR, 2011). The production of cork in the world is around 201 thousand tonnes per year, with Portugal having the largest production of cork, approximately 100 thousand tonnes per year (FAO, 2013).

The main components of cork are 40% suberin, 22% lignin, 20% hemicelluloses and celluloses, 15% extractives and 1% ash (Pena-Neira et al., 2000; Lopes et al., 2011). The elemental chemical composition of cork is 67% carbon, 23% oxygen, 8% hydrogen and 2%

nitrogen (Remaha, 2008). Furthermore, this raw material has unique chemical and physical properties, such as low density, low permeability to liquids and gases, elasticity and good heat and acoustic insulating.

Boshmonart (2011) showed that the industry cork sector can be divided into the following groups:

- Preparation cork industries: the activity where the raw cork slabs from the forest are transformed into prepared cork slabs.
- Natural cork producers: products are made from cork slabs, without the trituration or fractionation of the material. Therefore, single pieces of cork are obtained from solid cork (Pereira, 2007). Furthermore, two main products result: the end product (the natural cork stopper) and the intermediate product (the natural cork disc). The natural cork stopper is used for the top of wine bottles.
- Granulated cork producers: the activity where forestry cork by-products and wastes from the natural cork industry are transformed into small particles of cork. Therefore, an intermediate product is obtained, with adhesives or some other binding technique used, for example, temperature. Furthermore, two types of granulated cork are obtained, namely, white cork granulate, and black cork granulate (Pereira, 2007).
- Technical stopper producers: this sector uses white cork granulate and natural cork discs. Cork stoppers are obtained and the well know technical stopper is the champagne cork stopper.
- Speciality and other cork goods producers: this material can be used for many other products such as agglomerated panel for construction, furniture, thermal and acoustic insulation, flooring and wall panel and different decorative proposes (Remaha, 2008; Vazquez and Pereira, 2005).

The cork stripped from the tree represents at most 4% of the total biomass produced between successive cork extractions, and therefore has very little effect on ecosystem carbon storage (Pereira, 2008). Cork exploitation does not affect the ecosystem carbon sink role. Rives et al. (2011) found 86% of the raw material corresponding to reproduction cork and 14% corresponding to cork by-products.

According to Rives et al. (2011), an initial tonne of raw cork material converted into its most representative products has a distribution in mass of 19% natural cork stoppers, 41% champagne cork stoppers, 7% white cork granulate, 7% black cork granulate and 26% cork waste.

Moreover, for one unit of natural cork stopper (that weighed 3.7g) just 10.9g of CO_2 was generated during the production and for one unit of champagne cork stopper (that weighed 9g) 53.9g of CO_2 was emitted. It is stated that the carbon dioxide balance associated to natural cork stoppers was 234 g of CO_2 fixed per stopper, and 12 g of CO_2 per champagne cork stopper.

As a first approximation to the best available technique, it has been found that 770 kg of CO_2 were emitted in the production of a tonne of black cork granulate and 772 kg were emitted during the production of a tonne of white cork granulate (Rives et al., 2011). They have shown that approximately 3.4 tonnes of CO_2 were emitted to convert a tonne of raw cork and 18 tonnes of CO_2 are fixed. The overall CO_2 balance is that 14.6 tonnes of CO_2 could contribute to climate change mitigation. Assuming similar results, Boschmonart (2011) added that, if a tonne of raw cork converted into products results in 14.6 tonnes of CO_2 being fixed, the outcome for converting the 300,000 tonnes of raw cork produced globally would be the mitigation of about 4.38 million tonnes of CO_2.

2.4 Energy and Carbon Emissions Associated with Wood Processing

In the production processes, about one third of the carbon bound in timber was released into the atmosphere, but two thirds were still bound in products. After 100 years, more than 33% of the carbon initially in products was either still part of products in use or disposed to landfills (Karjalainen et al., 1994). Therefore, the amount of carbon in wood-based products could be maximised if products with long lifespan are preferred in forest-based production. An increase of 10% in the lifespan of products would increase the carbon balance in wood-based products by less than 4% (Karjalainen et al., 1994).

The conversion of timber into different products is based on the amount of timber needed to produce a particular product (Karjalainen et al., 1994). Therefore, use of logs in production process to produce sawn timber, the value of the conversion efficiencies is 43.5% for product, 43.5% for processable residue used (for pulp), and 13% for non-processable residue (for process energy) (Yearbook, 1990-1991).

Additionally, Bergman and Bowe (2008) showed that, in the north eastern part of the US, most mills are concerned about their lumber recovery factor. Therefore, 2.29 m^3 of hardwood are sawn into 1.46 m^3 of rough green lumber and dried to 1.37 m^3 of rough dry lumber. The rough dry lumber is transformed to around 1 m^3 of planed dry lumber for a total volume conversion of 43.7% from incoming logs. Generally, the log was reduced to around 45.8% of its original mass to produce the final product of planed dry lumber.

According to Skog and Nicholson (1998), carbon stored in harvested timber and net imports (i.e. import minus export) is followed through primary processing into products and various end uses (Fig. 1).

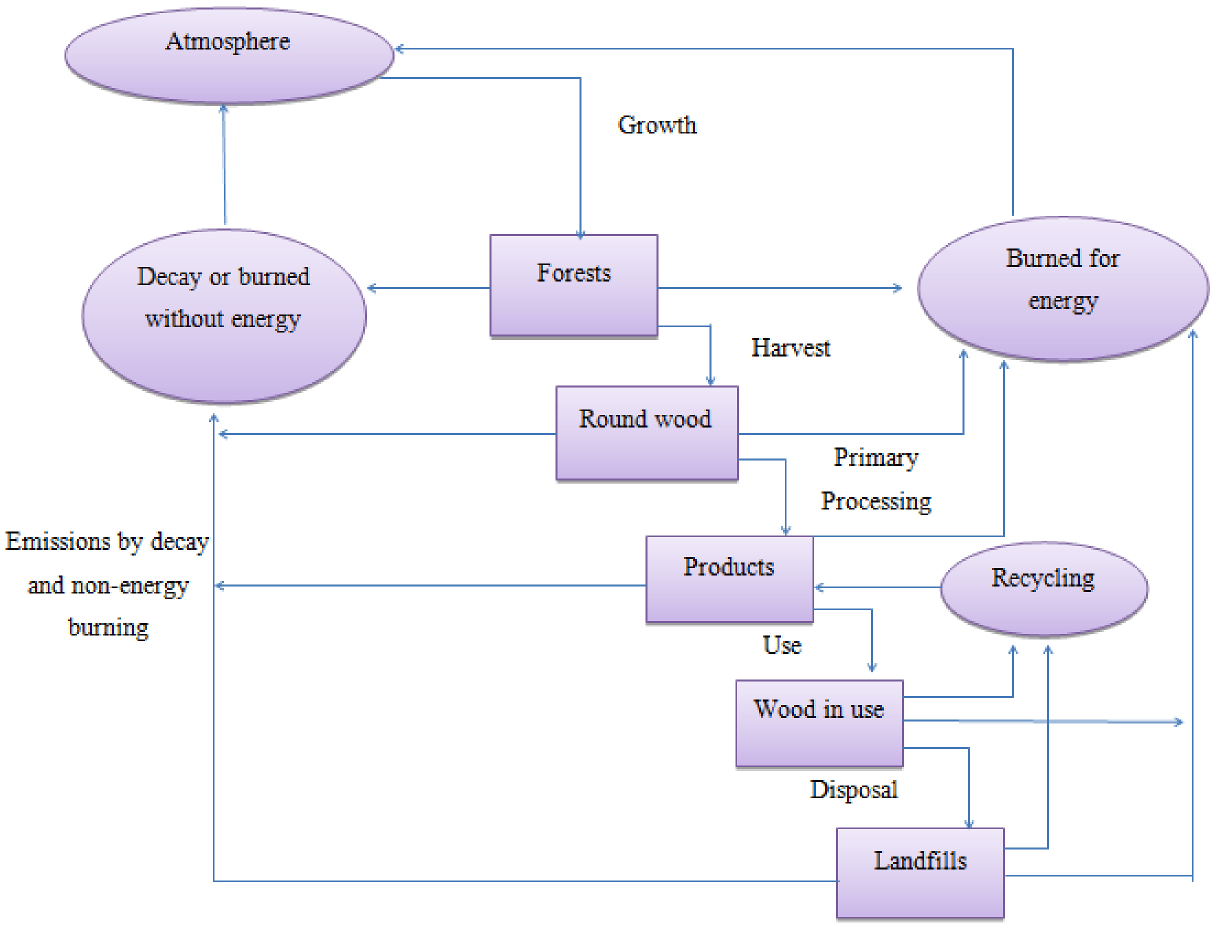


Figure 1. Cycling of carbon through wood products (Skog and Nicholson, 1998)

Similarly, Karjalainen et al. (1994) added that the main part of carbon in timber is stored into products while the rest of the carbon is emitted when by-products (e.g. sawdust, bark) are burnt to generate energy. The products can remain in use or can be recycled into raw material again, or they are retired from use and sent to landfills or burned (when carbon is emitted into atmosphere). When the products are removed from use, approximately one third of the products are recycled, one third is used to generate energy and one third is disposed in landfills.

2.5 The Lifespan of Wood Products

Karjalainen et al. (1994) divided wood products into four categories: short, medium-short, medium-long, and long lifespan categories. For example, sawn timber could have 50% distribution into medium long lifespan products and 50% into long lifespan products, while fuel wood has 100% short lifespan. Moreover, plywood could have 50% distribution into medium-long lifespan products and 50% in long lifespan products.

Paper and paperboard products have a limited lifespan, when they are tracked to diverse end uses and sent to landfills or burned (Skog and Nicholson, 1998). Some paper items are anticipated to have long lives in uses like books in libraries and antiques. When paper and paperboard are placed in end use, such as magazine production, some is discarded. Therefore, paper and paperboard are followed to recycling, disposal in landfills or burned.

According to Skog and Micales (1997), newsprint, which has a lignin content of 20% to 27%, is very resistant to decay. Other papers with less lignin are partly subject to decay. The estimates for maximum proportions of paper that are converted to CO_2 or methane (CH_4) in landfills are 16% for newsprint, 18% for coated paper, 32% for boxboard and 38% for office paper.

According to Ingerson (2009), as little as 1% of the carbon present in the standing tree may remain in solid wood products in use after 100 years. Landfills make a much larger contribution to long-term carbon storage, sequestering as much as 13% of the carbon originally present in the standing tree, which, after timber harvesting, logs represent approximately 60% of the volume of the trees. Furthermore, the proportion of carbon emitted from landfills as CO_2 is limited to about 40%, compared to 60% as methane (Skog and Micales, 1997).

The quantity of carbon remaining within the end product was calculated by Skog and Nicholson (1998), adapting an equation used by Row and Phelps (1996). The lifespan of the different product categories is calculated with an extended logistic decay function as shown in Eq. 2:

$$f(pu) = d - \frac{a}{1 + b^{(-ct)}}$$

(Eq. 2)

Where pu is the fraction of products in use, a, b and d are parameters (dimensionless), c is the reciprocal of the half-life period (year $^{-1}$) and t is time (years) (Row and Phelbs, 1996).

The carbon half-life in each end product is a key parameter. Half-life is defined as the time after which half the carbon stored in these products is no longer in use. For example, the half-life for paper is one year or less, except for the paper in long-lived printed publications which has a half-life of approximately 6 years.

Skog and Nicholson (1998) have calculated a value of 30 years for the duration of half-life carbon sequestration in end uses of furniture. According to Kloehn and Ciccarese, the average life is the average number of years a product is in use and can be calculated according to Eq. 3:

$$\text{average life} = \frac{1}{\frac{ln2}{half\text{-}life}} = \frac{1}{\frac{ln2}{30}} = 43 \text{ years}$$

(Eq. 3)

According to Palma (2017), the average lifetime for a kitchen cabinet is 18 years, the computed half-life is 12.5 years and the decay constant k for wooden kitchen furniture is $0.055yr^{-1}$. According to Lescop et al. (2010), the lifespan for kitchen furniture is 18.75 years for furniture elements made of wood or other materials and 17.5 years for kitchen furniture made of panel. The constant k was estimated (Eq. 4) presuming only one exponential decay as follows:

$$k = \frac{\log \frac{m0}{mt}}{t}$$

(Eq. 4)

where m_0 is the mean initial wood block mass and m_t is the mass recovered at time t in years (Crockatt and Bebber, 2015).

According to the IPCC (2014), the average lifespan for a wood-based panel is 25 years and the recycling percentage is 10%. Furthermore, using a 4-parameter asymmetric sigmoidal model, Coure et al. (2015), predicted that 90% of the original mass of medium density fibreboard is converted to waste within 15 years of production. Therefore, this interval of time has become the accepted lifespan for medium density fibreboard. Kitchen furniture contains both wood-based panel and MDF raw materials.

Timber used for construction is one of the most efficient ways to store carbon in wood products, because the lifetime of these products could be 80 years or more (Winistorfer et al., 2005).

According to Brunet-Navarro et al. (2016), two options were used to evaluate changes to the recycling rate and lifespan of wood products, and the consequent impact upon increasing the carbon storage. One study was a theoretical simulation exercise to examine the effect over time of increasing the average lifespan and raising the recycling rate of wood products on the carbon stock (carbon stock changed in wood products in use can be estimated to identify the carbon pool effect of wood products). The other study was a practical exercise with European data to analyse how average lifespan or recycling rate could be increased to achieve the aim of reducing the greenhouse gas (GHG) emissions at the time (Brunet-Navarro et al., 2016).

Brunet-Navarro et al. (2016) showed in their theoretical simulation that the carbon stock in the wood-based panel grows linearly when increasing the average lifespan. Furthermore, with an increasing recycling rate, the carbon stock in wood products increases exponentially. The explanation for these observations is that increasing the average lifespan just once affects the total amount of carbon; while an escalation in the recycling rate sees a positive impact upon the carbon stock which is repeated every time the wood product is recycled, thus following an exponential pattern. Nevertheless, the time taken to increase carbon stock in wood products by raising the recycling rate is higher than when increasing the average lifespan.

Extending the average lifespan of wood products or increasing the recycling rate both lead to the enhanced characteristics of the wood products involved. Therefore, the carbon stock in wood products needs time to reach a new equilibrium (Brunet-Navarro et al., 2016). In this new steady state, the carbon stock increases are once more equal to the reductions in emissions from the wood product pool.

Moreover, the strategies to increase average lifespan and recycling rate can be combined to achieve a good level of mitigation benefits (Brunet-Navarro et al., 2016). Furthermore, the best approach for the longer term is to lengthen the average lifespan of wood-based panels.

According to Brunet-Navarro et al. (2016), one effective strategy to increase the average lifespan of wood products is increasing the repartition of harvested wood products to long-lived wood products. Therefore, GHG emissions will be reduced in longer terms through extending the lifespan of all wood products. An example could be wastepaper that has undergone a recycling process. Thus, its fibres are damaged, and it is possible that the material is only recycled 4–6 times before the fibre reaches an unusably short length (Schmidt et al., 2007).

According to Canals (2014), the quantity of imported wood required decreases in factories if the amount of recycled wood increases. Therefore, carbon is maintained for longer periods and is not released into the atmosphere if the waste products and residues from wood are reintroduced into the wood processing and these are transformed into long lifetime wood products. For example, if 100 kg of paper is produced, presuming a rate of 70% for recycling, in the first step 70 kg of paper will be recycled, 49 kg in the second, 34.3 kg in the third, then 24.01 kg, then 16.81 kg, and in the sixth step 11.77 kg, which can be no longer recycled. It is very important to be aware about biomass quality when producing a new wood product from waste wood (Haberl and Geissler, 2000). Therefore, compared to particleboards made from original particles, particleboards are of inferior quality when they are produced from steam-recovered wood particle (Lykidis and Grigoriou, 2008).

2.6 Medium Density Fibreboard

Medium density fibreboard (MDF) is the second most manufactured wood-based panel product in the world with a product capacity over 92 million m^3 per year (Anon, 2014). Since 1965, MDF has been manufactured and it is used primarily for furniture and interior fitting (Irle et al., 2012). While the production of MDF began in 1965 in Deposit, US, the first factory in Europe started this production in 1973 (Irle et al., 2012). Therefore, the start of worldwide production of MDF has been considered to be 1973.

Because before 1995 MDF production was grouped with other fibreboard types, Coure et al. (2015) showed the growth in MDF production in this period using a five-parameter asymmetric sigmoidal model. Therefore, they estimated a MDF production of 50 000 m^3 in 1973 using the data 1995-2013 from FAOSTAT (2015). The production capacity of MDF in the world has risen exponentially (Coure et al., 2015).

In the American and Canadian economies, the composites panel industry is an important contributor. As one type of composites panel, MDF is appreciated for its homogeneity allowing precision machining and finishing, but it is also regarded as a sustainable material (AWC, CWC, 2014). The wood residues from other manufacturing processes can be utilised in the manufacture of MDF. The North American MDF manufacturers produced more than 3.3 million m^3 in 2012.

Thailand used imported logs, wood from plantations (e.g. Acacia species and bagasse), and log sides from sawmills as raw material for composite boards (Hengniran, 2010). In that country, manufacturing of fibreboards comes in two forms, namely hardboard and medium density fibreboard. Hardboard is produced only by the wet process and it uses raw materials such as eucalyptus, wood from plantations and bagasse. The manufacture of MDF uses eucalyptus, rubber wood, Acacia species and bagasse. Furthermore, the first factory in the world used bagasse as a raw material for MDF. According to the ITTO (2010), Thailand is the world's second tropical fibreboard exporter and approximately 80% of production is used on the domestic market, especially for furniture production.

MDF is being used as structural panels in building. In North America, MDF and low-density insulating board is approved for structural use by diverse government agencies and building codes (Maloney, 1996). MDF are structural panels, but they are also used as interior building materials. However, their surface can be veneered, laminated, or painted. One of the most important characteristics of MDF is its smooth and solid edge, which makes it easily machined and finished. Therefore, in the manufacture of edge-profiled panels, MDF is used as a furniture panel and thus the lumber core and the crossing band with veneer are eliminated (Suchsland and Woodson, 1986).

The wood-based panels category includes plywood, particleboard, fibreboard, and veneer sheets (Rivela et al., 2007). MDF is part of the fibreboard category. The term "fibre" is applied to any element with dimensions of the same order of magnitude, regardless of its origin. In the terminology of wood anatomy, this term is used for the fibre trachea which is a cell type in hardwood (Suschland and Woodson, 1986).

The term "fibreboard" is part of the big family of wood composition boards from solid wood, in that various sizes of wood elements are glued together by an adhesive bond (Suchsland and Woodson, 1986). The important steps in manufacturing of these products are the generation of elements or particles (a reduction process) and their recombination in sheet form (a lamination process). Panel products belong to the family of wood composites, which are defined as materials that have the commonality of being glued or bonded together (Maloney, 1996). Wood composites panels are manufactured from wood particles or wood fibres mixed with resin and other additives such as wax and dyes (Dettmer, 2013). The mixture is formed into a mat and pressed under pressure of approximately 2-3 x 10^6 N/m^2 and temperatures between 160°C and 200°C (Dettmer, 2013). This mat is pressed to some target thickness and is made up of between 88% and 94% wood and approximately 12% to 6% of resin and additives, according to composite type, resin, and application (Papadopoulus, 2007).

Wood Wool Cement Board was manufactured for the first time in Thailand in 1956 (Hengniran, 2010). The raw material used was Sompong (or Tetrameles nudiflora), which today is imported from Myanmar. Furthermore, in 1989 Wood Cement Particleboard was manufactured from eucalyptus. Since 2000, Wood Cement Fibreboard has been produced from around 90% cement and 10% of recovered paper, mixed with a small amount of asbestos (Hengniran, 2010). Cement bonded board is cold pressed.

The wood-based composites are divided into solid wood products, modified wood products, engineered wood products, chipboard products (particleboard and fibreboard) and wood fibre products (Bodig, 1982; Barbu, 1999). Therefore, the wood-based composites can be made from solid wood, veneer, particles, and fibres (Fig. 2). Fibreboard products are divided into porous fibreboards, hard fibreboards and medium density fibreboards and further classified by their production process, as follows:

- Wet process fibreboards
- Dry process fibreboards
- Semi-dry process fibreboards

Early fibreboard was all made by wet processes, extensions of the paper technology (Suchsland and Woodson, 1986). More recent developments have led to the production of dry process fibreboards, which evolved in some cases from particleboard technology. Therefore, porous fibreboards are produced by the wet process and their density is between 150 kg/m^3 and 400 kg/m^3 hence the term Soft Board or insulation board (Barbu, 1999).

The hard fibreboards made by the wet process can have a relatively high density (higher than 900 kg/m^3), termed Hard Board (HB), or can have a density between 400 and 900 kg/m^3, being then called Semi-Hard Board or building board. Also, the hard fibreboards could be made by a dry process and the products called High Density fibreboards (HDF) or could be made by semi-dry process fibreboards. In the semi-dry process, adhesive is added to the fibres with a moisture content of 30% and the pressing is similarly as in the dry technological process (Barbu, 1999).

MDF are made by dry or wet processes, with a density approximately between 600 kg/m^3 and 850 kg/m^3 (Barbu, 1999). In the wet process, the difference between hardboard and MDF is one of densification. An important element in the dry process manufacture of MDF is the pressurized refiner, which produces a pulp of very low bulk density (Suchsland and Woodson, 1986). Bulk density is the bulking effect of loose material like particles, dry fibres, or chips, namely the density of the uncompressed material.

The definition of MDF in Europe is stipulated in **EN-316** standard and the minimum requirements for MDF are founded in **EN 622-5**. The important grades of MDF are: General-purpose boards for use in humid conditions (H); General-purpose boards for use in dry conditions (MDF); Load-bearing boards for use in humid conditions (HLS); and, Load-bearing boards for use in dry conditions (LA) (Irle and Barbu, 2010).

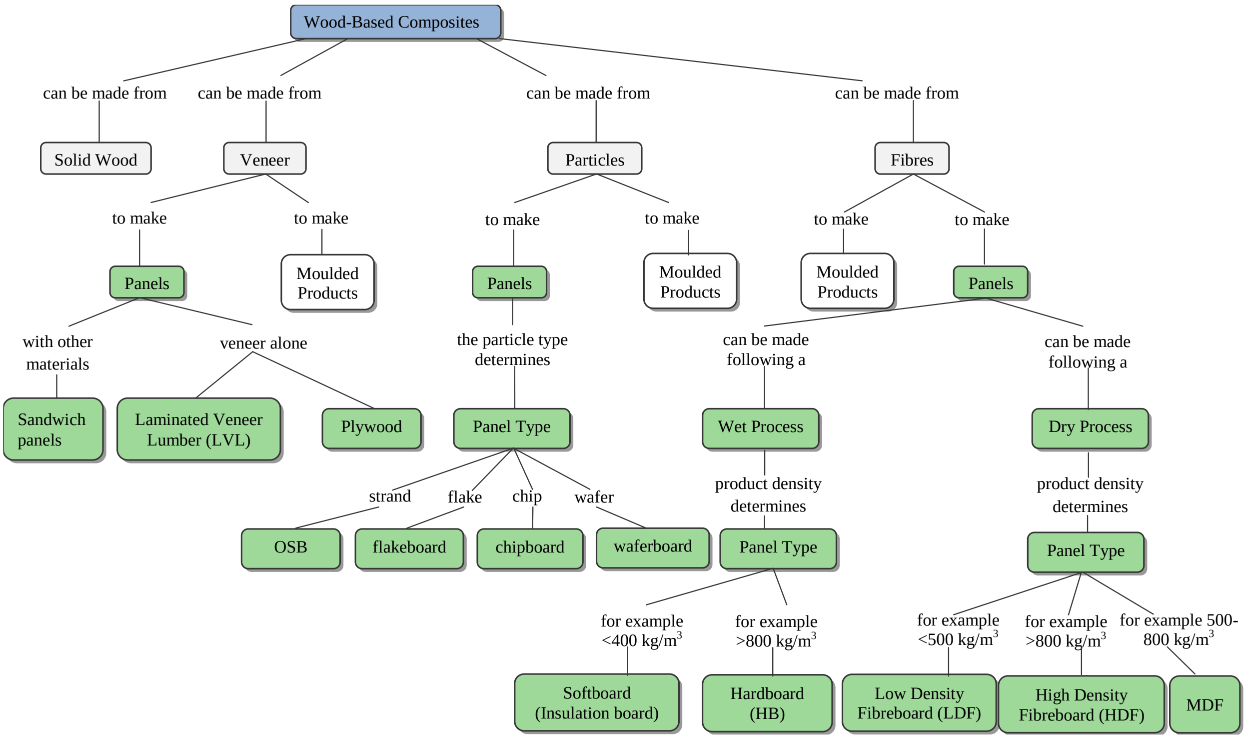


Figure 2. A classification of wood-based composites (Irle and Barbu, 2010)

2.6.1 Manufacture of Fibreboards

According to Irle and Barbu (2010), the thermo-mechanical pulping process (TMP) is used to make MDF fibres. The middle lamella, which is rich in an amorphous polymer called lignin, is a region where the wood cells are joined (Irle and Barbu, 2010). Furthermore, lignin can absorb small quantities of water and therefore, the moisture content is dependent on its softening temperatures. The strength of the middle lamella region may be reduced when in the TMP with high temperatures of approximately 170-195°C and around 60-120 % humidity (Irle and Barbu, 2010).

The most important reactions in the fibreboard process take place during the pulping stage and in the hot press. Bonding between solids depend on attractive forces of surface molecules and therefore, bonding is possible without the use of an adhesive (Suchsland and Woodson, 1986). In the manufacture of insulation board such bonding is very important. Furthermore, an adhesive in liquid form is required in most bonding, which interacts with both surfaces. This type of adhesive joint is used in the manufacture of dry formed fibreboard. Resin adhesives such as urea-formaldehyde resins are used in the manufacture of MDF. The chemical reaction takes place in the hot press, where urea-formaldehyde has significant water resistance (Suchsland and Woodson, 1986). The weather resistance of composition boards is not guaranteed by quality of glue line.

Moreover, bonding can be determined between fibres even without the use of resin adhesive. These bonds occur in the hot press between various wood components, based on chemical and physical interactions (Suchsland and Woodson, 1986).

The tensile strength of individual fibres is usually very high but in the structural configuration of fibreboard it is used just a fraction. Furthermore, if the length of overlap between two fibres is shortened, the quality of the bond is reduced (Suchsland and Woodson, 1986). Therefore, in low and MDF failures occur in the bond, while in high board density these occur in the fibres (Jones, 1960). This reflects both a more intimate contact between the fibres and the possible modification of the characteristics of high-density fibre in severe conditions in the press.

Suchsland and Woodson (1986) showed that MDF and hardboard seem to be less sensitive to species characteristics than are wet-formed boards. In general, hardwoods improve the wet process, shorter fibres resist water drainage, while softwoods require more energy in the pulping process and their content of volatiles tends to be higher than in hardwoods. Therefore, in the wet process it requires longer press cycles (Eustis, 1980). For maintaining consistent product performance levels, it is important to have good uniformity of raw material or to maintain uniformity of mixture composition.

Raw material-preparation

Through some combination of refiners, or defibrator and refiner, the pulping operation requires wood raw material in a homogeneous form and a continuous and uniform rate (Suchsland and Woodson, 1986). The manufacture of pulp chips includes slashing, debarking, chipping, and screening (chip thickness is approximately 2-7 mm). A considerable portion of the raw material entering the process is water (given the processing of green pulp wood) and it is therefore necessary to monitor the wood moisture content. The approximate chip moisture content is less than 35% in the shives in the pulp (Eustis, 1980). The pulping process, based upon automatic process control, needs continuous and accurate moisture content determination. One method for the continuous measurement of moisture content of chips is based on conductivity and the resonance of the polar water molecule in an electric field of low or high frequencies, using an electrode, wall console and a control unit (Lundstrom, 1970).

In the pulping process, pulp chips are converted to fibres by a mechanical process. To soften the lignin or other wood component, no chemicals are added. Pulping consumes more than half the total energy expended in the fibreboard manufacturing process (Suchsland and Woodson, 1986). Furthermore, three methods are used in fibreboard manufacture: the masonite[1] explosion process, the atmospheric refining process, and the pressurised disk refining process.

[1] **Masonite** is a kind of engineered wood, a type of hardboard, which is made of steam-cooked and pressure-moulded wood fibres in a process patented by William H. Mason (Mason Fibre Company) in 1924. Masonite was first made in England in 1898 by hot-pressing wastepaper. In 1928 the Mason Fibre Company was called the Masonite Corporation.

The raw material for medium density fibreboard can be the wood which is chipped using a drum chipper, the sawdust or residues from sawmills using chipper canter technology (Irle and Barbu, 2010). Moreover, the sizes used are square particles of around 5 mm thick and sides of approximately 25 mm.

The storage of chips can be made on platforms or in silos. The handling of chips is more efficient through their storage, but during long storage the deterioration of wood chips is accelerated because the respiration of living parenchyma cells raises the temperature and later bacterial action and chemical oxidation occurs (Suchsland and Woodson, 1986).

While the chips stored on a platform could experience contamination with soil, biodegradation or freezing, in the round steel silos with or without insulation, no wind blowing the stock, and this is protected from water and snow. The silos have diameters of approximately 25 m to 42 m and volumes between around 5,000 m^3 to 30,000 m^3 (Irle and Barbu, 2010).

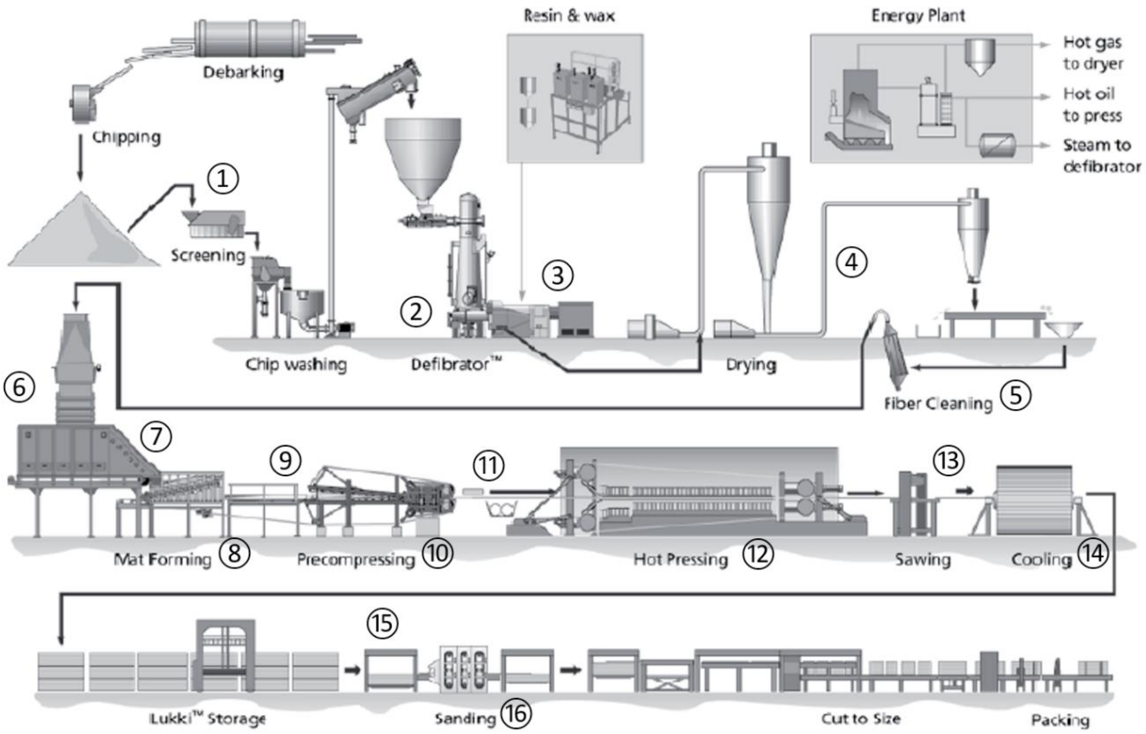


Figure 3. The processing line of medium density fibreboard (Irle and Barbu, 2010)

The different production stages of MDF are shown in the Fig. 3. After bark, soil, sand, and other hard contaminants are removed, the chips are sent for washing. The frost chips stored outdoors and the chips from species with high resin content can be washed with heated water (Irle and Barbu, 2010). Furthermore, the water eliminated from the chips plug screw is in the same circuit with the water used for chips washing. The washed chips can be heated at approximately 40-60°C, at atmospheric pressure thus forming a plug of particles in the conical screw feeder (Irle and Barbu, 2010). Accordingly, a high pressure is maintained in the tube and this is known as the preheated or digester stage. The free water in the chips is eliminated out through the plug screw and this water must be treated as a part of the steam condensates.

The colour and quality of fibres are influenced by the retention time of the chips in the preheated stage, which is determined by the screw feeder speed (Irle and Barbu, 2010). A radio-active measuring device directs and controls the digester level. Furthermore, depending on the wood species, chip size, digester size (around 5 m^3-18 m^3) and required fibre quality, the chips are heated with saturated steam at approximately 0.6 to 1 N/mm^2 and for 3 to 7 minutes, where the internal temperature reaches approximately 175-195°C (Irle and Barbu, 2010).

The steamed chips are transformed into fibre bundles through the refiner. The refiner generally has two discs, one stationary and another that rotates at approximately 1500 rpm, according to the diameter of the discs (Irle and Barbu, 2010). Furthermore, in the middle of the stationary disc there is a hole where the wood chips are inserted. The quality of the final fibre is influenced by the surface of the discs. These surfaces are equipped with exchangeable refining segments which have different dams and grooves and therefore by centrifugal forces, the wood chips are driven across the radius of the disc, where they are gradually broken down into fibre bundles. Moreover, with saturated stems the refiner is pressurized to approximately 0.8-1 N/mm^2 (Irle and Barbu, 2010). The most efficient and economical approach for the MDF industry is the one-disc refiner, rather than the two-disc design where the counters are rotating against each other.

The wet process

In the wet fibreboard process, an important element is the removal of the water from the pulp, quickly or slowly, respectively resulting in free or fast pulp and less free or slow pulp (Suchsland and Woodson, 1986). The pulp's freeness is a physical characteristic of the fibre and influences productivity and product properties.

Additives

Chemical additives are added to fibreboard furnishes for acidity control, improvement of water resistance, establishment of fibre bond, protection from decay, fire protection and coloration (Suchsland and Woodson, 1986).

Waxes are hydrocarbons derived from crude oil and are insoluble in water. Wax sizes are used in fibreboard only to improve resistance in water. Therefore, waxes slow down the rate of water absorption. The homogenized sizes are mixed to the stock at the temperature below the melting point of the wax. Also, the wax is used in the melted form in the dry fibreboard process as an emulsion directly applied to the chips or fibres, or it is added together with the liquid resin solutions.

Binders

In fibreboard manufacture, the lignin is the most important binder, but for dry-formed hardboard and dry-formed MDF adhesives must be added. Phenol-formaldehyde resins are thermosetting adhesives used in wet and dry-formed hardboard, with respective bonding levels of approximately 1%-2% and around 5%-6% (Suchsland and Woodson, 1986). Urea-formaldehyde resins, thermosetting adhesives, are used for MDF (dry process) with a bonding level of approximately 8% -11%.

Initially, the process of dry-formed MDF was based on a combination melamine-urea-formaldehyde resin of low molecular weight, low viscosity, and low tackiness. Later, urea-resins with low tack were used. In short retention blender, these resin binders are applied, the retention time being between 1 and 3 seconds. Based on dry fibre weight, the solid resin contents range from 8% to 10% (Suchsland and Woodson, 1986).

Urea-formaldehyde resins used in these processes have some advantages such as water solubility, fast curing, good performance in the panel and lower price, despite two disadvantages such as formaldehyde emission from the panel and limited resistance to water (Park et al., 2011). Moreover, the chemical properties for this adhesive, for example used in the MDF production line in Anhui province, are: viscosity/s = 16.5, curing rate = 75, pH = 8, water soluble multiples = 0.66 and solid content = 50.3% (Wang et al., 2013).

The best balance is offered by the combination of high resin content and high density (Halligan and Schniewind, 1974). This rule did not apply for internal bond at high moisture content, greater that 15%. Therefore, high resin content and low density determine the highest internal bond.

Dry process

A dry fibreboard process is any board process where air is used for transporting the fibres and for forming the mat. A pulp of very low bulk density of approximately 32 kg/m^3 or less, which is produced by pressurized refiners and, used in combination with a typical pulping machine, is utilised in the manufacture of MDF (Suchsland and Woodson, 1986). This is the first unique element of the MDF process. The exiting fibres are controlled by a blow valve which may be switched to production (blow line) if the process parameters are constant and the fibres have an acceptable quality and resin (Irle and Barbu, 2010).

The blow line is a pipe of approximately 80 to 120 mm diameter which drives the hot and wet fibres, and steam to the dryer. Usually, a formaldehyde-based resin adhesive is injected at high pressure (approximately 12-14 N/mm^2) into the blow line with other additives (Irle and Barbu, 2010). Furthermore, depending on the type of panel the quantity of adhesive will vary between around 8% and 15% (resin solid / oven dry wood basis).

The fibre blending with the resin has two stages. In the first stage the resin is applied in the blow line and in the second stage the resin is applied in a separate blender, after drying the fibres. This drum blender has a ring in the front of the open in-feed. On this ring are mounted air-nozzles whereby resin is applied, and a fibre blow is generated by the internal paddles for a real blending. Gentle drying to the target moisture content is recommended for saving resin of approximately 35% (Irle and Barbu, 2010).

With a speed of approximately 30 m/s the wet resonated fibres are blown through a flash tube dryer, which is over 100 m in length and approximately 1 m to 3 m in diameter (Irle and Barbu, 2010). Therefore, the dried fibres are separated from the steam through cyclones of approximately 3 m to 5 m diameter, and the moisture content is approximately 8%-12% after the fibres are dried. According to Irle and Barbu (2010), there could be a one stage dryer with longer and less temperature control or there could be two stage dryers which require more energy for operation.

A system of classifiers and filters manage the dry fibres to the mat formers with a pneumatic transport. The mat formers are designed to distribute a uniform layer of fibres. The fibres are carried up onto a moving belt, which has a speed that is dictated by the required thickness of the panel (Irle and Barbu, 2010). Moreover, the dosing bin and the spreader system that are necessary for the fibre mat forming should assure a constant fibre flow.

An example of a mat for an 18 mm thick MDF has a bulk density of approximately 23 kg/m^3 and this is around 680 mm high. The mat, for a 38 mm thick MDF has a height of approximately 1 m that reduces to around 350 mm after pre-pressing (Irle and Barbu, 2010). Often those mattresses bigger than around 200 mm are preheated. Moreover, the mat is compressed in pre-pressing to increase its density by reducing the air content, and for reducing the time in the hot pressing.

To accommodate the thickness of the mat, presses with enough ‘daylight’ (clearance between adjacent platens) are used. These press openings are sized to fit the mats after pre-compression.

The binder composition is the second unique element of the MDF process. The bulky fibres can be prevented from becoming tangled together using a situ resin system, where a pre-condensation of these occurs. Furthermore, the pre-condensation is finished at a very low molecular weight and then follows a complete condensation in the hot-press (Suchsland and Woodson, 1986).

The third unique element of MDF is the conservation of the resin in the press with radio frequency energy, which produces a uniform temperature. During the compression period, the relationship between time and temperature must be the same in all parts of the mat. In the finished board, there should not be any variation in density over the cross section, so the compressibility would be uniform (Suchsland and Woodson, 1986).

In short retention mixers, the resin is applied to the dry fibres and retention times are just a few seconds. The main equipment has base vacuum.

Another forming machine is one in which the fibres are pneumatically delivered and without being condensed they are separated from air. The air flow is such that the fibres are stored and packaged in the form of a flat plank between the upper and lower condensers. Therefore, in the simultaneous cross-section of the mats, fine furnish fractions are concentrated on both surfaces (Suchsland and Woodson, 1986).

By pressing with a continuous band, the mats of thickness between 230 and 610 mm are pre-compressed to a thickness of approximately 75-150 mm. To assure density of the finished board, mats are trimmed and weighed and then they are transferred to the press.

Besides, a large part of the existing plants uses regular steam-heated presses instead of radio frequency.

The moisture content necessary in the press is usually between around 9% and 13% so, the fibres with the resin attached are dried and then formed into a mat with uniform mass per unit area (Chapman, 2004).

Pressing

The mat is converted to MDF in the hot-press where the pressure is approximately 0.5-5 N/mm^2 and the temperature is around of 180-210°C (Irle and Barbu, 2010).

The time between initial pressure and the moment when the mat is compressed to the final thickness is called the press closing time. Furthermore, Suchsland and Woodson (1986) showed that at high pressure, density is highest at a relatively short closing time and there is higher compression on the faces. For a longer closing time the mat is heated entirely, and the densification is more uniform. The pressure values for the good closing times (around 0.5 to 1.5 min) are between approximately 3 and 5 N/mm^2 and the total press time could be 8 to 10 minutes for 19 mm board.

Many plants used high frequency heating for the press and others used steam or hot water. In the first model, electrodes are placed between the press platens and the mat. In addition, the platens of the press are heated by hot water or steam at a temperature over 100°C. This temperature is necessary to avoid condensation on the surface of the panel. The press cycle is shorter if it uses high frequency heating (Suchsland and Woodson, 1986).

Usually, the cycle of the press consists of three steps: press closure, transient relaxation, and asymptotic relaxation (Wolcott, 1989). During the press closing time the pressure is low and large voids in the mat are eliminated. When the pressure on the mat decreases rapidly and sharply, the transient relaxation region starts. In some regions of the mat, the individual wood elements continue to densify while others recover accumulated elastic deflection. The asymptotic relaxation region starts when the change of pressure with time decreases steadily at an approximately constant value. The amount of stress relaxation is much bigger in the face than in the core of the panel. Therefore, when the press is opening, the core will experience more recovery of elastic deflection the face, thus, influencing the density gradient in the final product.

After pressing the panels are exposed to ambient air for quick cooling. The panel is finished by trimming, sanding, and cutting to size. Moreover, the panel may be laminated, profiled, or painted (Irle and Barbu, 2010).

Volatile organic compounds (VOCs)

In the manufacturing process of MDF, fibre hot-pressing is a source of VOCs emissions. To optimise this process, it is important to understand about the components and amounts of substances emitted from the hot-pressing.

The quantities of total VOCs, aldehyde and ketones were investigated in an MDF production line in Anhui Province, part of the East China region, with a production capacity of 80 000 m^3/year (Wang et al., 2013). The raw materials were pine, poplar, and other various woods with a mass ratio of 6:3:1 and the gases were collected from the output of the fibre hot-pressing. The quantity of total VOCs, released from fibre hot-pressing, were calculated.

Wang et al. (2013) showed that the total concentration of VOCs touched approximately 1.8940 mg/m^3. The concentration of the mixture of aldehyde and ketones, including saturated hydrocarbons, was around 5.1136 mg/m^3.

Competition between the producers has increased with the new requirements for low formaldehyde emission panel products resulting in increased pressure to the actual world financial crises and therefore, the impacts on the wood processing industry it is difficult to provide (Barbu et al., 2013).

Examples of MDF manufacturers

An ultra-modern MDF production line was launched in 2016, as part of the second construction stage of the Egger plant in Gagarin/Russia. They use one of the world market leaders of presses in the wood-based panel areas, namely Contiroll presses. Furthermore, because the production of MDF requires precise operating machines, they use Siempelkampf machines (a precision brand recognised in the engineering industry) for the packing of the finished boards. The capacity for the production line is around of 600,000 m^3 per year, and they produce MDF boards with a range of thicknesses from 6 to 38 mm. The standard board size is 2800 x 2070 mm and special sizes are available depending on the requirements.

MDF and HDF boards must be stored horizontally, in stacks no higher than 5.5 m, horizontally in stacks and the temperature must be at least 5°C. Moreover, the relative air humidity must not exceed 65%, the MDF and HDF boards should be protected from heat, direct sunlight, and UV rays and their storage at the warehouse must not be more than 1 year. Time of storage can be short if there is some risk to the product losing its quality (for example, through warping). The storage of bords with thickness less than 8 mm, is typically not longer than 6 months. At a humidity of 65%, the storage of MDF boards has a lower effect on the mechanical and physical properties and on the dimensional stability of the panel (Khalil et al., 2008). Furthermore, the formaldehyde emissions to air resulting from the stored fibreboards fall within permissible limits, usually less than 0.03 parts per million in both outdoor and indoor environments (Kharkeshi et al., 2014). Therefore, good ventilation and air conditioning should also be used at the warehouse.

The main process stations of the MDF production line at the Gagarin site consists of the following steps, as shown in Figure 3:

Debarking of the logs → Chipping the wood to produce chips → ① Screening → Chips washing → ② Defibration in the refiner → ③ Adhesives (wax is added together with the liquid resin solutions) → Drying the fibres to approximately 2-3% residual moisture → ④ Shaker (suction of fibres in blow line, moisture content is 12%) → ⑤ Fibre cleaning → Application of resin to the fibres → ⑥ Spreading of the glued fibres onto a moulding conveyor → ⑦ conveyor belt → ⑧ Mat forming → ⑨ Dieffensor → ⑩ Precompression → ⑪ Trimming and weight → ⑫ Compression of the fibre mat in a continuously operating hot press → ⑬ Cutting laboratory → Sawing and trimming the fibre strand into raw board formats → ⑭ Cooling the raw boards in star coolers → Lukki raw board storage → ⑮ Piling into large stacks → ⑯ Sanding of the top and bottom surface after the acclimatisation phase → Cut to size → Packing.

According to Anastasiya Cherkasova, a Quality and Development Analyst at the Gagarin site, the species of wood used in the production line are Aspen and Birch. In terms of the pressing process, there are 5 temperatures and 4 pressure zones inside the press, although this can vary for different press models. The zones correspond to each other in the following way (temperature zone-pressure zone): 1-1; 2, 3-2; 3, 4-3; 5-4. The corresponding temperatures and pressures for a 19 mm board are given in Table 15 and Table 16.

Table 15 The correlation between temperature zones from inside the press and temperature, in the pressing process for a board of 19 mm, Gagarin site (Cherkasova, A.)

Temperature zone number	1	2	3	4	5
Temperature, °C	242	240	232	198	181

Table 16 The correlation between pressure zones from inside the press and pressure, in the pressing process for a board of 19 mm, Gagarin site (Cherkasova, A.)

Pressure zone number	1	2	3	4
Pressure, N/mm^2	30	22	24	19

Furthermore, the 1st and 2nd pressure zones are needed to make the surface layers; the 3rd is to "cook" the middle layer and the 4th is to bring the board to the correct thickness. Moreover, the speed of the press is 230 mm/s (Cherkasova, A.).

2.6.2 The Lifespan of Medium Density Fibreboard

According to Mitchell and Stevens (2009), and their examination of the MDF manufacturing industry in the UK, 72% of the waste is used for energy production and the remaining 28% is now disposed in landfill. More recently, in line with this study it is assumed that approximately 25% of the MDF products becomes waste during the first year (Coure et al., 2015). The rate of this conversion is likely to be more rapid in the first few years with a gradual slowing over time.

The lifespan of MDF was explained previously in Chapter 2.5, from which the lifespan time was accepted to be 15 years (Coure et al., 2015).

2.6.3 Physical Processes

Many processes are involved in the hot pressing of MDF, namely: physical, chemical, and mechanical. During these processes, the following respective actions occur, heat and mass transfer, resin cure and viscoelastic deformation (Bastias, 2006).

A physical model of heat and mass transfer during MDF hot-pressing was presented by Bastias (2006). These simultaneous transfers take place between the hot-platen and the mat. To optimise this process, it is important to understand the heat and mass transfer involved (Bastias, 2006). Furthermore, the principal factors for the pressing of medium density fibreboards are the temperature of pressing, the moisture content, the speed of the closing press and the duration of the pressing (Bastias, 2006). They are important because they determine the final density profile.

Therefore, the moisture content of the surface decreases more rapidly than the moisture content in the centre because the vapours run to the interior of the mat (Bastias, 2006). Gases are transported in the thickness direction during the pressing and when the temperature increases significant steam generation is induced. Moreover, the pressure increases at the centre of the mat. The gas pressure was considered as the sum of air and vapour pressure (Bastias, 2006). These gases develop a pressure gradient from the centre to the edges of the panel. Furthermore, the moisture content is permitted to diffuse only through the lateral edges in the industrial hot-pressing. Therefore, on the edges the boundary layer gets stronger (Bastias, 2006).

An increase in board density resulted in a decrease in thickness swelling. The lower moisture content is absorbed by the higher density board and this represents a primary reason for this observed behaviour. An additional explanation is an increase in the interparticle bonding at the higher moisture content during pressing. Therefore, the high-density mat limits the escape of moisture and in the final panel, allows increasing the compressive set (Kelly, 1977).

The total density of the system is the sum of densities of dry wood, bound water in the cell wall, air from the void spaces between the fibres, water vapours from the cell lumen and void spaces, and resins (Bastias, 2006). Before hot-pressing, the initial moisture content of fibres is assumed to be under fibre saturation point, therefore, free water is not considered.

The density of bound water in the cell wall is represented as being density of dry wood multiplied by the moisture content (Bastias, 2006). In addition to this, it is more difficult to extract the bound water from wood cells when denser wood was used (Garcia, 2002). Therefore, panels of higher density lead to higher values of moisture content.

According to Belley (2009), density had an important effect on the gas permeability of medium density panels. Moreover, the thermal conductivity of MDF increases with density, moisture content and temperature.

Arriving at the centre of the mat, the vapours condense and the temperature in the mat is lower. The heat of the vapours is converted into energy and the temperature and moisture content rise fast in the centre of the panel. The temperature of covering layers increases and approaches the temperature of the platen in the press. The gas pressure increases towards the centre of the mat while the vapours continue to reach the surface. The heat transferred by conduction is accelerated due to the action of the press on the mat. This heat input causes the temperature of the centre to rise and evaporates the water particles, thus creating an increase in pressure. This will escape through the edges of the mat and a mass transfer engages to leave the energy of the press platens. According to Belley (2009), conduction and convection are important phenomena during the pressing.

On the other hand, the temperatures and internal vapour pressures were measured in flakeboard mats during steam injection pressing. Steam injection pressing provides the ability to take control of a wide range of environmental variables that influence the bonding of adhesive in wood-based composites (Johnson et al., 1993).

Therefore, flakeboard mats were bonded with liquid phenol-formaldehyde red adhesive or polymeric-isocyanate resin, with respective contributions by weight being approximately 5% and 4%. The steam was injected into the mats during pressing for periods from 4 to 21 seconds. Furthermore, the maximum gas pressure measured in isocyanate-mats was about two times higher than those recorded in phenolic mats for all steam programs. This was caused by the generation of CO_2 during the polymerisation of isocyanate in the presence of water (Geimer et al., 1992). The difference in the measured gas pressure between the two adhesives can easily be accounted by the CO_2 (Johnson et al., 1993). Moreover, the dimensional panel stability was improved by partial hydrolysis of some hemicellulose components.

The reduction of total press time in the steam injection pressing procedure did not affect internal bond or other mechanical properties for the mats containing isocyanate resin bonding. While in the mats with phenol resin incorporated, the time of approximately 400 seconds is needed for bonding, for isocyanate bonding boards the total press time could be reduced to around 200 seconds (Geimer et al., 1992). Therefore, compared to conventional board, the heat and moisture transfer into a steam injection pressed board is very fast. Moreover, acceptable phenol-bonded boards were obtained at lower temperatures (150°C) extending press times with 30%, while isocyanate-bonded boards responded well to environmental conditions of steam injection pressing (Geimer et al., 1992).

The two adhesives in steam injection pressing had different chemical reaction in the presence of water. The phenol condensation polymerisation reaction generated water, whereas isocyanate adhesive reacts with water forming polyurea that is useful in isocyanate adhesive bonding (Johnson et al., 1993). Moreover, in steam injection pressing board the maximum temperatures achieved were between 104°C and 150°C, while in the conventional boards the maximum was of approximately 132°C (Geimer et al., 1992).

2.6.4 Physical and Mechanical Properties of Medium Density Fibreboard

The Egger MDF are medium density fibreboards made by dry pressing of fine wood fibres at high pressure and temperature. MDF has physical, technological, and mechanical properties comparable with those of solid wood. According to Egger, MDF has a fine surface, solid edge with good profiling possibilities, even fibre structure, good elastic mechanical properties, high load-bearing strength, but low swelling behaviour.

Egger MDF-MB E1, for board thickness between 12 mm-19 mm, has the following mechanical properties:

- Internal bond strength EN 319 $\geq$ 0. 85 N/ mm^2
- Bending strength EN 310 $\geq$ 35 N/ mm^2

- Modulus of elasticity EN 310 ≥ 3200 N/ mm^2
- Swelling in thickness 24h EN 317 ≤ 12%
- Surface soundness EN 311 ≥ 1.2 N/ mm^2
- Screw withdrawal surface ≥ 1250 N
- Screw withdrawal edge ≥ 1080 N
- Sand content ≤ 0. 02%
- Moisture content EN 322 6 ± 2%
- Surface absorption 180 mm
- Formaldehyde content EN 120 E1 mg / 100g

Egger MDF-ST E1, for board thickness between 12-19 mm, has the following mechanical properties:

- Internal bond strength EN 319 > 0.55 N/ mm^2
- Bending strength EN 310 > 20 N/ mm^2
- Modulus of elasticity EN 310 > 2200 N/ mm^2
- Swelling in thickness 24h EN 317 < 12%
- Surface soundness EN 311 > 1.0 N/ mm^2
- Screw withdrawal surface >1080 N
- Screw withdrawal edge > 900 N
- Sand content < 0.02%
- Moisture content EN 322 6 ± 2%
- Surface absorption >210 mm
- Formaldehyde content EN 120 E1 mg / 100g

MDF often has very good physical and mechanical properties with ideal surface properties (Li, 2004). These properties can be summarised as:

- Density (kg/m^3)
- The moisture content (%) is an important factor in determining the mechanical properties of fibres used in the MDF manufacture
- The fibre saturation point
- Resin content (%)

The durability and strength of wood-based composites are functions of the mechanical and physical properties of the component fibres (Li, 2004).

Anatomical analysis of the fibre includes the examination of the fibre's length, width, length/width ratio and specific gravity (size of fibre in mm = fibre length, fibre characteristics and anatomical structures).

The ambient ageing of fibre has an effect on the properties of the MDF panels. According to Bai and Gao (2011), the MDF made with ambient-age fibre has poorer mechanical properties than the MDF made with fresh fibre. The wood fibres were kept for 6 months at a humidity around 20-70% and ambient temperature of approximately 15-35°C, without sunshine. The final moisture content for the fibres was around 9.4-9.8%. Moreover, the concentration of carbonyl groups in the fibres increased by approximately 144% and the pH value of wood fibres decreased from 5.2 to 4.7. Therefore, the surface energy decreased because the poorer wettability of fibres with urea formaldehyde resin after fibre ageing (Bai and Gao, 2011).

Specific gravity (SG) is a measure of the density of a substance and it is a comparison of its density to that of water, which is < 1. The ratio between the apparent specific gravity (for the saturated state) and the real specific gravity represents the compaction, as follows:

$$\text{Compaction ratio} = \frac{density\ panel}{density\ material} > 1 \qquad \text{(Eq. 5)}$$

The specific gravity of a wood species has a negative effect on the strength properties of dry-formed MDF. The specific gravity of wood does have a positive effect on the mechanical properties of hardboards. Morphology of fibres has an important role in wet mat formation. Therefore, longer fibres allow the fast drain of water and stimulate strength development in wet and dry mats (Suchsland and Woodson, 1986).

For porous materials, the compactness (C) and porosity (P) are calculated depending on the apparent volume (Va) with the saturated fibre, and real volume (Vr), as follows:

$$C = \frac{V\ real}{V\ apparent} = \frac{\frac{mass}{real\ density}}{\frac{mass}{bulk\ density}} = \frac{bulk\ density}{real\ density}$$

(Eq. 6)

$$P = \frac{V\ pores}{V\ apparent} = \frac{V\ apparent - V\ real}{V\ apparent} = 1 - \frac{V\ real}{V\ apparent} = 1 - C$$

(Eq. 7)

$$P + C = 1$$

(Eq.8)

Wettability is the ability to form a coherent film on a surface, due the predominance of the molecular attraction between the liquid and the surface and related to the cohesive force of the liquid itself (Padday, 1992). Furthermore, in the theory of adhesion, bond formation involves wetting, adsorption, and inter-diffusion of the resin regarding the adhered substrate (Kaeble, 1967). Adhesive wettability of wood is usually estimated by contact angle measurement (Shi and Gardner, 2001). Contact angle measurements (^{o}) are often the basis for estimating the wetting properties of a material (Li, 2004). Different methods are used to obtain measurement of the contact angle of urea-formaldehyde resins on the surface of various wood fibre layers.

Other mechanical properties for MDF are the following:

- Modulus of rupture (MOR) (MPa)
- Modulus of elasticity (MOE) (GPa)
- Compressive properties: Compressive stress (f_c) and Young's modulus (E_c) strength parallel and perpendicular to the longitudinal direction (MPa)
- Internal bound strength, with different resin content (MPa)
- Water absorption (%)
- Thickness swelling (%)
- Vascular bundle concentration

2.6.5 Density and Vertical Density Profile of Medium Density Fibreboard

The density

The real wood density is considered to be 1500 kg/m^3 for softwood and 1550 kg/m^3 for hardwood. This is a report between the mass of the anhydrous wood and the maximum volume with the saturated fibre (Furdui and Fekete, 2009).

The bulk density (the apparent density) is approximately 450 kg/m^3 for softwood and around 750 kg/m^3 for hardwood, for the saturated state. Therefore, the apparent volume (Va) is bigger than real volume (Vr) and the bulk density (ρa) is smaller than real density (ρr) (Furdui and Fekete, 2009), as follows:

$$\rho r = \frac{m}{Vr} \qquad \rho a = \frac{m}{Va}$$

(Eq. 9)

In Eq. 9 m is the mass of the anhydrous wood.

$$Va > Vr \qquad \rho a < \rho r$$

The wood fibre is a porous material which contains abundant polar groups compatible with those in urea-formaldehyde resin such as hydroxyl group, carbonyl group, amino groups, and ether linkages (Bai and Gao, 2011).

According to Krump et al. (2005), the adsorption theory is intermolecular contact between two materials and implies surface forces (van der Waals forces) that develop between the atoms in both surfaces. Therefore, the adhesion properties in MDF will change if the type and number of polar groups on the fibre surfaces change.

The vertical density profile of MDF

The density profile through the panel thickness is a key attribute for MDF. The vertical density profile is the distribution of density within the thickness of the panel (Chapman, 2004). Moreover, the vertical density profile is also determined by hot-pressing parameters (Bastias, 2006).

Wang et al. (2004) showed that the vertical density profile is formed from a combination of actions that take place both during compaction, and after the press has reached the end position. Therefore, the density profile describes the panel density change in the thickness of the panel and typically has a very high surface density and a lower density in the core (Wang et al., 2004). According to Sebera et al. (2014), increasing complexity of the vertical density profile occurs with board thickness. Furthermore, the manufacturing process comprises more layering systems in the case of thicker MDF. The thicker boards of MDF present less total density (Sebera et al., 2014).

The face density of MDF has a strong correlation with the modulus of elasticity in bending (Suchsland and Woodson, 1986). Furthermore, by pressing dry-formed MDF with less binder, the face density is controlled by overall density (Suchsland et al., 1986). The face density increases by increasing overall density and the overall modulus of elasticity increases as well. In addition, the density of the surface of the panel is important for its finishing (Chapman, 2004).

In the MDF process, specifically during the press, the changes in mat thickness are important for density profile development (Thoemen and Ruf, 2008). Furthermore, after first densification the mat thickness level influences the density difference between core region and surface. Therefore, a common problem in MDF production is the minimum and maximum density between the surface and the central plane of the mat. Moreover, the density distribution on the perpendicular plane of the panel has an important impact on the MDF properties (Thoeman and Ruf, 2008).

In the panel manufacture, it is a requirement that the cross-sectional density profile is adapted to the specifications of the product by suitable process technology and careful program control. Therefore, the choice for the course of mat densification throughout the hot pressing-process is important for the development of the cross-sectional density profile (Thoemen and Ruf, 2008). Moreover, Thoeman and Ruf (2008) showed that, for pressing schedules with an accentuated second densification step, intermediate density maxima appear. These were determined by the time span between press closure and final densification. Furthermore, around 20 seconds are necessary to move the composite mat in a continuous press from the point of first steel belt-mat contact to the point of maximum pressure.

Moreover, in their study the local temperature and moisture content during pressing have determined density variations, as shown by computer simulation. Simulation models based on fundamental principles can supply information for a fundamental understanding about the cross-sectional density profile (Thoeman and Ruf, 2008).

The pressing program was connected to the local rheological mat conditions which are functions of mat temperature, moisture content and state of adhesive cure. Usually, the core layer density is reduced, compared with the core layer density near the edge. Therefore, the differences in the density profiles over the mat width are caused by unequal horizontal distribution of temperature and moisture content (the intrinsic gas pressure decreases from the middle toward the edge of the panel). Therefore, differences in the internal mat conditions could be compensated by adjustments at the pressing load acting on the mat (Thoeman and Ruf, 2008). Moreover, according to Thoeman and Ruf (2008), the modelling approach allows inclusion of information about the internal and rheological mat conditions and its results in variations of density.

The peak density of the panel is not located at the surface because the effect of rapid moisture loss is balanced by the thermal softening effect in the surface layer (Li, 2013). Therefore, the density peak is near the surface and could be representative of the surface density if the differences in this area are ignored.

Wu and Xiong (2001), proposed the following equation to determine the vertical density profile (D_x):

$$D_x = 1.0258 - 1.3917X + 1.3205X^2 \quad \text{(Eq. 10)}$$

X = the nominal depth, the ratio of the position depth and the total thickness

Whereas Wu and Xiong (2001) have taken one type of MDF, Gupta et al. (2006) showed that an equation using the mean density, could be generally applied to determine the peak density (D_P) as follows:

$$D_P = 0.5295 D_M + 513.65 \quad \text{(Eq. 11)}$$

D_P = the peak densities; D_M = the mean densities

Gupta et al. (2006) used the mean value to determine the peak densities but because the difference between the bulk and mean densities is approximately less than 5% it is reasonable to consider these to be the same.

$$D_x = \frac{(0.9691 D_M + 280.45)}{1000} - 1.3917X + 1.3205X^2 \quad \text{(Eq. 12)}$$

$$1000 D_x = 0.9691 D_M - 1391.7X + 1320.5X^2 + 280.45 \quad \text{(Eq. 13)}$$

$$X = \frac{\frac{L0}{2} - \left| L - \frac{L0}{2} \right|}{L0} \quad \text{(Eq.14)}$$

L_0 = the thickness of the panel; L = the depth measured from either surface

Therefore, the vertical density profile of a board can be calculated using equations (10) and (11). The core density can be calculated as:

$$D_C = 0.9691 D_M - 85.28 \quad \text{(Eq. 15)}$$

D_C = the core density; D_M = the mean densities

According to Li (2013), the MDF has a surface density two times denser than the centre density. Based on a few sets of experimental data, an empirical model was developed to predict the vertical density profile of MDF. Therefore, the simplified equation offers a useful predictor of density and it can be utilised to reproduce the density profiles for numerical modelling.

Examples

An experimental method was used by Wang et al. (2004) in the southern United States, which uses southern pine furnish as the basic mixture. Urea-formaldehyde resin and wax are used, and the fibre mats were pressed, trimmed, and transferred to the press. The target panel density was approximately 752 kg/m^3 and the target panel thickness was approximately 19 mm. The pressing cycle had a duration of around 400 seconds and the mat was produced at a platen temperature of approximately 160°C.

The used methodology was made up of two periods and five stages during the formation of the density profiles in MDF mats. The first period is called the uniform consolidation stage between different layers and before closing the press. The second period, called the non-uniform consolidation stage, was after the press has attained the final position. Moreover, it includes the consolidation of the surface layer then the core layer consolidation. Finally, it 'springs-back' from the mat when the press is opened (Wang et al., 2004).

The density of three horizontal-planes through the mat increased quickly before the press attained the final position. When the press attained the final position, it was maintained like that and the density of the top and bottom layers continued to increase while on the core layer the density decreased. When the time of pressing attained approximately 240 seconds, the density of the top and bottom layer started to decrease, and the core layer density started to rise. This period ends after the mat has been pressed for around 350 seconds (Wang et al., 2004).

According to Chapman (2004), the fibres stand in the plane of the panel and the density of the fibres mat is around 30 kg/m^3, while the density of the final product is between 500 and 800 kg/m^3.

2.6.6 Carbon Storage in Medium Density Fibreboard

According to Bonnacorsso (2013), the calorific value of the carbon produced in the MDF is determinate of the lignin and cellulose content, which are complex organic substances. Furthermore, these substances are unstable at high temperatures and can be oxidised by air or can be decomposed under specific environmental conditions.

In the biomass, the percentage of cellulose and lignin are important for the quality of carbon produced. In general, there is a higher lignin content than cellulose in biomass (Bonnacorsso, 2013).

When subjected to a pyrolysis process, the biomass yields a residual solid part called carbon or bio-carbon. Furthermore, the production of this carbon mass depends on the pyrolysis temperature and the percentage of lignin in the biomass, and its structure is less complex than that of lignin (Bonnacorsso, 2013). The pyrolysis process is used to produce carbon under an inert atmosphere which does not contain any oxygen molecules. The pyrolysis process has the principle that at high temperature it is a complex process of chemical decomposition resulting in molecular rearrangements and divisions.

While the residual mass of carbon pyrolysed at approximately 450°C should be around 33%, Bonnacorrso (2013) showed that the residual mass for MDF pyrolysed under nitrogen was 28.77%. After pyrolysis of MDF at 500°C, under nitrogen with a ramp rate of 8°C/min, the carbon fuel obtained has a composition of organic elements as follow: 70.41% carbon, 3.53% hydrogen, 4.63% nitrogen, 21.43% oxygen (Bonnacorsso, 2013).

To activate the surface of MDF, the urea-formaldehyde resin was made to react with resorcinol. The resorcinol reacted with the free formaldehyde and the chemical surface of the lignin was improved. Therefore, the lignin of fibres was consolidated by polymerisation between the resorcinol and the free formaldehyde (Bonnacorsso, 2013).

In addition, the surface of the carbon fibre was activated by burning of the polymer that has grown on the surface of the fibres. A value of 234.54 m^2/g was achieved from the surface area measured.

Many performance characteristics of wood, such as the dimensional stability and durability, could be improved through wood modification at a molecular level. One chemical wood modification process is acetylation, namely the free hydroxyl groups are replaced by acetyl groups within the cell wall (van der Lugt, 2016). Recently, acetylated wood under the names of Accoya (acetylated timber) and Tricoya (acetylated fibres for products as MDF) has been developed.

Using the PAS 2050 methodology for the CO_2 sequestration in acetylated wood from the Sneek Bridge (the Netherlands) the following measurements were established (van der Lugt, Vogtlander, 2014):

1. Density of wood (based upon radiata pine at 12% moisture content) = 450 kg/m^3

2. Assumed carbon content of wood = 50%

3. CO_2 sequestration excluding PAS 2050 weighting [1x2x44/12] = 825 kg CO_2/m^3

4. Expected lifespan of the bridge = 80 years

5. CO_2 sequestered including PAS 2050 weighting [3x4/100] = 660 kg CO_2

6. CO_2 emitted during production (Acetylated Radiata Pine) = 391 kg

7. Total CO_2 sequestered during production and use [5-6] = 269 kg CO_2/m^3

According to the Environmental Product Declaration (EPD) for MDF (2013), presented by American Wood Council (AWC) and Canadian Wood Council (CWC), one cubic metre of North American MDF weighs 745.95 kg. The average weights of different types of resins used by various MDF manufacturers are:

- Wood residues: 667.48 oven-dry kg (89.48%)
- Urea formaldehyde: 71.13 kg (9.54%)
- Urea: 0.81 kg (0.11%)
- Melamine urea formaldehyde resin: 0.72 kg (0.10%)
- Scavenger: 1.45 kg (0.20%)
- Catalyst: 0.11 kg (0.01%)
- Slack wax: 4.25 kg (0.57%)

These results are based on Life Cycle Assessment studies that took into account the whole range of MDF products, sizes and functions. The oven-dry unit measure contains free moisture in cell cavities, and it does not include bound moisture in cell walls. (EPD, 2013).

This EPD includes the cradle-to-gate processes. Production of MDF begins with the transport of residues from the upriver sawmills and it continues with the drying of these materials, blending with resins, then shaping into boards that are pressed and finished. These processes consume both electricity from regional grids, fossil fuel and internally generated biomass (EPD, 2013).

By now, the value for carbon sequestration has been accepted on an international level to be 50%, to estimate dead wood carbon (Weggler et al., 2012). The volume of dead wood is composed of coarse woody waste, smaller woody waste, and dead roots. Furthermore, two conversion factors are required to convert dead wood volume into carbon: wood density and carbon concentration (Weggler et al., 2012). Therefore, the carbon sequestered in one cubic metre of MDF is approximately 50% of its oven-dry weight (EPD, 2013). Considering that one cubic metre of average North American MDF weighs 745.95 kg and the percent of wood residues is 89.48%, the oven-dry mass obtained is 667.48 kg. Therefore, the carbon sequestered is calculated as:

$$\text{Carbon} = 667.48 \text{ x } \frac{50}{100} = 333.74 \text{ kg}$$

Considering Equation 1 shown in Chapter 1.1, it can be obtained as follows:

$$333.74 \text{ kg (Carbon) x } \frac{M\ CO2}{M\ C} = 333.74 \text{ kg x } \frac{44}{12} = 1223.71 \text{ kg } CO_2 \text{ equivalent}$$

M_{CO2} is the molecular mass of CO_2 and M_C is the atomic mass of carbon.

Therefore, approximately 1223.71 kg of CO_2 are absorbed from the atmosphere to produce 667.48 kg of dried biomass.

Forest Product Innovations and Athena Institute (2013) presented a carbon sequestration tool for wood and estimated the biogenic carbon balance at year 100, considering the fact that the carbon dioxide emissions from the combustion of internally used wood fuels are balanced by the carbon dioxide uptake in the forest when the tree grows. Moreover, the life estimations for various end uses for MDF and the average landfill decay rate are included. Some of the important results are summarised below.

Carbon sequestered in the product, as manufactured in the cradle-to-gate processes, gives rise an equivalent emission of CO_2 as follows:

$$1223.71 \text{ kg } CO_2 \text{ equivalent} = -\ 1223.71 \text{ kg } CO_2 \text{ equivalent emission}$$

Methane emitted from landfill:

$$5.69 \text{ kg } CH_4 = 142.37 \text{ kg } CO_2 \text{ equivalent emission}$$

Carbon sequestration at year 100, net of biogenic carbon emissions:

$$677.02 \text{ kg } CO_2 \text{ equivalent} = -\ 677.02 \text{ kg } CO_2 \text{ equivalent emission}$$

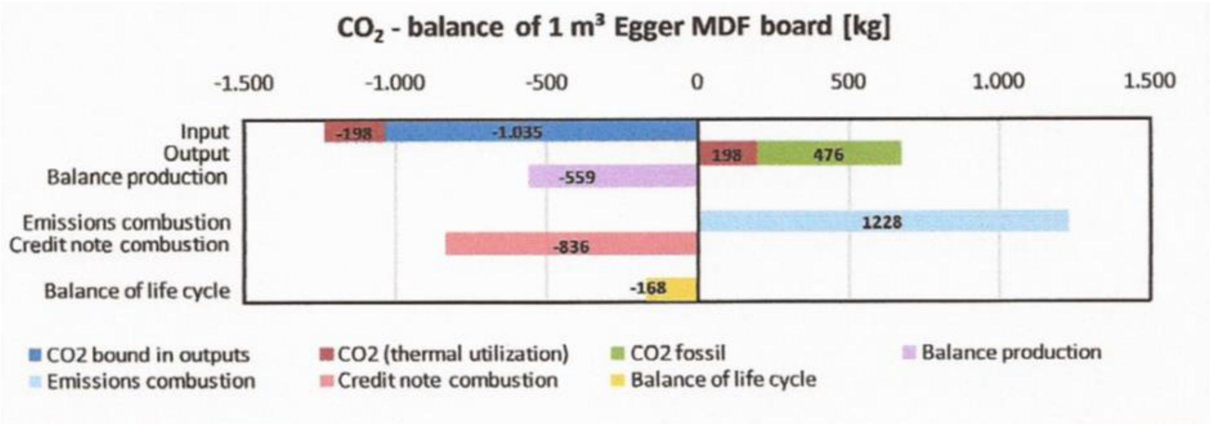


Figure 4. CO_2 balance for manufacturing of 1 m^3 of MDF board (EPD Egger, 2008)

According to Environmental Product Declaration (Egger, 2008), for the biomass-generating plant modelled above, during the production stage in order to obtain one m^3 of MDF board, 674 kg of CO_2 are emitted. These consist of thermal utilisation of wood (198 kg CO_2) and fossil fuel emissions (476 kg CO_2), (Fig. 4).

Then, for one cubic metre of MDF board a total of 1233 kg CO_2 is captured from the atmosphere and, through photosynthesis as the tree grows, stored in the wood. Only 1035 kg CO_2 per cubic metre remains sequestered in the wood and at the end of its lifecycle this is released back into the atmosphere (1233 kg CO_2 - 198 kg CO_2 from thermal utilisation of wood). The overall CO_2 balance of the production stage is 559 kg /m^3 MDF board, thanks to carbon binding in the product (1035 kg CO_2 - 476 kg CO_2 from fossil emissions). If a substitution of fossil fuel takes place, from the combustion of these energy source results 836 kg CO_2 emissions.

According to an Environmental Product Declaration (Egger, 2015), the MDF of 15-19 mm has a density between 670-730 kg/m^3. The weight per unit area of the 18 mm board is 12.1-13.1 kg/m^2. Standard board sizes are 2800 x 2070 mm and 4110 x 2070 mm (with a thickness range of 8-38 mm).

MDF with thickness between 8-40 mm and average density of 720 kg/m^3 have the following composition (expressed as % by weight per 1m^3 of production):

- wood chips, wood type mainly spruce and pine, approximately 82%
- water approximately 5-7%
- melamine - urea – formaldehyde resin approximately 11%
- paraffin wax emulsion < 1%

According to Egger, 1 m^3 of MDF binds in 505 kg of CO_2 (equivalent to around 138 kg carbon).

The IPCC's default carbon conversion factor for MDF with an oven-dry density of 691 kg/m^3 is 295 kg C/m^3, giving a carbon fraction of 0.427. These factors could be replaced with country specific data if it is available (Technical Paper, 2013).

According to this European Standard the amount of atmospheric carbon dioxide coming from biogenic carbon content is quantified using a calculation method, which is based on the atomic weights of carbon (12) and carbon dioxide (44).

The mass of carbon dioxide based on biogenic carbon content can be calculated using the following formula, according to the BSI (2014):

$$P_{CO_2} = \frac{44}{12} \times cf \times \frac{\rho_\omega \times V_\omega}{1 + \frac{\omega}{100}} \quad \text{(Eq. 16)}$$

P_{CO_2} = the biogenic carbon oxidized as carbon dioxide emission from the product system into the atmosphere (e.g. energy use at the end-of-life)

cf = the carbon fraction of woody biomass, oven dry mass (0.5 as the default value)

ω = the moisture content of the product (e.g. 12%)

ρ_ω = the density of woody biomass as the product at that moisture content (kg/m^3)

V_ω = the volume of the solid wood product at that moisture content (m^3)

For wood-based products, wood volume content $V_\omega = VP \times percentage\ of\ wood$, where VP is the gross volume of the wood-based product.

Moreover, the estimation of the total amount of carbon dioxide for any project is calculated by quantifying the volume of wood of each species used in each wood and wood-based product and applying the calculation in each case (i.e. $P1_{CO_2} + P2_{CO_2}$, etc).

2.6.7 Areas of Use of Medium Density Fibreboard

The primary composite panel products, as particleboard and MDF, are used in the manufacture of furniture, kitchen cabinets, laminate flooring, moulding, door parts, and many other products (Wu and Vlosky, 2000). As a result of the decreasing reserve of prime timber, the southern United States use the composite panels for their consistent uniformity and availability in quality. For example, the surface of MDF is smooth, flat, dense, and uniform. Furthermore, the edge of MDF is homogeneous and permits a good finishing technique for the products.

MDF is usually used in producing furniture, moulding, display fixtures and millwork (Wu and Vlosky, 2000). Wu and Vlosky (2000) conducted a survey in the southern United States on the uses of composite panels in furniture and cabinet manufacturing. As a raw material, 11% of all the MDF produced is made into kitchen cabinets and 26% into office furniture. Therefore, companies are planning to increase their usage of MDF by 52% in the manufacture of kitchen cabinets (Wu and Vlosky, 2000). The companies participating in the survey gave some important motivations for using MDF: economics reasons (57% of the companies); the finishing characteristic of MDF (53%); the dimensional stability, uniform thickness, and surface stability of board (48%).

Similarly, a perspective from furniture and cabinet manufactures was derived in Turkey by Nemli et al. (2007). They found that 42% of the companies used MDF as a raw material and the reasons given for its use were the high strength characteristics of MDF (22% of the companies), dimensional stability (20%), machining capability (14%) and finishing characteristics and surface stability (11%).

2.6.8 Medium Density Fibreboard Used in Kitchen Furniture

One of the biggest furniture factories in Ethiopia, Finfine Furniture Factory (3F), has established plants which are only dedicated to kitchen and built-in cabinets (Tekle, 2014). The raw materials used for kitchen cabinet manufacturing are: particle boards (47.2% of the total wood used per functional unit), MDF (18.4% by weight), lumber (34.4% by weight), ethylene vinyl acetate glue, PVC sheet and different tops (Tekle, 2014). Furthermore, the wood and wood-based materials are the preponderant materials which compose the kitchen furniture. Resins represent up to 15% of the total mass of the wood-based material and are produced from non-renewable materials (Dinwoodie, 2000; Doran, 1992). Moreover, kitchen furniture manufacturing requires consumption of raw material and energy use which leads to large amounts of waste and emissions.

Based on their design, the kitchen cabinets are straight run, L-shaped, Galley, U-shaped, and G-shaped (Tekle, 2014). MDF is a good substrate for laminate, including melamine, vinyl foils and wood veneers. According to Tekle (2014), the amount of MDF consumed per unit kitchen cabinet is around 0.026 m^3, with design tall and single straight kitchen cabinet, or approximately 0.136 m^3 for full L-shaped and 0.179 m^3 for full U-shaped kitchen cabinet (Tekle, 2014). The MDF used for making kitchen cabinets has a density of around 741 kg/m^3, 16 mm thickness, 2440 mm length and 1220 mm width. Moreover, a subgroup of MDF of 3 mm thickness is included.

To show the carbon stored in MDF for kitchen furniture, as a basis for this current research, three kitchen designs have been chosen for analysis: one design with MDF doors, one design with oak doors, and a further one with chipboard doors. Similar to Tekle, L-shaped and U-shaped kitchen furniture designs have been included for analysis.

Kitchen design 1 (galley kitchen), length 8.400 m for base units (no cooker stove) and 5.100 m for wall units, consisting of doors of 16 mm, drawer fronts, drawer bottoms and back panels of base and wall units made of MDF, worktop-Basalt Slate (3000 x 600 x 38 mm), (Appendix 3a, Model 1).

Kitchen design 2 (L-shaped kitchen), length 7.200 m for base units (no cooker stove) and 4.680 m for wall units, consisting of oak doors of 18 mm (Elvira), worktop-Madura Garnet (3000 x 600 x 38 mm). Base and wall unit backs and drawer bottoms are made of MDF (Appendix 3b, Model 8).

Kitchen design 3 (U-shaped kitchen), length 6.500 m for base units (no cooker stove) and 4.240 m for wall units, consisting of chipboard doors-cream doors of 18 mm (Chancery-Cream), worktop of beech-Solid wood (3000 x 640 x 40 mm). Base and wall unit backs and drawer bottoms are made of MDF (Appendix 3c, Model 15).

Considering the variant A, according to the Environmental Product Declaration for MDF (AWC, CWC, 2013), one cubic metre of North American MDF weighs 745.95 kg and consists of 89.48% wood residues. Therefore, the mass of MDF and the carbon sequestered in its oven-dry mass for the three kitchen designs can be calculated as follows:

For kitchen design 1:

$$V_{1MDF} = 0.146375 \text{ m}^3$$

$$M_{1MDF} = 745.95 \text{ x } V_1 = 745.95 \text{ x } 0.146375 = 109.19 \text{ kg}$$

$$\text{Wood residues (oven-dry)} = 109.19 \text{ x } \frac{89.48}{100} = 97.70 \text{ kg}$$

$$M_{1C} = 97.70 \text{ x } \frac{50}{100} = \mathbf{48.85\ kg}$$

V_{1MDF} is the volume of MDF, M_{1MDF} is the mass of MDF and M_{1C} is the mass of carbon.

For kitchen design 2:

$V_{2MDF} = 0.045972 \text{ m}^3$

$M_{2MDF} = 745.95 \text{ x } V_2 = 745.95 \text{ x } 0.045972 = 34.29 \text{ kg}$

Wood residues (oven-dry) = $34.29 \text{ x } \frac{89.48}{100} = 30.68 \text{ kg}$

$M_{2C} = 30.68 \text{ x } \frac{50}{100} =$ **15.34 kg**

V_{2MDF} is the volume of MDF, M_{2MDF} is the mass of MDF and M_{2C} is the mass of carbon.

For kitchen design 3:

$V_{3MDF} = 0.035431 \text{ m}^3$

$M_{3MDF} = 745.95 \text{ x } V_3 = 745.95 \text{ x } 0.035431 = 26.43 \text{ kg}$

Wood residues (oven-dry) = $26.43 \text{ x } \frac{89.48}{100} = 23.65 \text{ kg}$

$M_{3C} = 23.65 \text{ x } \frac{50}{100} =$ **11.83 kg**

V_{3MDF} is the volume of MDF, M_{3MDF} is the mass of MDF and M_{3C} is the mass of carbon.

Variant B is according to Egger's Environmental Product Declaration, (2015) that one cubic metre of MDF weighs 720 kg and 82% of it is made up of wood residues. Therefore, the mass of MDF and carbon sequestered in its oven-dry mass can be calculated for the three kitchen designs as below:

For kitchen design 1:

$$M_{1MDF} = 720 \times V_{1MDF} = 720 \times 0.146375 = 105.39 \text{ kg}$$

$$\text{Wood residues (oven-dry)} = 105.39 \times \frac{82}{100} = 86.42 \text{ kg}$$

$$M_{1C} = 86.42 \times \frac{50}{100} = \mathbf{43.21\ kg}$$

For kitchen design 2:

$$M_{2MDF} = 720 \times V_{2MDF} = 720 \times 0.045972 = 33.10 \text{ kg}$$

$$\text{Wood residues (oven-dry)} = 33.10 \times \frac{82}{100} = 27.14 \text{ kg}$$

$$M_{2C} = 27.14 \times \frac{50}{100} = \mathbf{13.57\ kg}$$

For kitchen design 3:

$$M_{3MDF} = 720 \times V_{3MDF} = 720 \times 0.035431 = 25.51 \text{ kg}$$

$$\text{Wood residues (oven-dry)} = 25.51 \times \frac{82}{100} = 20.92 \text{ kg}$$

$$M_{3C} = 20.92 \times \frac{50}{100} = \mathbf{10.46\ kg}$$

Using the methodology of Life Cycle Assessment, Rosso (2007) showed that for one kitchen refurbishment the real use of the important raw material was approximately 290 kg of softwood (QD) (on relative stand density RD and the quadratic mean diameter QD) of which 50% is wasted during manufacturing processes (Hiesl P. et al, 2015). Furthermore, the study determined a total embodied energy of around 8.8 GJ (gigajoule: x 10^9 joules) associated with approximately 467 tonnes of CO_2.

The useful life of individual kitchen components is considered to be 20 years and often the refurbishment of a domestic kitchen can take place within the first three years of occupancy of the house (Rosso, 2007). Moreover, the variability values of embodied energy for kitchen materials are commonly bigger than 40% and there is a possible connection between these values and the high frequency of kitchen refurbishment.

The major contributors are softwood and resin. However, the use of recycled wood in the manufacturing of components for kitchen refurbishment was found to save around 24% of the CO_2 emissions and approximately 450 kg of consumption of virgin softwood (Rosso, 2007). In addition, using a solid hardwood worktop in place of laminated chipboard worktop would save around 30% of the consumption of resin.

Considering the kitchen to be replaced every three years over the building lifetime of 100 years, the consumption of virgin softwood would be 9.6 tonnes for the case of 33 kitchen refurbishment turnovers (100/3 = 33). Furthermore, this is eight tonnes more than the situation from where the kitchen is refurbished only when needed.

Moreover, by using the Life Cycle Assessment kitchen refurbishment model, Rosso (2007) showed that the kitchen of weight 336.3 kg (net mass) consumed approximately 500 kg of various materials, of which around 290 kg was softwood, approximately 83 kg was recycled wood and resin was around 29 kg (gross mass) like a sourcing material. Furthermore, the net mass of materials like laminate chipboard is around 280 kg and the gross mass is approximately 338 kg (280/338 = 0.83) and this represents around 80% of the total material mass.

In addition, the mass of a kitchen carcass could be between around 10 kg (500 mm wall unit) and approximately 30 kg (1000 mm base unit) (Rosso, 2007). The functional life of individual kitchen parts is regarded to be 20 years and aesthetic service life could be 5 years, over 100 years' lifetime of buildings, these were calculated at 5 years (100/20 = 5) and respectively 20 years (100/5 = 20) (Rosso, 2007).

2.7 Hypotheses

Hypothesis 1: The perceptions about furniture impact on climate change depend on the social characteristics of the respondents.

Hypothesis 2: The behaviour of furniture change/upgrade pattern is predictable, being correlated to other behaviours.

Hypothesis 3: The variability of carbon dioxide equivalent in kitchen furniture is mainly produced by kitchen design, but the raw material also has a significant contribution.

CHAPTER 3 Methodology

3.1 Introduction and Overview

The factors identified in the literature review were used in order to guide the design for this research. Furthermore, focus group discussions was used in order to determine the most suitable structure for the questions and responses in the questionnaire. The fieldwork then consisted of the following steps:

- A focus group was formed taking into consideration the elements identified from the literature review. It was used to conduct discussions aimed at developing the structure of the questionnaires as well as to determine the scope of the survey.
- The questionnaire was written, and pilot tested.
- After the pilot survey was conducted, the questionnaire was revised and then the full survey conducted. The respondents were encouraged to identify possible issues and elements that had not been acknowledged in the literature review.

3.2 Design and Administration of Questionnaire

A questionnaire makes the use of quantitative methods for data analysis possible (Attach, 2011). The process of questionnaire development is supported by the focus group as an important tool for obtaining feedback on the elements and variables. According to Kitzinger (1995), focus groups are "*a form of group interview that capitalises on communication between research participants in order to generate data*". This method has been used in social and market research and has been increasingly used in recent times (Bloor et al., 2001). According to Kitzinger (1995), interaction between members of the group can be used to encourage research participants to develop their own analysis of shared experiences.

For this study, it was decided that the focus group should be used to identify the elements for the questionnaire through the literature review. While other researchers have used approximately 15 participants (Goss and Leinbach, 1996), focus groups are normally composed of around 8-12 persons (Gomm, 2008). According to Bloor et al. (2001), the optimum size for focus group discussion is between six and eight participants. The ability to interact is restricted by the size of this group.

The focus meeting lasted around one hour. Before the start of the meeting, the group was informed about the purpose of the meeting. At the end of the discussion, the participants were told about the next steps and a summary of the topics was presented. The focus group discussions identified the following elements:

- The group generally accepted the limitations identified by the literature review.
- Other elements were identified.

Furthermore, the idea behind the research was to find participants with a broad range of interests and backgrounds. The focus group was used to identify the key issues from which the questionnaire was developed for pilot testing (Hundley and van Tejingen, 2001).

The hypotheses would be tested by means of the questionnaire. The assumption of the study is that there is a link between the social and economic status of the respondent (e.g. level of income, age, education) and the frequency with which they change their furniture.

3.2.1 Design of Questionnaire

The scope of the study was defined with the help of the focus group meeting. The discussions of the focus group and the literature review were used to find the variables (de Vaus, 2002).

This new research is aimed at developing an understanding of what the drivers are and their influence on how and when individuals change their furniture. The rationale for the research is based on the fact that the more frequently residential wooden furniture is changed, the lower the lifespan of the carbon kept sequestered in biomass, with negative consequences for climate change mitigation efforts.

3.2.2 Pilot Study

In order to obtain feedback on the hypotheses that were proposed and the questionnaire, these were pre-tested, by means of the pilot study which allowed for the development of a clearer questionnaire. With the pre-testing, it was possible to:

- Rephrase questions that were found to be unsuitable.

- Eliminate confusing and unnecessary questions.
- Test the techniques for data collection and analysis in order to reduce the risk of failure (de Vaus, 2002).
- Identify any possible problems with the investigation procedure.
- Assess the adequacy of the cover letter and the time spent by respondents to complete the questionnaires.

3.2.3 Sampling Frame

A questionnaire was developed to be applied to a sample of the adult population of London, UK. The population for the survey was therefore represented by inhabitants of London, aged 21 and older.

3.2.4 Test for Reliability

The correlation of an item, scale or instrument with a hypothetical one which really measures what it is supposed to measure represents a test for reliability or a test for internal consistency. Furthermore, the results of research cannot be reproduced if any data collection instrument used in the research is not reliable. A measure of internal consistency is Cronbach's alpha, and this is a coefficient of reliability.

3.2.5 Administration of Questionnaire

The questionnaire contained an introduction explaining the importance of the study and an assurance to respondents of the confidentiality of their responses. Furthermore, the questionnaires were administered by survey on the street on a voluntary basis (Appendix 1).

The questions in the questionnaire used for the survey were the following:

1. What is your gender? (Male; Female; Other)

2. What is your age?

3. What is your level of education?

4. Which of these describes your personal income last year? (£0 to £9999; £10,000 to £24,999; £25,000 to £49,999; £50,000 to £75,000; £75,000 and above; Prefer not to answer)

5. Do you own a property?

6. In your opinion, is climate change happening?

7. Are you worried about climate change effects?

8. How knowledgeable are you about carbon storage in wooden furniture?

9. What category of home furniture have you upgraded most often?

10. What would be your main reason for a furniture upgrade (or change)?

11. In your view, what is the most frequent occasion for a furniture upgrade?

12. How often have you changed your kitchen furniture?

13. How often have you changed your bedroom furniture?

14. How often have you changed your living room furniture?

15. When changing furniture (any kind), what do you usually do with the old items?

16. Does the type of raw material (in the old furniture) influence your decision on whether to send it to landfill or sell/donate it?

17. What wooden raw material is most abundant in your current home furniture?

18. When choosing furniture, are you interested in the raw material?

19. Which wooden raw material would you prefer?

20. Which is the most important aspect for you when purchasing new furniture?

21. If you experienced a significant increase in your income, would you change your furniture more often than you currently do?

22. If the selection of raw material could help in the fight against climate change, would you consider selecting the most climate-friendly raw material?

23. If keeping the current furniture longer could help in the fight against climate change, would you keep it just for that reason?

24. If purchasing used furniture could help in the fight against climate change, would you consider buying used furniture?

In order to identify zones for administering the questionnaire, five concentric circles were drawn on a map of London, taking St Paul's Cathedral as the centre point (Appendix 2). The first circle had a radius of 3 km and the radius of each subsequent circle increased by a further 3 km. This gave the outer circle a radius of 15 km. Four widely spread points were chosen at random within each of the zones created by these five circles, in order to have a representative sample of the population of London.

The survey started at the nearest tube or train station to each established point on the map and continued in adjacent streets, where people were invited to respond to the questionnaire.

The centre of the concentric circles was considered to be St Paul's Underground Station.

The following tube and train stations corresponded to the randomly selected positions in each of the five described zones:

1. For the first circle: King's Cross, Elephant and Castle, Liverpool Street, Green Park
2. For the second circle: Kentish Town, Herne Hill, Hackney Central, Earl's Court
3. For the third circle: Wood Green, Putney Bridge, Custom House for Excel, Leyton
4. For the fourth circle: New Southgate, Wimbledon, Snaresbrook, Gunnersbury
5. For the fifth circle: Southgate, East Croydon, Barking, Richmond

The researcher travelled to each of these stations and approached people in the nearby streets. The context was explained to them, that is, a postgraduate student conducting research into carbon storage in wood furniture. People were asked if they would be willing to take a few minutes to complete the questionnaire. They were first asked if they lived in London, to ensure that they were eligible to participate in the survey. After being shown an introduction to the questionnaire, they were asked to confirm that they were willing to provide responses to it.

In total, 161 responses to the questionnaire were gathered. It is well established that the sample size depends on the size of the population, on the preferred margin of error and on desired confidence level (Cochran, 1977; Bartlett et al., 2001). For a population the size of London's, with a 5% margin of error and 95% desired confidence, a typical sample size would be approximately 385-400 people (Bartlett et al., 2001). However, despite the misconception that for a given population size the sample size is invariant (MacCallum et al., 1999), the sample size depends on the study itself. That is because the standard deviation in the population, which is used for calculation of sample size, depends on the questions they are asked and on the complexity of the questionnaire (Morse, 2000). Therefore, given the low complexity of the questions, the sample size can be smaller than the typical one.

The questionnaire was designed to collect four types of information:

(i) personal information on the respondent, such as gender, age category, education level, level of income and status as homeowner or renter (Q 1-5).

(ii) the respondent's perception of climate change, where the intention was to find out whether or not the respondent believes that climate change is real and how worried s/he was about the consequences of climate change (Q 6-7).

(iii) the respondent's knowledge, behaviour and priorities in relation to their home furniture and the raw materials used to make it, with the aim being to find which category (which room) of furniture is changed most often, how often it is changed, the reasons for doing so and what happens with the old furniture (Q 8-15). A further purpose was to find out what wooden raw material is most abundant in their home, if they are interested in that, their preferences and priorities when they buy new furniture (Q 16-20).

(iv) the respondent's response to different hypothetical scenarios, by asking them to consider how likely they would be to change their furniture if, for example, their income were to grow significantly, or if they knew that their decision would have a significant impact on climate change mitigation (Q 21-24).

3.3 Analysis and Questionnaire Responses

The questionnaires that were completed were checked for any errors. Data analysis was performed using R (R Core Team, 2017), an open source software for statistical computing. Because the data obtained from the questionnaire was categorical, non-parametric methods were used. However, for Likert scale responses, parametric tests (e.g. *t*-test, F-test) were also employed if the data was normally distributed (Sullivan and Artino, 2013; Harpe, 2015).

For the non-Likert scale responses, non-parametric tests such as the Mann-Whitney U test (Mann and Whitney, 1947) were used and non-parametric alternatives to the Pearson correlation coefficient, such as the Goodman and Kruskal tau measure of association between two categorical variables (Somers, 1962). This asymmetric association measure allowed for the detection of asymmetric relations between categorical variables.

The degree of association is based on the concept of covariance. The standardised measure of covariance is the correlation. Correlation reporting involves reporting its intensity, meaning, and significance threshold. From the survey results descriptive statistics have been obtained in various forms, as tables and bar graphs. Various plots were developed for a graphic presentation of the data. Therefore, correlation analysis involves both numerical interpretation and graphic analysis (Opariuc-Dan, 2011).

The simplest correlational study involves obtaining a pair of observations or measurements in two different variables of several individuals. The paired measures are analysed statistically to determine if there is any relationship between them (Ho, 2006). Furthermore, the threshold of significance shows the chances we have for the obtained indicator to result in traces of sampling errors. To accept the significance of this index, the null hypothesis is rejected-only if this chance is less than 5%, and we are at a threshold of significance < 0.05. The null hypothesis is when there is no association between two variables.

To test whether the correlation coefficient is different from zero, several tests are used: Pearson, Spearman, Kendal. The Pearson coefficient is the most common correlation coefficient for parametric data and is used to analyse the relationship between two quantitative variables (Opariuc-Dan, 2011).

The Spearman correlation coefficient can be used for ordinal variable derived from continuous variables or continuous variables that do not meet the conditions of applying parametric statistics. The Kendal correlation coefficient has several forms and is based on inversion and agreement calculations. It is used for variables that occur naturally at a level of orderly measure or quantitative variables that do not meet the conditions for application of parametric statistics.

The probability that Pearson correlation $r = 0$ (no association present) is given by the coefficient p (Table 17). If the probability $p < 0.05$ then the probability that $r = 0$ is small, so the hypothesis that $r = 0$ is rejected and the hypothesis that $r > 0$ is adopted.

The reason for using all three of these tests is to reduce the uncertainty related to the significance test and to reduce type I and type II errors. If the probability p is not less than 0.05 in at least one of the tests, there is insufficient evidence.

3.4 Sample Structure

Out of 161 respondents, approximately 61% of respondents are females (99 persons) and 39% are males (62 persons) (Fig. 5, a). The age structure of the sample is presented in Fig. 5,

b. Therefore, approximately 10% of respondents (16 persons) are between 21 and 25 years old, around 35% of respondents (56 persons) are between 26 and 35 years old, while the largest proportion around 47% of respondents (76 persons) are between 36 and 65 years old. Only circa 8% (13 persons) are older than 65 years. Most of the respondents have a tertiary level education (Fig. 5, c). Around 35% of respondents (56 persons) have at least an undergraduate degree, 33% of respondents (53 persons) have a postgraduate degree, so a total of 68% have a University education. Therefore, we can conclude that this is a highly educated sample of respondents.

Around 47% of the respondents (76 persons) have an income between £25,000 and £49,999 (GBP) and approximately 34% of respondents (55 persons) earn between £10,000 and £24,999 (Fig.5, d). Only 16 respondents have an income last year of over £50,000. Furthermore, approximately 60% of respondents (97 persons) do not own their own property (Fig. 5, e).

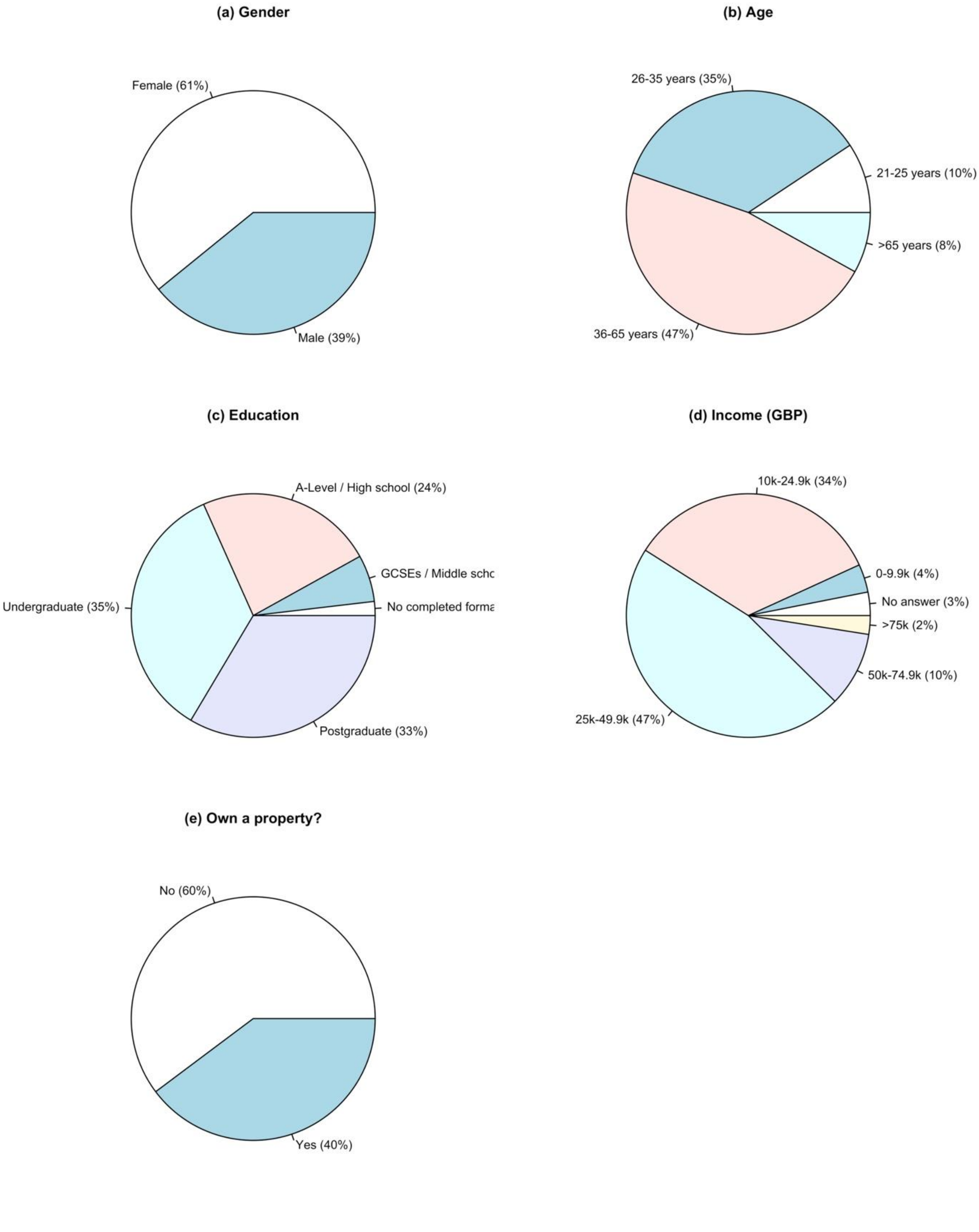


Figure 5. Sample structure

3.5 Evaluation of Kitchen Furniture Carbon Content

According to the findings of the study, a large percentage of the respondents have changed their kitchen furniture in comparison to other types of furniture. Therefore, kitchen furniture was chosen as a focus for subsequent research about carbon storage in furniture. Twenty-one different kitchen designs were included within the scope of the research: seven kitchen designs with MDF doors (Models 1-7); seven designs with oak doors (Models 8-14); and a further seven with chipboard doors (Models 15-21). Furthermore, the stored carbon content was calculated for these different kitchen designs by base unit and wall unit in each case. Therefore, in the attached Appendix 3 there are a total of 21 base unit models and 21 wall unit models for which the quantity of carbon was calculated.

- Kitchen Model 1 (galley kitchen), length 8.400 m for base units (no cooker stove) and 5.100 m for wall units, consisting of doors of 16 mm, drawer fronts, drawer bottoms and back panels of base and wall units made of MDF, worktop-Basalt Slate (4100 x 600 x 38 mm). Models 2a, 3a, 4a, 5a, 6a and 7a are similar with Model 1, galley kitchen with length of 3.700 m for base units (no cooker stove), 2.550 m for wall units for Models 2b, 3b, 5b and 6b, and 2.500 m wall units for Models 4b and 7b, but with different numbers of cabinets and designs (Appendix 3a).

The volume for each wood component has been calculated. According to Egger's Environmental Product Declaration (EPD), the average density for MDF is around 720 kg/m^3 and the percentage of wood mass is approximately 82%. Furthermore, the density for melamine faced chipboard is around 660 kg/m^3. According to Egger's EPD the percentage of wood mass for chipboard is approximately 84-86% and, therefore, an average value of 85% was used in the calculation.

According to standard BS EN 16449:2014, for wood-based products, wood volume content (V_ω) at the moisture content of the product (e.g. 12%) is:

$$V_\omega = VP \times percentage\ of\ wood \qquad \text{(Eq. 17)}$$

where VP is the gross volume of the wood-based product. Therefore, the wood volume content (oven-dry biomass) was calculated by quantifying the volume of wood of each type used in each wood/wood-based product.

As discussed in Chapter 2.6.6 the carbon fraction of woody biomass (oven-dry mass) of 0.5 was used as the default value.

- Kitchen Model 8 (L-shaped kitchen), length 7.200 m for base units (no cooker stove) and 4.680 m for wall units, consisting of oak doors of 18 mm, back panels of base and wall units, drawer bottoms made of MDF (Elvira), worktop-Madura Garnet (4100 x 600 x 38 mm). Models 9a, 10a, 11a, 12a, 13a and 14a are not L-shaped kitchens, they are in one line, length 3.850 m for base units, but with different numbers of cabinets and designs. Furthermore, Model 9b has a length of 2.380 m for wall units**,** Models 10b, 12b and 13b have length of 2.540 m and Models 11b and 14b have wall units of length 2.600 m (Appendix 3b).

According to Korkut and Hiziroglu (2014), the average oven dry density of red oak is 657 kg/m^3 and the density for oak, American red or English brown is around 740 kg/m^3.

- Kitchen Model 15 (U-shaped kitchen), length 6.500 m for base units (no cooker stove) and 4.240 m for wall units, consisting of chipboard doors-cream and drawer fronts of 18 mm, base and wall units with back panels and drawer bottoms made of MDF (Chancery-Cream), worktop of beach-Solid wood (3000 x 640 x 40 mm). Models 16a, 17a, 18a, 19a, 20a and 21a are L-shaped kitchens, with a length of 4.950 m for base units, but with different numbers of cabinets and designs. Furthermore, Models 16b and 18b have wall units of length 3.540 m, Models 17b, 19b, 20b and 21b have wall units of length 3.500 m (Appendix 3c).

The density of beech, according to European Wood Japan, is around 712 kg/m^3. The average oven-dry density for beech is 450-600 kg/m^3, and so a mid-value of 570 kg/m^3 was used (Pivaru and Zavoianu, 1981).

3.6. Accounting the Variance in Furniture Carbon Content

To account for the variance that was due to differences between door raw materials (i.e. solid wood oak, MDF and chipboard) and due to furniture design, an Analysis of Variance (ANOVA) model was used:

$$C_{ij} = \mu + \sigma_j + \varepsilon_{ij}$$

(Eq. 18)

Where C_{ij} represents the carbon dioxide equivalent (CO_2e) content (kg per metre of furniture) of furniture design *i* with the front door from raw material *j*; μ is the overall mean of carbon content; σ_j is the random effect that was due to differences between raw materials of front door $\sigma_j \sim N(0, \sigma_{door}^2)$; ε_{ij} is the error term of carbon content of furniture of design type *i* and door raw material *j* $\varepsilon_{ij} \sim N(0, \sigma_\varepsilon^2)$.

Furthermore, the Variance Partition Coefficient (VPC) was used to assess the proportion of variance that was due to differences between furniture design types:

$$VPC_{design} = \frac{\sigma_\varepsilon^2}{\sigma_{door}^2 + \sigma_\varepsilon^2} \times 100 \quad \text{(Eq. 19)}$$

And between door raw material type:

$$VPC_{door} = \frac{\sigma_{door}^2}{\sigma_{door}^2 + \sigma_\varepsilon^2} \times 100$$

(Eq. 20)

3.7 Conclusion

In this section the methodology and research design have been presented. The elements and variables from questionnaire were identified using a focus group. Furthermore, the data collection and analysis methods were developed. The primary data was collected by means of a survey. The next chapter presents the results of the study. In the context of the literature review the results are analysed.

CHAPTER 4 Results and Discussion

4.1. Analysis of Public Perceptions on Carbon Sequestration in Wooden Furniture

4.1.1 Descriptive Results

The results of the questionnaire revealed that people generally express some concern about the effects of climate change (Fig. 6, a and b) and are willing to make efforts for climate change mitigation, although the way furniture can contribute to climate change mitigation is not generally well understood. Most of them (i.e. 76%, 122 respondents) believe that climate change is really happening.

The respondents were asked to evaluate their level of understanding of the role of furniture in climate change mitigation and most of them (i.e. 90%, 145 respondents) declared they have no knowledge or limited knowledge about carbon sequestration in wooden furniture (Fig. 6, c). This result is not too surprising, since most communications towards general public on this matter are focused on forests only. In order to avoid bias in responses, no details about the link between furniture and climate change were given to the respondent until all questions were answered.

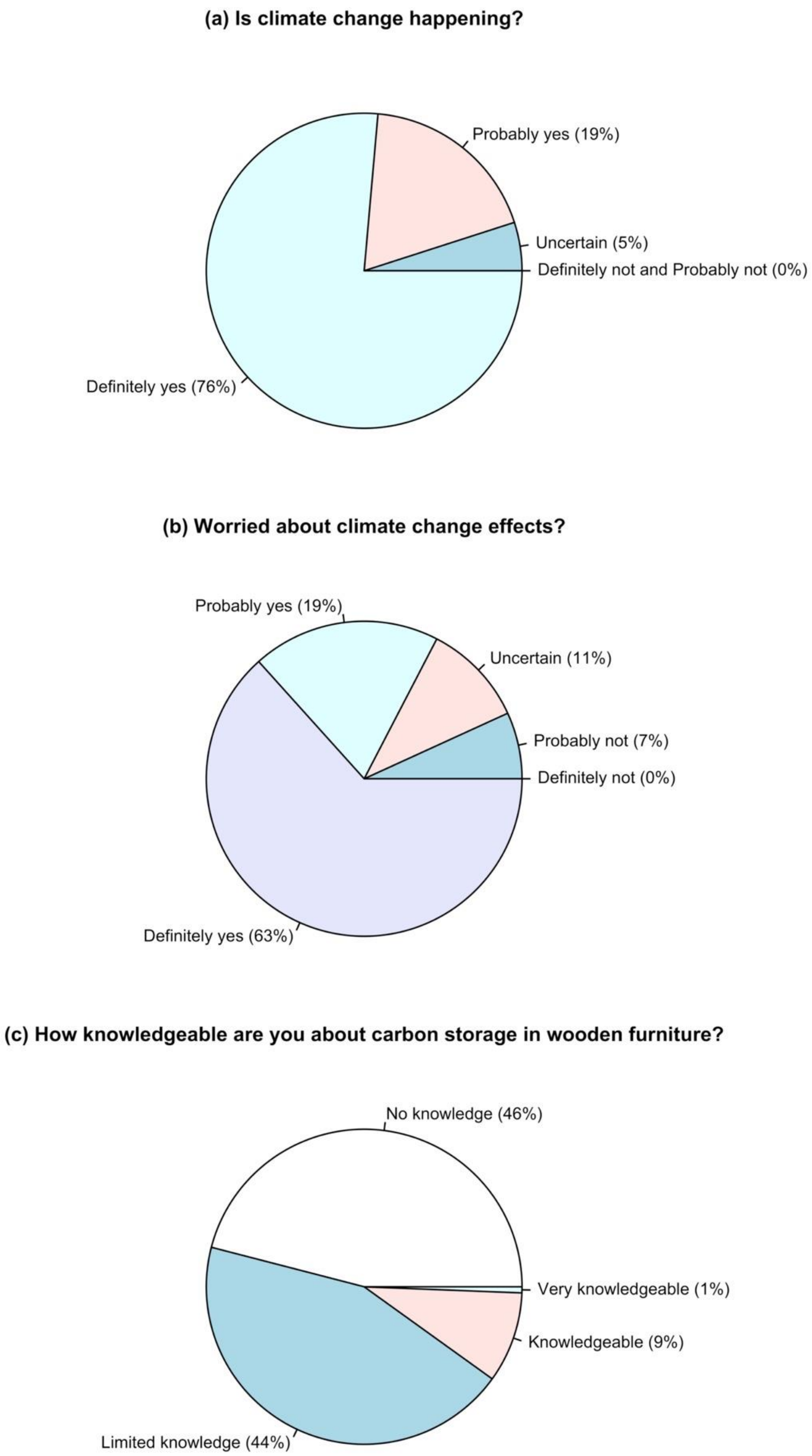


Figure 6. Results of asking respondents whether they believe climate change is happening (a), whether they are concerned about the effects of climate change (b), and whether they have any knowledge about the link between wooden furniture and climate change mitigation (c)

Because the behaviour of changing the furniture is linked to climate change mitigation (i.e. changing the wooden furniture faster, reduces the half-life of HWP) the questionnaire was structured in a way that all common furniture categories in a house were investigated. Three types of home furniture were considered: (i) kitchen furniture, (ii) bedroom furniture and (iii) living room furniture. The results showed that approximately 38% of respondents (i.e. 61 respondents) upgraded their bedroom furniture more often than other types of furniture (Figure 7, a). However, this proportion is not very different from the other two furniture categories (i.e. kitchen and living room). The decision to upgrade the furniture is usually driven by many factors such as being worn/deteriorated, outdated/old-fashioned or to improve functionality. Around 42% of the respondents (i.e. 67) declared that the main reason for changing their furniture was based on it being worn/deteriorated (Figure 7, b). Approximately 38% (62 respondents) considered that improved functionality is the main reason for a furniture upgrade and only 32 respondents (around 20%) agreed that outdated/old fashioned could be the reason for this update (Figure 7, b). Although buying furniture for an unfurnished new house would be a necessity, the most frequent occasion for furniture update was when renovating, therefore, for those upgrading the existing furniture in their current (not new) house (Fig. 7, c). Approximately 43% (69 respondents) answered ‘upgrade of furniture in current house (renovation)’, around 29% (47 respondents) answered ‘purchase of furniture for unfurnished new house’ and approximately 28% (45 respondents) responded ‘upgrade of existing furniture when moving to a new house’ (Fig. 7, c).

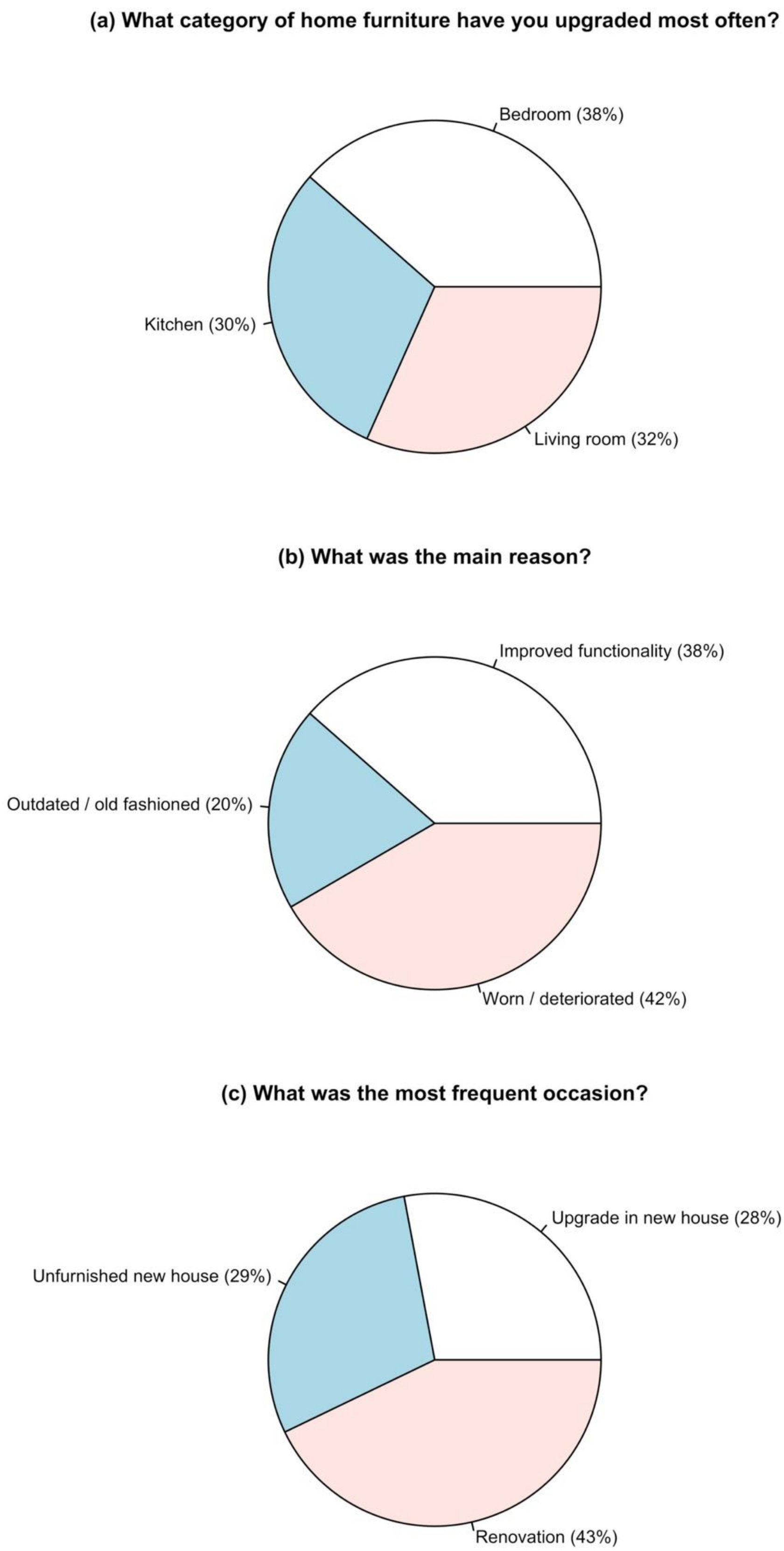


Figure 7. Results of asking respondents which category of furniture they update most often (a), for what reason (b), and on what occasion (c)

The frequency people change their home furniture may depend on a complexity of factors, including economic and social factors. In Fig. 8, it can be observed that the respondents reported they changed the furniture most often between 6 and 10 years, regardless of furniture type.

Therefore, a wide category of respondents has changed their kitchen furniture more often than their bedroom furniture or living room furniture. Around 53% (85 respondents) have changed their kitchen furniture every 6-10 years (Fig. 8, a) and a smaller number of respondents have changed bedroom and living room furniture every 6-10 years, around 38% (61 respondents) and 41% (66 respondents) in each case (Fig. 8, b and c).

A majority of respondents have changed their furniture every 10 years or less. Therefore, most of the respondents (around 72%) have changed their kitchen furniture every 10 years or less (around 19% answered ‘every 5 years or less’ and approximately 53% answered ‘every 6-10 years’). Similarly, a majority of respondents (almost 67%) changed their bedroom furniture every 10 years or less (around 29% gave the response ‘every 5 years or less’ while approximately 38% answered ‘every 6-10 years’). A slightly smaller majority of respondents (around 62%) changed their living room furniture every 10 years or less (approximately 21% answered ‘every 5 years or less’, around 41% ‘every 6-10 years’). In the case of each type of furniture, a small minority of respondents (1%-3%) answered that they keep their furniture for 31 years or longer.

An even smaller group (approximately 35%, or 56 respondents) have changed their living room furniture less frequently, only every 11-30 years (Fig. 8, c).

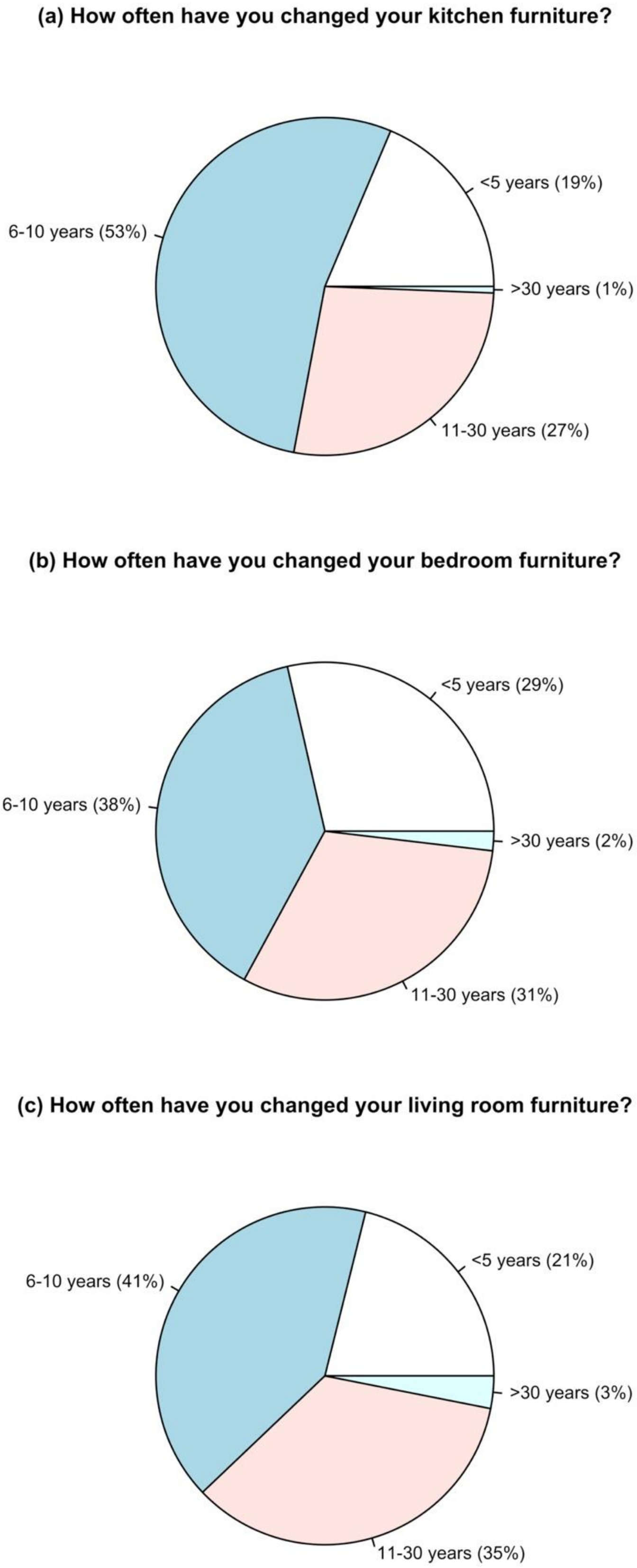


Figure 8. Results of asking respondents about the frequency with which their kitchen (a), bedroom (b), and living room (c) furniture is changed

Most of the respondents (84%, 135 respondents, Fig. 9, a) prefer to sell or donate their used furniture when upgrading to new furniture, whereas the remaining 16% (26 respondents) preferred to send it to landfill. From the point of view of carbon sequestration in HWP, to sell or donate is a good thing, because the carbon that is sequestered into the wood will be kept in this form for longer, and therefore, the half-life of HWP is prolonged.

The decision to send the used furniture to landfill or to sell/donate seems to be influenced by the type of raw material (Fig. 9, b). A larger share of respondents (47%, 76 respondents) reported that they are “definitely” or “probably” influenced by the raw material used in furniture in their decision, compared to those responding: “definitely not” or “probably not” influenced (32%, 52 respondents). The lowest number of respondents (16 respondents) were very certain that the type of raw material does not influence their decision. This result could be either reflected by the economic residual value of the used furniture or by the awareness of the respondents for a climate-responsible behaviour (i.e. a behaviour that has climate-friendly consequences). The relatively large proportion of respondents that reported they are not influenced in their decision by the type of raw material suggest that people are not very much aware of the fact that carbon dioxide remain sequestered in wood products. These respondents could be either people who sell/donate the used furniture regardless of their residual value and regardless of their climate impact, or people who send the furniture to landfill, again regardless of its value of climate impact.

Solid wood seems to be the most abundant raw material in the furniture of respondents. Around 29% of respondents (47 persons) reported that solid wood is the most important wooden raw material in their home furniture (Fig. 9, c). However, MDF comes very close to solid wood (26%, 42 respondents), and a relatively large proportion of respondents that did not know which raw material is the most abundant in their furniture (27%, 43 respondents).

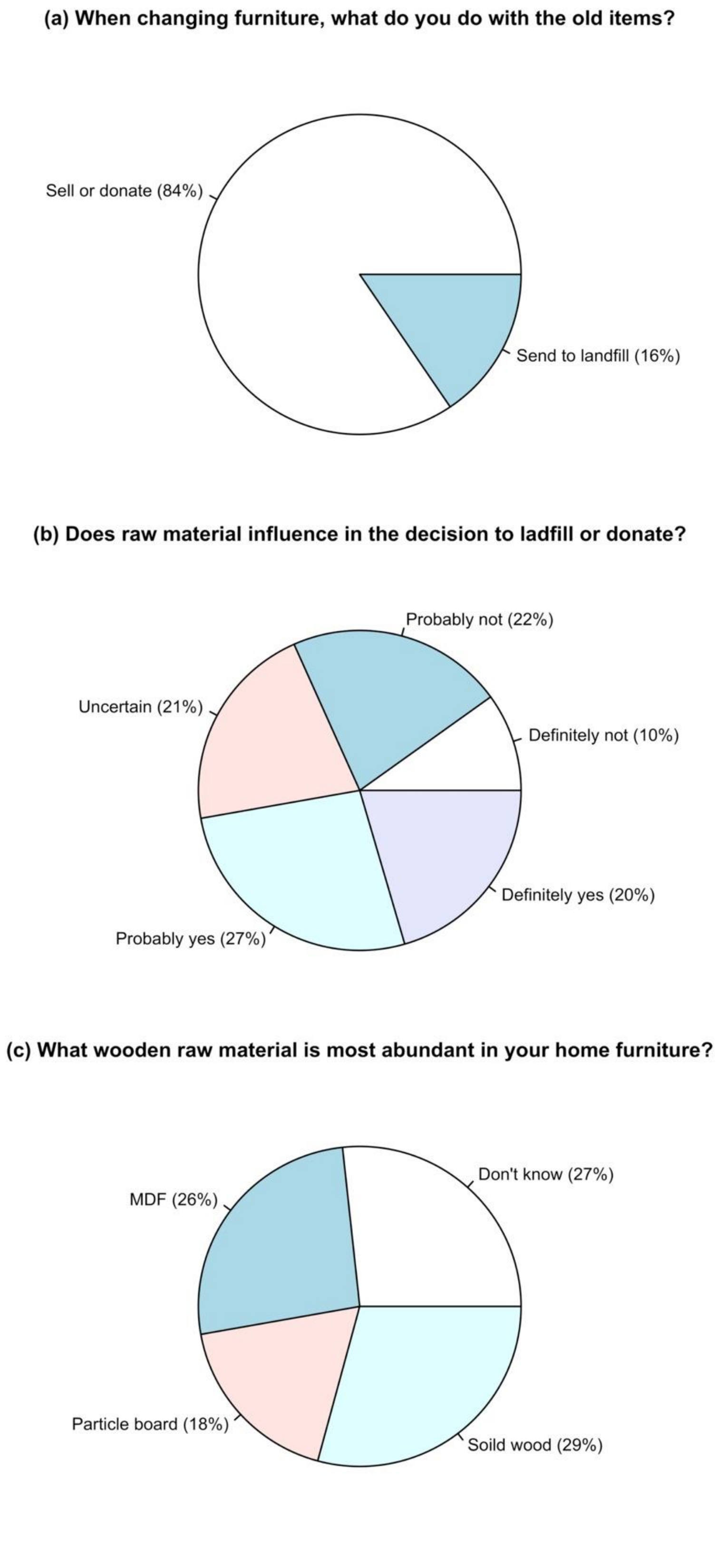


Figure 9. Results of asking respondents about what they do with the old furniture (a), whether the raw material influences her/his decision to send to landfill or donate/sell the furniture (b), and which raw material is the most abundant in their current furniture (c)

A majority of the respondents (57%, 92 respondents) declared they are interested in the raw material when purchasing new furniture. Only 6% of the respondents were absolutely sure that they are not interested in the raw material. The other 20% declared they are probably not interested in the raw material, therefore a total of 26% declared themselves not interested in the raw material (Fig. 10, a).

However, around 13% of respondents (21 persons) were not interested in wooden raw materials when answering the question ‘Which wooden raw material would you prefer?’ (Fig. 10, b). The largest share of respondents (around 63%, 101 respondents) prefer solid wood as a wooden raw material. Approximately 15% of respondents (24 respondents) prefer MDF, whereas about 9% (15 respondents) prefer particle board (Fig.10, b).

Quality was the most important characteristic taken into account when purchasing new furniture, with approximately 37% of respondents (60 persons) expressing this view (Fig. 10, c). Price came second on the preferences of respondents with about 24% (39 persons), followed by ‘practicality’ (about 21% of respondents) and ’design’ (about 18% of respondents) (Fig. 10, c).

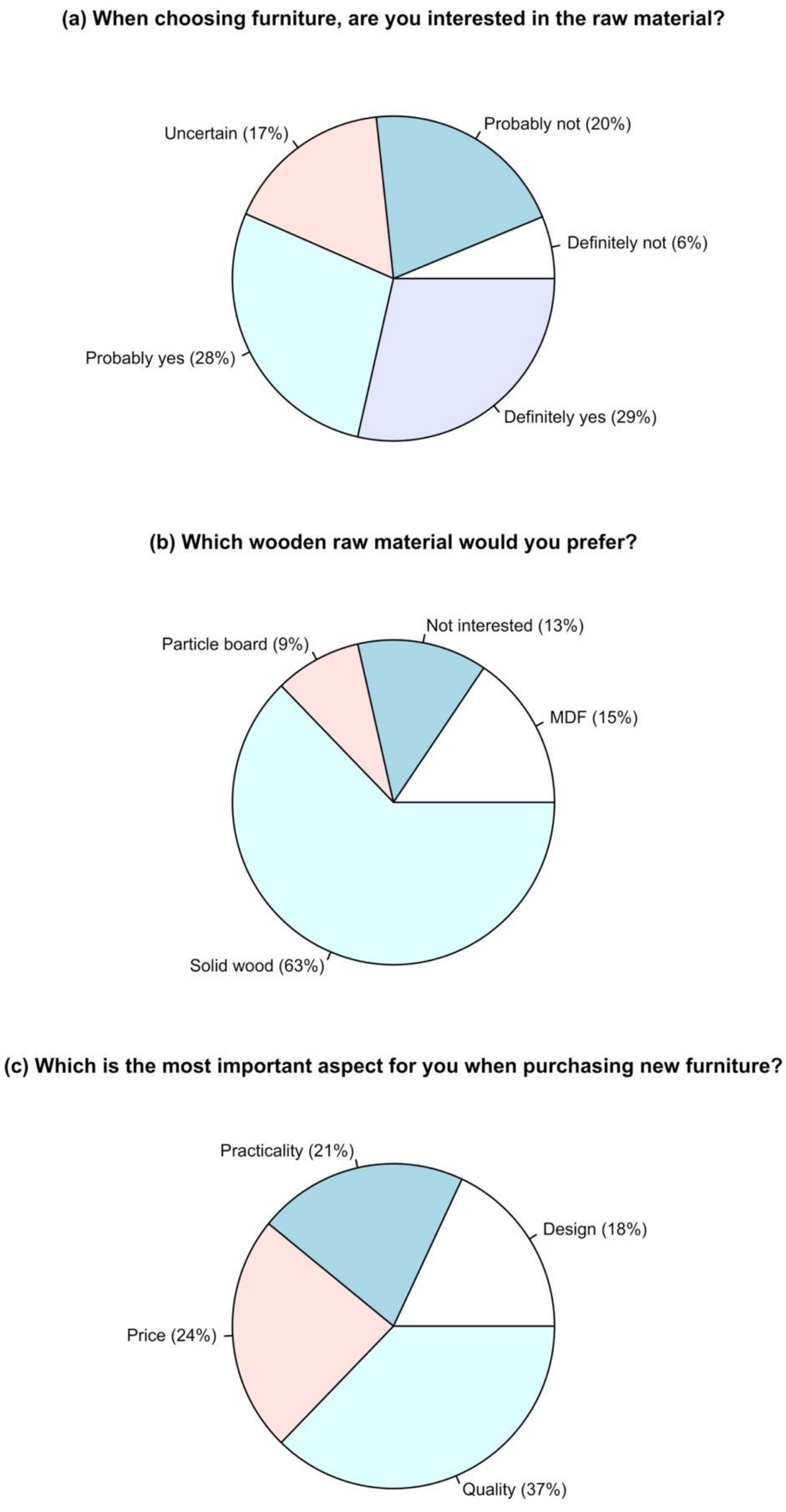
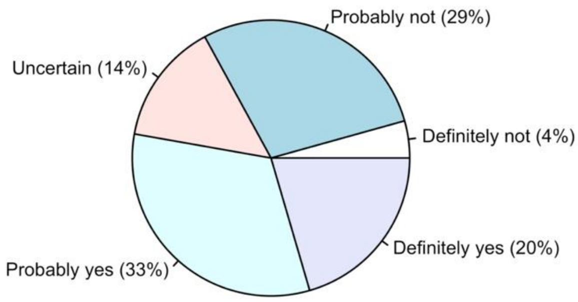


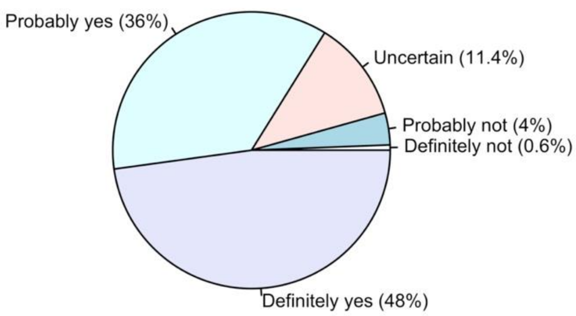
Figure 10. Results of asking respondents about their interest in the raw material (a), the preference of wooden raw material (b), and the most important aspect when purchasing new furniture (c)

Further, the respondents were introduced into a scenario, to find if an increase in income would change their usual habits. The results show that approximately half of the sample (53%, 85 respondents) would probably and change their furniture more often if there were a significant increase in their income. Only 53 respondents (33%) declared they would not change their furniture if experiencing an income increase (Fig. 11, a).

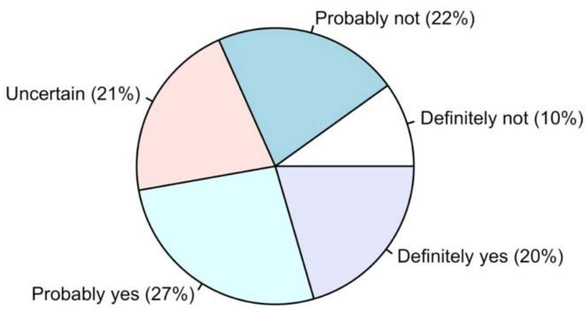
(a) Would a significant increase in income make you change the furniture more often?



(b) Would you choose climate-friendly raw materials?



(c) Would you keep the furniture in use for a longer time?



(d) Would you buy used furniture?

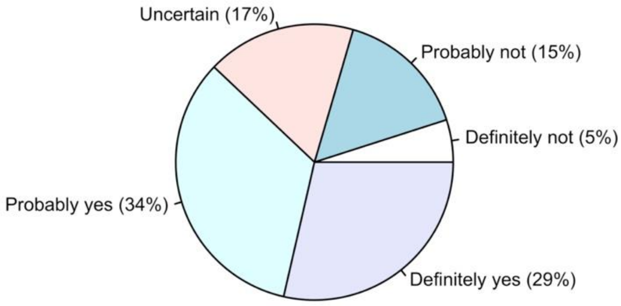


Figure 11. Results of asking respondents about their willingness to change furniture more often given a higher income (a), to select more climate-friendly raw material (b), to keep furniture for longer (c), and to buy used furniture (d)

Most respondents (84%, 135 respondents) would choose climate-friendly raw materials for their new furniture, showing therefore, solidarity and commitment in the fight against climate change. There was only one response stating that would not use climate-friendly raw material, and another 6 respondents declaring that they would probably not use climate-friendly raw materials (Fig. 11, b).

When asked whether they are willing to keep the furniture for a longer time if their action would help fight climate change, many of the respondents said they are (approximately 47%, 76 respondents), however, a small proportion were not willing to do that (around 10%, 16 respondents) (Fig. 11, c). Instead, many respondents (63%, 101 respondents) were willing to buy used furniture (approximately 34% of respondents answered, 'Probably yes' and around 29% of respondents 'Definitely yes') (Fig. 11, d).

4.1.2 Correlations

The Likert scale response type was used whenever possible since this type of response permitted the use of parametric analysis. Therefore, for questions using Linkert scale responses only the correlation plot result is presented in Fig. 12.

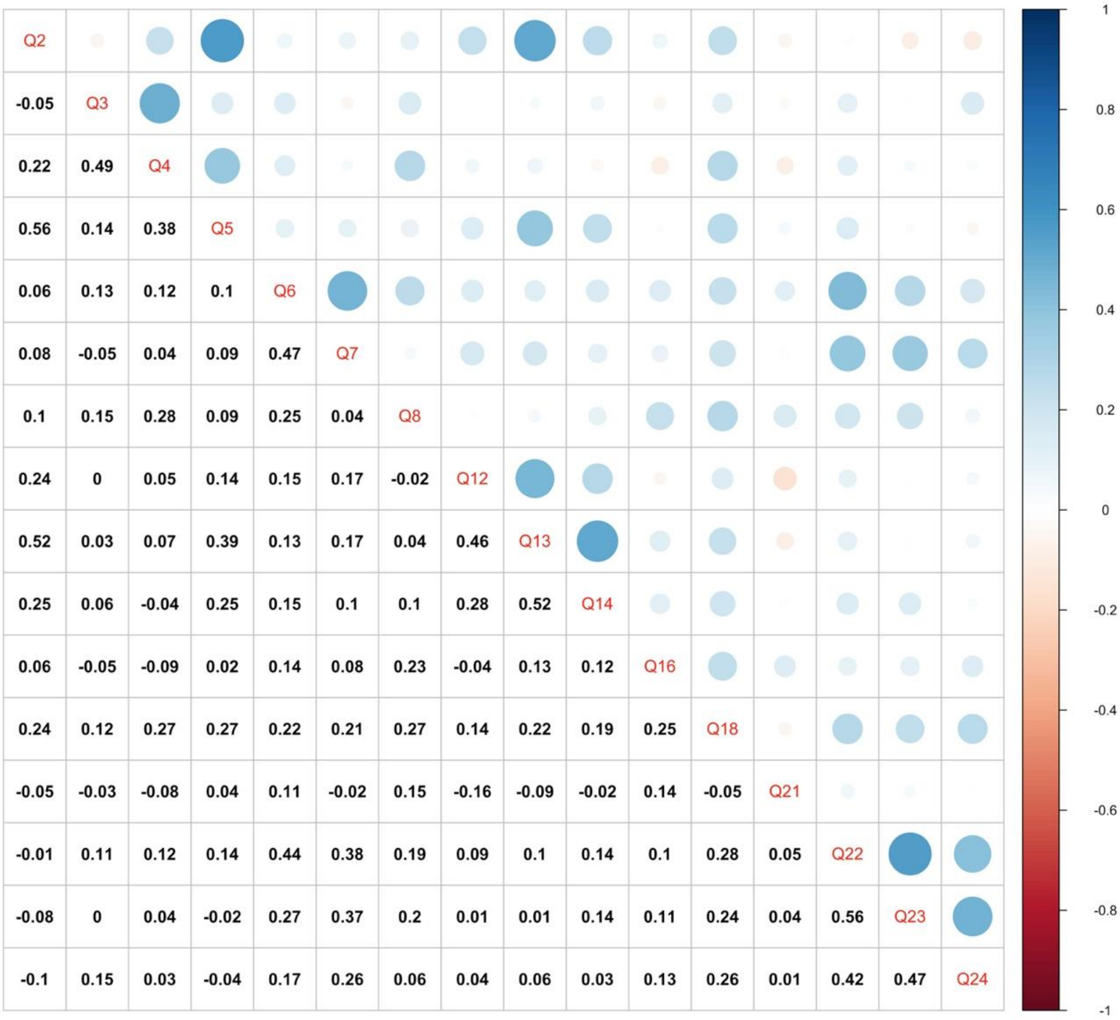


Figure 12. Correlation plot (presented only for those questions using Likert scale answers) Note: For Q2 to Q24, see Section #3. The size of the bubble and the intensity of the colour show the extent of the correlation between responses (the smaller the bubble, the lower the correlation and the larger the bubble, the greater the correlation). However, the correlation coefficients corresponding to each bubble can be found diagonally opposite, under the diagonal axis. When it is blue, the correlation is positive and when it is brown, the correlation is negative.

Furthermore, these correlations were tested using both parametric and non-parametric approaches. Out of 120 combinations presented in Fig. 12, 69 combinations have been identified that showed a correlation coefficient (r) larger than 0.1 and which are presented in Table 17.

In Table 17 the test value and p-value for each combination and each type of test are presented. When non-parametric correlation tests were used (i.e. Spearman and Kendal), out of the 69 combinations for which the correlation coefficient was larger than 0.1, there were 44 combinations with statistically significant correlations ($p < 0.05$).

In Table 17 we can see all correlation tests (Question A vs. Question B) for correlations with $r > 0.1$. Moreover, the obtained correlation results are presented in Fig. 12 and the significance of these correlations are shown in Table 17.

Table 17. Correlation tests (Question A vs. Question B) for correlations $r > 0.1$ in Fig 12. Note: Three types of test have been used: Pearson (parametric), Spearman (non-parametric) and Kendal (non-parametric). The p-value shows the probability that null hypothesis ($r = 0$) is true. If $p < 0.05$ the null hypothesis is rejected and can be concluded that the correlation is significant.

Responses tested		R	Pearson		Spearman		Kendal	
Question A	Question B		t-value	p-value	S	p-value	Z	p-value
Q#2	Q#4	0.22	2.852	0.0049	516900	0.0221	2.390	0.0168
	Q#5	0.56	8.650	5.3e-15	287710	3.0e-16	7.416	1.2e-13
	Q#12	0.24	3.246	0.0014	529730	0.0023	3.063	0.0021
	Q#13	0.52	7.441	5.9e-12	325800	4.0e-13	6.917	4.6e-12
	Q#14	0.25	3.504	0.0005	499340	0.0003	3.611	0.0003
	Q#18	0.24	3.015	0.0029	532940	0.0028	2.924	0.0034
Q#3	Q#4	0.49	6.892	1.3e-10	314440	2.2e-11	6.362	2.0e-10
	Q#5	0.14	1.823	0.0701	581130	0.0370	2.080	0.0375
	Q#6	0.13	1.633	0.1043	644060	0.3509	0.937	0.3488
	Q#8	0.15	1.951	0.0528	588980	0.0523	1.917	0.0551
	Q#18	0.12	1.495	0.1368	619880	0.1697	1.349	0.1771
	Q#22	0.11	1.441	0.1515	656560	0.4803	0.713	0.4755
	Q#24	0.15	1.714	0.0884	629340	0.2298	1.236	0.2161
Q#4	Q#5	0.38	5.088	1.0e-06	414340	1.0e-05	4.296	1.7e-05
	Q#6	0.12	1.522	0.1299	569220	0.2126	1.252	0.2104
	Q#8	0.28	3.553	0.0005	466750	0.0009	3.301	0.0009
	Q#18	0.27	3.490	0.0006	474650	0.0016	3.128	0.0017

	Q#22	0.12	1.461	0.1460	576900	0.2735	1.085	0.2776
Q#5	Q#13	0.39	5.075	1.1e-06	439070	1.4e-06	4.663	3.1e-06
	Q#14	0.25	3.140	0.0020	535430	0.0033	2.911	0.0035
	Q#18	0.27	3.631	0.0003	502100	0.0003	3.517	0.0004
	Q#22	0.14	1.683	0.0942	611280	0.1259	1.532	0.1255
Q#6	Q#7	0.47	7.254	1.6e-11	383350	2.3e-09	5.719	1.1e-08
	Q#8	0.25	2.979	0.0033	525510	0.0017	3.089	0.0020
	Q#12	0.15	2.215	0.0281	592270	0.0602	1.873	0.0609
	Q#13	0.13	2.092	0.0379	579820	0.0349	2.114	0.0344
	Q#14	0.15	2.369	0.0190	568990	0.0209	2.312	0.0207
	Q#16	0.14	1.342	0.1814	619350	0.1667	1.383	0.1666
	Q#18	0.22	2.400	0.0175	568870	0.0207	2.306	0.0210
	Q#21	0.11	1.483	0.1401	630690	0.2396	1.197	0.2312
	Q#22	0.44	5.938	1.7e-08	410700	6.9e-08	5.191	2.1e-07
	Q#23	0.27	3.677	0.0003	508830	0.0005	3.403	0.0006
	Q#24	0.17	2.568	0.0111	552620	0.0089	2.626	0.0086
Q#7	Q#12	0.17	2.466	0.0147	578880	0.0334	2.155	0.0311
	Q#13	0.17	2.542	0.0119	565520	0.0175	2.380	0.0172
	Q#14	0.1	1.643	0.1022	629170	0.2287	1.219	0.2225
	Q#18	0.21	2.315	0.0218	577250	0.0310	2.159	0.0307
	Q#22	0.38	5.145	7.7e-07	401850	2.4e-08	5.404	6.4e-08
	Q#23	0.37	4.977	1.6e-06	458770	9.9e-06	4.422	9.7e-06
	Q#24	0.26	3.625	0.0003	495290	0.0002	3.729	0.0002
Q#8	Q#14	0.1	1.067	0.2873	639270	0.3078	1.019	0.3081
	Q#16	0.23	2.983	0.0032	519380	0.0011	3.256	0.0011
	Q#18	0.27	3.610	0.0004	508840	0.0006	3.418	0.0006
	Q#21	0.15	1.895	0.0598	599440	0.0805	1.764	0.0776
	Q#22	0.19	2.389	0.0180	583680	0.0415	2.049	0.0403
	Q#23	0.2	2.450	0.0153	591800	0.0590	1.917	0.0551
Q#12	Q#13	0.46	6.600	5.8e-10	382660	2.1e-09	5.792	6.9e-09
	Q#14	0.28	3.823	0.0002	499990	0.0003	3.621	0.0003
	Q#18	0.14	1.597	0.1122	607310	0.1089	1.618	0.1055
	Q#21	- 0.16	-1.775	0.0777	797770	0.0627	-1.871	0.0612
Q#13	Q#14	0.52	7.900	4.3e-13	323450	2.6e-13	6.890	5.5e-12
	Q#16	0.13	1.235	0.2184	623940	0.1939	1.286	0.1981

	Q#18	0.22	2.612	0.0098	561290	0.0141	2.431	0.0150
	Q#22	0.1	1.392	0.1658	630540	0.2385	1.172	0.2412
Q#14	Q#16	0.12	1.046	0.2971	624970	0.2004	1.284	0.1989
	Q#18	0.19	2.215	0.0281	574890	0.0277	2.186	0.0288
	Q#22	0.14	1.901	0.0590	594050	0.0648	1.855	0.0635
	Q#23	0.14	1.895	0.0598	575170	0.0281	2.243	0.0248
Q#16	Q#18	0.25	3.199	0.0016	519980	0.0012	3.350	0.0008
	Q#21	0.14	1.778	0.0773	605040	0.1000	1.717	0.0858
	Q#22	0.1	1.136	0.2575	638110	0.2979	1.052	0.2924
	Q#23	0.11	1.313	0.1909	630520	0.2384	1.174	0.2400
	Q#24	0.13	1.699	0.0911	590490	0.0558	1.912	0.0558
Q#18	Q#22	0.28	3.498	0.0006	521210	0.0013	3.217	0.0012
	Q#23	0.24	2.825	0.0053	521690	0.0014	3.191	0.0014
	Q#24	0.26	2.957	0.0035	526890	0.0019	3.114	0.0018
Q#22	Q#23	0.56	8.483	1.4e-14	304770	8.9e-15	7.383	1.5e-13
	Q#24	0.42	5.777	3.8e-08	395510	1.1e-08	5.601	2.1e-08
Q#23	Q#24	0.47	7.090	4.1e-11	312020	3.4e-14	7.228	4.9e-13

Although the parametric correlation (i.e. Pearson) identified the same number of pairs with significant correlation ($p<0.05$), these pairs did not entirely match the non-parametric tests. The reason the non-parametric correlations did not entirely match the parametric correlations is due to the fact that non-parametric correlation uses ranks instead of actual values of observed data. Because of that, the computed p-values were slightly different. There were two pairs for which parametric tests indicated a significant correlation, but non-parametric tests did not (Q#6 vs. Q#12 and Q#8 vs. Q#23) and two pairs for which non-parametric tests indicated a significant correlation, whereas parametric tests did not (Q#3 vs. Q#5; Q#14 vs. Q#23). These cases are highlighted in blue in Table 17.

On the other hand, it was expected that responses to the question 'How often have you changed your kitchen furniture?' would show a correlation with the question 'When choosing furniture, are you interested in the raw material?', ($r = 0.14$, $p > 0.05$, Q#12 vs. Q#18). This was a surprising outcome because it had been expected that those who change their kitchen furniture more often would be interested in the raw material used for the new furniture purchased.

Age of the respondent was strongly related to whether the respondent owned a house or not ($r = 56$, $p < 0.05$) and with the level of income ($r = 0.22$, $p < 0.05$). Since the correlations were both positive, that means the older the respondent, the higher the frequency of owning a house, and the higher the income of the respondent (Table 17, Q#2 vs. Q#5 and respectively Q#2 vs. Q#4). Furthermore, there was a significant positive correlation between the age of respondents and how often they have changed their kitchen furniture ($r = 0.24$, $p < 0.05$), bedroom furniture ($r = 0.52$, $p < 0.05$) and living room furniture ($r = 0.25$, $p < 0.05$). It shows that older respondents tend to change more often the kitchen, bedroom and living room furniture compared to young respondents (Table 17, Q#2 vs. Q#12 and Q#2 vs. Q#13 and Q#2 vs. Q#14). **Also, the age of respondents was correlated to their interest in the raw material of furniture**. Older people were more interested in the raw material compared to young people ($r = 0.24$, $p < 0.05$).

The level of education (Q#3) was significantly correlated (all three types of correlation test agreed) only with the level of income (Q#4), which was to be expected ($r = 0.49$, $p < 0.05$). However, the non-parametric correlation tests revealed that the level of education was also correlated to whether the respondent owned a house or not (Q#5). Although the parametric correlation tests showed a p-value of 0.07, which is above the threshold of 0.05, the non-parametric tests both showed a p-value lower than 0.05 ($r = 0.14$, Spearman: $p = 0.037$, Kendall: $p = 0.0375$, see Table 17, Q#3 vs. Q#5). Therefore, a higher level of education involved a greater frequency of respondents to own a house.

The level of income (Q#4) was significantly correlated with whether the respondents owned a house ($r = 0.38$, $p < 0.05$), being suggested that the higher the income the larger the share of respondents owning a house (Table 17, Q#4 vs. Q#5) which was to be expected. The level of income was also correlated with the knowledge about carbon sequestration in wooden furniture (Table 17, Q#4 vs. Q#8, $r = 0.28$, $p < 0.05$) and with the interest in the raw material (Table 17, Q#4 vs. Q#18, $r = 0.27$, $p < 0.05$). **Therefore, the higher the income, the more that people are knowledgeable/aware about the carbon sequestration in wood products and the more they are interested in the raw material of their furniture**.

Owning a house or not (Q#5, Table 17) was correlated with the frequency of changing bedroom ($r = 0.39$, $p < 0.05$) and living room ($r = 0.25$, $p < 0.05$) furniture, but also with the interest in raw material ($r = 0.27$, $p < 0.05$). The respondents owning a house tend to update their furniture (bedroom and living room) at a slower pace compared to those not owning a house (Table 17, Q#5 vs. Q#13 and Q#5 vs. Q#14) and also tend to be more interested in the raw material of their furniture (Table 17, Q#5 vs. Q#18).

The way the respondents answered to the question “In your opinion, is climate change happening?” (Table 17, Q#6) was correlated to answers for other questions. First of all, it was correlated with the responses on whether the respondents were worried about the effects of climate change (Table 17, Q#6 vs. Q#7, $r = 0.47$, $p < 0.05$), therefore people strongly agreeing that climate change is actually happening tend to be more worried about the effects of climate change. Also, people that believe the climate change is happening tend to be more knowledgeable about the contribution of harvested wood products to the carbon cycle (Table 17, Q#6 vs. Q#8, $r = 0.25$, $p < 0.05$), tend to change the furniture later (Q#6 vs. Q#13, $r = 0.13$, $p < 0.05$ and Q#6 vs Q#14, $r = 0.15$, $p < 0.05$) and tend to be more interested in the raw material from which their furniture is made (Q#6 vs. Q#18, $p = 0.22$, $p < 0.05$). Furthermore, **the respondents that believe climate change is occurring, are more willing to adopt measures that help against it.** For example, they were more willing to select a climate-friendly raw material for their furniture (Q#6 vs. Q#22, $r = 0.44$, $p < 0.05$), more willing to keep the furniture for a longer time (Q#6 vs. Q#23, $r = 0.27$, $p < 0.05$) and more willing to purchase used furniture (Q#6 vs. Q#24, $r = 0.17$, $p < 0.05$), if all these measures would be proven helpful against climate change. Furthermore, because the responses to question Q#7 are correlated to those of Q#6, the Q#7 follows a similar pattern as Q#6. Therefore, the respondents that were worried about the effects of climate change tended to change their kitchen and bedroom furniture later (Table 17, Q#7 vs. Q#12, $r = 0.17$, $p < 0.05$ and Q#7 vs. Q#13, $r = 0.17$, $p < 0.05$). They were also more interested in the type of raw material when choosing their furniture (Q#7 vs. Q#18, $r = 0.21$, $p < 0.05$), were more willing to select a climate-friendly raw material for their furniture (Q#7 vs. Q#22, $r = 0.38$, $p < 0.05$), more willing to keep furniture for longer (Q#7 vs. Q#23, $r = 0.37$, $p < 0.05$) and more willing to buy used furniture (Q#7 vs. Q#24, $r = 0.26$, $p < 0.05$).

The level of knowledge/awareness about carbon sequestration in wooden furniture (Table 17, Q#8), was significantly correlated with the type of raw material when deciding if the old furniture should be sent to landfill or sold/donated (Q#16). Therefore, the greater the knowledge about carbon sequestration in wooden furniture, the greater the chance that the decision of selling/donating or landfill is influenced by the type of raw material ($r = 0.23$, $p < 0.05$). Also, **respondents that were more knowledgeable about carbon sequestration in**

wooden furniture were more interested in raw material when they are choosing their furniture (Q#8 vs. Q#18, $r = 0.27$, $p < 0.05$) and were more willing to select the most climate-friendly raw materials for their furniture if that it could help in the fight against climate change (Q#8 vs. Q22, $r = 0.19$, $p < 0.05$). The parametric correlation test (i.e. Pearson) showed that there is a significant positive correlation ($r = 0.2$, $p = 0.015$) between the level of knowledge (about carbon sequestration in wooden furniture) and the willingness of respondents to keep the furniture longer (Table 17, Q#8 vs Q#23). However, the non-parametric tests did not confirm the parametric results. The p-values for Spearman and Kendall tests were just above the 0.05 threshold ($p = 0.059$ and $p = 0.055$ respectively).

Changing the furniture more rapidly (i.e. at a faster pace) was linked to a higher interest in the raw material. Therefore, the frequency of changing the bedroom and living room furniture (Q#13 and Q#14) was significantly positively correlated to the level of interest in raw materials when they are choosing their furniture (Table 17, Q#13 vs. Q#18, $r = 0.22$, $p < 0.05$ and Q#14 vs. Q#18, $r = 0.19$, $p < 0.05$). Frequency of changing kitchen furniture (Q#12) was also correlated to the frequency of changing bedroom (Q#13) and living room furniture (Q#14), suggesting that **people who have changed their furniture frequently also tended to change all furniture in their house more often** (Table 17, Q#12 vs. Q#13, $r = 0.46$, $p < 0.05$; Q#12 vs. Q#14, $r = 0.28$, $p < 0.05$; Q#13 vs. Q#14, $r = 0.52$, $p < 0.05$). Furthermore, the frequency in changing living room furniture was correlated to the willingness of the respondents to keep the furniture longer in order to help in the fight against climate change (Table 17, Q#14 vs. Q#23). However, this correlation was significant only under non-parametric tests ($r = 0.14$, Spearman $p = 0.028$, Kendall $p = 0.025$) and was just at the limit for the Pearson correlation test ($p = 0.059$).

Whether the type of raw material influenced or not the decision if the old furniture should be sent to landfill or sold/donated was correlated to the interest in raw materials (Table 17, Q#16 vs. Q#18). Respondents that were more influenced in their decision by the type of raw materials showed more interest in raw materials when they are choosing their new furniture ($r = 0.25$, $p < 0.05$). Furthermore, the level of interest in raw materials (Q#18) was significantly correlated to the respondent’s willingness to contribute to the fight against climate change. **The respondents that were more interested in raw materials when they are choosing new furniture were more willing to select the most climate-friendly raw materials** (Table 17, Q#18 vs. Q#22, $r = 0.28$, $p < 0.05$), were more willing to keep the furniture longer (Table

17, Q#18 vs. Q#23, r = 0.24, p < 0.05) and were also more willing to buy used furniture (Table 17, Q#18 vs. Q#24, r = 0.26, p < 0.05). There was a significant correlation between selecting the most climate-friendly raw materials and keeping the current furniture longer (Q#22 vs. Q#23, r = 0.56, p < 0.05) and willingness to buy used furniture (Q#22 vs. Q#24, r = 0.42, p < 0.05) and also between willingness to keep the furniture longer and willingness to buy used furniture (Q#23 vs. Q#24, r = 0.47, p < 0.05).

Therefore, a majority of people would definitely/probably both choose environmentally friendly raw materials and buy used furniture in order to help the environment. **The selection of raw material for their furniture becomes important when the respondents know that it could help in the fight against climate change.**

As was shown in Chapter 3.4, the survey gathered socio-economic characteristics such as gender, age, education level, and income. In Fig. 13, there are graphs with the percentages of those who responded in a certain way, and with the proportion of males and females that participated in this study. Therefore, based on the responses given by women or men, the following conclusion can be drawn.

Stern et al. (1993) assert that differences in men's and women's value orientations justify gender differences in environmental concern. Therefore, in this study **females reported stronger worries on climate change effects, compared to males** (Fig. 13, a).

On average, women and men differ in their knowledge and perceptions of science. In general, men demonstrate greater scientific knowledge and scientific literacy than do women (e.g., Arcury et al. 1987; Hayes 2001; Miller 2007). Therefore, the survey showed that men were self-assessed as being more knowledgeable about carbon sequestration in wooden furniture compared to women (Fig. 13, b), showing a correlation coefficient r = 0.23.

Both men and women responded in a relatively similar manner when asked what the main reason for the furniture update would be and what do they do with the old items when changing the furniture (Fig. 13, c and d).

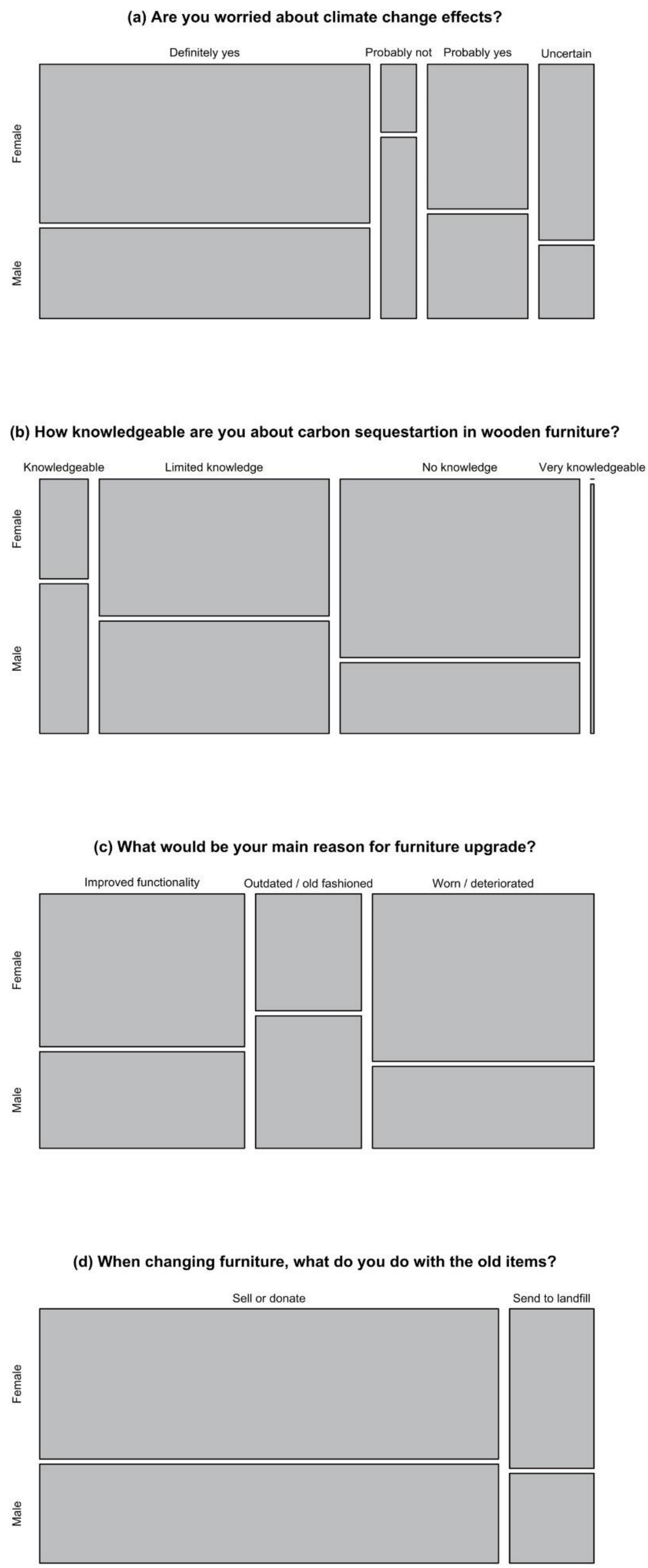
The answer 'Uncertain' to the question 'When choosing furniture, are you interested in the raw material?' tends to be given more often by women than men (Fig. 13, e).

When purchasing new furniture, the female respondents seem to be more interested in design compared to men (Fig. 13, f).

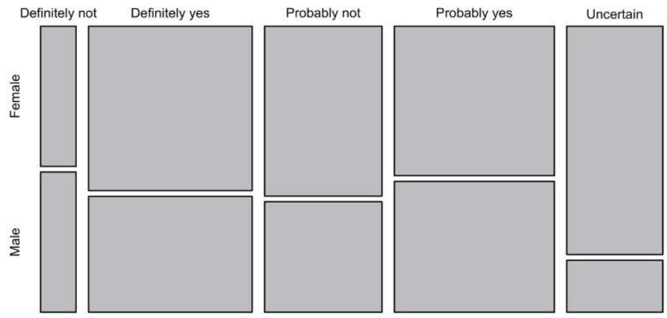
The answer ‘Definitely not’ to the question ‘If you experienced a significant increase in your income, would you change your furniture more often than you currently do?’ tends to be given more often by women than men (Fig. 13, g).

In general, women are more concerned about general environmental issues than are men (Blocker and Eckberg 1997; Davidson and Freudenburg 1996). Therefore, the answer ‘probably not’ tends to be given more often by women than by men to the question ‘If the selection of raw material could help in the fight against climate change, would you consider selecting the most climate-friendly raw material?’ (Fig. 13, h).

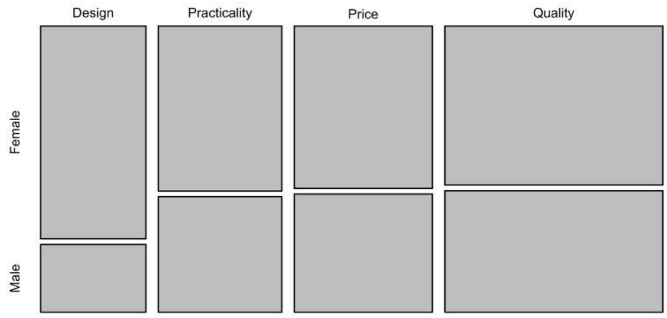
No important differences between males and females were observed for the other questions.


(a) Are you worried about climate change effects?
Definitely yes
Probably not
Probably yes
Uncertain
Female
Male
(b) How knowledgeable are you about carbon sequestartion in wooden furniture?
Knowledgeable
Limited knowledge
No knowledge
Very knowledgeable
Female
Male
(c) What would be your main reason for furniture upgrade?
Improved functionality
Outdated / old fashioned
Worn / deteriorated
Female
Male
(d) When changing furniture, what do you do with the old items?
Sell or donate
Send to landfill
Female
Male

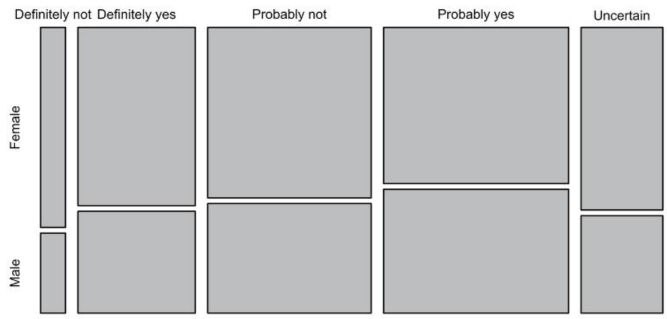
(e) When choosing furniture, are you interested in the raw material?



(f) What is the most important aspect for you when purchasing new furniture?



(g) Would you change your furniture more often?



(h) Would you consider selecting the most climate-friendly raw material?

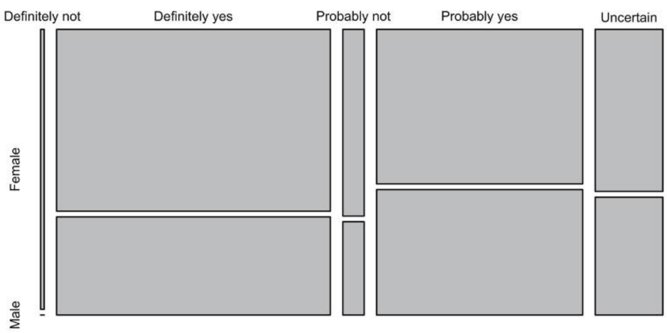


Figure 13. The proportion of responses by gender

4.2 Evaluation of Kitchen Furniture Carbon Content

The standardised carbon content in kitchen furniture (expressed per linear metre of furniture) depends on the kitchen design and on raw materials used (Table 18).

Each of the GHGs covered by the Kyoto Protocol has a different potential impact on global warming. Their combined contributions can be translated into a single unit CO_2 equivalent, and this is the most accepted method of reporting their impact. The evaluation of carbon content for kitchen furniture was expressed in kg per linear metre (kg/m) of furniture. The reason this metric was used instead of kg/m^3, has to do with its simplicity, being much easier for ordinary people to understand the metric. Another reason is because the height and the depth of kitchen furniture are relatively standardised across the industry. Consequently, the length of the furniture is the one parameter that drives and correlates with the volume of furniture, and therefore the length was used a surrogate metric for furniture volume.

For the base units, the equivalent CO_2 (CO_2e) content varied between 73.66 kg/m and 81.00 kg/m when MDF was used for front door, between 77.11 kg/m and 83.82 kg/m when using solid oak, and between 77.40 kg/m and 85.95 kg/m when using chipboard doors. For the wall units, the carbon content varied between 49.13 kg/m and 55.15 kg/m when using MDF, between 51.33 and 55.95 kg/m when using solid oak, and between 50.93 kg/m and 58.04 kg/m when using chipboard for front doors (Table 18).

Table 18. Seven kitchen designs with MDF doors, seven designs with oak doors and seven with chipboard doors, dimensions, dry biomass calculation, carbon content of each kitchen design, carbon per metre content and the equivalent CO_2 content.

Model No:	Cabinet type	Door raw material	Length (m)	Depth (m)	No of cabinets	Volume of dry biomass (m^3)	Carbon (kg)	Carbon (kg/m)	CO_2e (kg/m)
1a	Base units	MDF	8.400	0.565	11	0.55	185.35	22.06	80.89
2a	Base units	MDF	3.700	0.565	6	0.26	80.48	21.75	79.75
3a	Base units	MDF	3.700	0.565	4	0.24	74.34	20.09	73.66
4a	Base units	MDF	3.700	0.565	6	0.27	81.73	22.09	81.00
5a	Base units	MDF	3.700	0.565	5	0.25	77.79	21.02	77.07
6a	Base units	MDF	3.700	0.565	5	0.26	79.90	21.59	79.16

7a	Base units	MDF	3.700	0.565	5	0.25	78.06	21.10	77.37
8a	Base units	Oak	7.200	0.565	10	0.45	151.44	21.03	77.11
9a	Base units	Oak	3.850	0.565	6	0.26	88.02	22.86	83.82
10a	Base units	Oak	3.850	0.565	6	0.25	85.70	22.26	81.62
11a	Base units	Oak	3.850	0.565	6	0.25	84.54	21.96	80.52
12a	Base units	Oak	3.850	0.565	6	0.25	85.18	22.12	81.11
13a	Base units	Oak	3.850	0.565	6	0.24	82.23	21.36	78.32
14a	Base units	Oak	3.850	0.565	6	0.26	87.50	22.72	83.31
15a	Base units	Chipboard	6.500	0.565	9	0.42	143.29	22.04	80.81
16a	Base units	Chipboard	4.950	0.565	6	0.31	104.50	21.11	77.40
17a	Base units	Chipboard	4.950	0.565	6	0.31	105.93	21.40	78.47
18a	Base units	Chipboard	4.950	0.565	7	0.32	109.98	22.22	81.47
19a	Base units	Chipboard	4.950	0.565	8	0.34	116.01	23.43	85.91
20a	Base units	Chipboard	4.950	0.565	7	0.32	109.62	22.15	81.22
21a	Base units	Chipboard	4.950	0.565	8	0.34	116.04	23.44	85.95
1b	Wall units	MDF	5.100	0.330	10	0.20	68.38	13.40	49.13
2b	Wall units	MDF	2.550	0.330	6	0.11	36.91	14.47	53.06
3b	Wall units	MDF	2.550	0.330	5	0.11	36.12	14.16	51.92
4b	Wall units	MDF	2.500	0.330	6	0.10	34.47	13.79	50.56
5b	Wall units	MDF	2.550	0.330	5	0.11	37.23	14.60	53.53
6b	Wall units	MDF	2.550	0.330	6	0.11	37.12	14.56	53.39
7b	Wall units	MDF	2.500	0.330	6	0.11	37.59	15.04	55.15
8b	Wall units	Oak	4.680	0.330	10	0.21	69.51	14.85	54.45
9b	Wall units	Oak	2.380	0.330	6	0.11	36.31	15.26	55.95
10b	Wall units	Oak	2.540	0.330	5	0.11	37.82	14.89	54.60
11b	Wall units	Oak	2.600	0.330	4	0.11	36.96	14.22	52.14
12b	Wall units	Oak	2.540	0.330	5	0,11	38.56	15.18	55.66
13b	Wall units	Oak	2.540	0.330	5	0.11	35.56	14.00	51.33
14b	Wall units	Oak	2.600	0.330	5	0.11	37.72	14.51	53.20
15b	Wall units	Chipboard	4.240	0.330	9	0.18	59.38	14.00	51.33
16b	Wall units	Chipboard	3.540	0.330	8	0.15	55.39	15.65	57.38
17b	Wall units	Chipboard	3.500	0.330	8	0.15	48.60	13.89	50.93
18b	Wall units	Chipboard	3.540	0.330	7	0.15	50.42	14.24	52.21
19b	Wall units	Chipboard	3.500	0.330	7	0.16	51.75	14.78	54.19
20b	Wall units	Chipboard	3.500	0.330	7	0.15	50.59	14.45	52.98
21b	Wall units	Chipboard	3.500	0.330	9	0.17	55.43	15.83	58.04

As shown in Table 18, the highest value (highlighted in blue) of carbon per metre of base units for the three categories of kitchen models was as follows: 22.09 kg/m for Model 4a (more base units such as two base units of 500 mm and one base unit of 400 mm with door and drawer); 22.86 kg/m for Model 9a (two base units of 500 mm with four drawers); 23.44 kg/m for Model 21a (two base units of 400 mm and one base units of 600 mm with three drawers).

Furthermore, the highest value (highlighted in blue) of carbon per metre of wall units for the three categories of kitchen models was as follows: 15.04 kg/m for Model 7b (two wall units of 500 mm with shelf and no door but with back panels made of chipboard); 15.26 kg/m for

Model 9b (three wall units of 600 mm with door and two shelves); 15.83 kg/m for Model 21b (two wall units of 300 mm).

Analysing the data presented in Table 18, the mean CO_2e content regardless of door raw material was 80.28 kg/m for the base units and 53.39 kg/m for the wall units (Table 19). For the base units, 79% of the mean carbon content variance was produced by the variability in furniture design and only 21% is caused by door raw material. For the wall units, the proportion of variance caused by differences between different kitchen designs was larger, accounting for 99% of total variance of the mean carbon content, whereas the effect of door raw material was almost inexistent (i.e. only 1% of variance was caused by differences between door raw materials).

The mean carbon content varied only slightly with the door raw material. The mean CO_2e content for base units varied between 79.18 kg/m when MDF was used as door raw material to 81.06 kg/m for chipboard doors (Table 19). For the wall units, the differences were even smaller, the mean CO_2e content for wall units being 53.36 kg/m when using solid oak as raw material for doors, and 53.41 kg/m when using solid wood or chipboard (Table 19).

Table 19. The mean CO_2e content, by type of cabinet and door raw material, and the variance partition coefficient (VPC) for kitchen design and door raw material.

Cabinet type	Overall mean carbon content (μ, Eq. 18, in kg CO_2e/m)	VPC_{design}	VPC_{door}	Door raw material	Mean CO_2e content by raw material (kg CO_2e/m)
Base units	80.28	0.79	0.21	MDF	79.18
				Solid oak	80.61
				Chipboard	81.06
Wall units	53.39	0.99	0.01	MDF	53.40
				Solid oak	53.36
				Chipboard	53.41

Palma et al. (2017) estimated that the carbon storage in kitchen furniture units of Western Europe (16 countries) was approximately 15 million t C in 2013. The assumption for this estimation was that each kitchen unit used an average of around 0.70 m^3 of wood (with an average of 11 kitchen cabinets). Furthermore, the material volume of particleboard and sawn wood for one kitchen cabinet is estimated at 0.0375 m^3. The average volume of wood used in kitchen furniture production in 2013 was 3,472,681.60 m^3/year (Europe value – the furniture industries sector) and the average lifetime of kitchen furniture is 18 years. European consumers buy a new kitchen every 15-20 years on average. These are related to moving to a new home and various other factors, such as the desire for a new design or renovation.

Showing some similarity with the work of Palma, these current studies show that a model of kitchen furniture with 11 kitchen cabinets as base unit and 10 kitchen cabinets as wall unit contains 0.55 m^3 of dry biomass as base units and 0.20 m^3 of dry biomass as wall units, a total of 0.75 m^3 of dry biomass. The material volume of MDF and chipboard for one base unit of 400 mm with MDF doors is $(5.11 + 19.50) \times 10^{-3} = 0.02461$ m^3. Also, for one wall unit of 400 mm with MDF doors the material volume of MDF and chipboard is $(5.11 + 14.56) \times 10^{-3} = 0.01967$ m^3. Therefore, a base unit and wall unit each of width 400 mm and with doors made of MDF have a material volume of MDF and chipboard of 0.0442 m^3. This includes 0.0374 m^3 of dry biomass ($2.08 \times 10^{-2} + 1.66 \times 10^{-2}$). According to this study, for a majority of respondents, the main occasion for a furniture upgrade was home renovation and the principal reason was worn/deteriorated state of their old furniture.

According to Palma et al. (2017), there are data gaps in the wooden furniture sector, especially in the volume of wood used by manufacturers. Furthermore, data for the volume of wooden furniture may not actually show the existing wood volume used. The volume of harvested wood products at the tertiary level (furniture) is not constantly reported and represents an important absence within the available information. For this reason, it is difficult to quantify the total carbon pool of this sub-sector.

4.3 Discussions

The results of the first component of the research revealed important trends in how often and why respondents change or update their wooden furniture. An initial finding was the general lack of knowledge of laypeople about carbon sequestration in wooden furniture and about the link between furniture and climate change mitigation. Therefore, there is an urgent need to develop knowledge and awareness among laypeople regarding carbon sequestration in wooden furniture. Climate change mitigation relies, among other factors, on the capacity of plants to sequester CO_2 from the atmosphere through photosynthesis and store it in plant biomass. However, retaining the carbon in wooden structures for a longer time, for example in furniture, has a beneficial impact on the mitigation of atmospheric CO_2, which is the main cause of climate change. Improving awareness and knowledge of how furniture can contribute to climate change mitigation could make people more frequently adopt those behaviours which help to retain carbon in wooden biomass for longer, with a consequent positive impact on climate change mitigation. The significant correlations that were found between the level of respondents' knowledge and the decisions that they make suggest that increasing the public's level of knowledge will result in people making more climate-responsible decisions about their furniture (i.e. decisions that help to combat climate change).

Furthermore, believing in climate change seems to increase people's interest in improving their knowledge of climate change mitigation options. The results showed a significant correlation between the extent to which a respondent believes in climate change and his/her level of knowledge. Poortinga et al., (2019) confirmed that the perceptions of climate change were influenced by demographics of gender, age, and education; they also showed that there were differences between countries and therefore cannot be generalised. The significant correlation demonstrated between the perceptions of respondents, about furniture's impact on climate change, and their gender, age, education, income, and house ownership confirm **Hypothesis 1** of the study.

As shown in Chapter 4.1.2, the older the person, the more often they change their furniture and respondents aged 36–65 years were more likely to be interested in the raw materials used to make their furniture. Although more than half of the respondents do not own a property, they are likely to be interested in the raw materials used to make the furniture they choose to buy. The respondents' income is related to how interested they are in the raw material used to make their furniture.

Investigation of respondents' interest in raw material type was a key component of the questionnaire. This is because the raw material type influences not only the quantity of carbon that is sequestered in furniture, but also affects the lifetime of the product with direct consequences on climate change mitigation. People who have limited or no knowledge about carbon storage in wooden furniture responded that their decisions when choosing new furniture were influenced by the type of raw material. Therefore, it seems that people who are more knowledgeable about the impact of furniture on climate change, and who generally believe that climate change is happening, are more interested in raw materials.

The same people are more willing to adopt measures in order to help fight climate change. Strobel et al. (2017) found that there is a significant relationship between physical properties of wood material and the preference for the raw material. The varying preferences of respondents in relation to raw materials when choosing their furniture can lead to the choice of raw materials with a longer lifespan. Therefore, the preference for longer lasting raw materials (e.g. solid wood) is not necessarily linked to climate change mitigation but rather to the quality and lifespan of the product. A more resistant raw material is likely to be recycled at the end of its lifecycle, thus extending its life. Therefore, increasing the decay period of carbon is an important way to keep the carbon captured in biomass for a longer time. All these results confirm that the behaviour of people in terms of changing/upgrading their furniture is predictable, being significantly linked to other behaviours, thus confirming **Hypothesis 2** of the study.

The aim of the second component of this research was to assess the quantity of carbon dioxide that remains sequestered in kitchen furniture, and to find the sources of variability in the amount of carbon dioxide equivalent that is retained by one unit of kitchen furniture. Since the United Kingdom is ranked second after Germany in the European Union in terms of the proportion of wood volume in kitchen furniture, carbon sequestration in kitchen furniture can have a significant impact (Palma et al., 2017). It was suggested that kitchen furniture alone can contribute to the sequestration of approximately 15 million tonnes of carbon per year (Palma et al., 2017). The findings of this research are important, showing that the variability of carbon content (or carbon dioxide equivalent) in kitchen furniture carbon is mainly driven by differences in kitchen design and less so by the raw material used particularly for the front doors. These results partly confirm the **Hypothesis 3**, that kitchen design was the main driver of variability in kitchen furniture carbon content. However, the front doors influence in terms of raw material was insignificant.

The mean of equivalent carbon dioxide (CO_2e) totals 133.67 kg CO_2e per metre of kitchen furniture (composed of both base and wall cabinets). Therefore, for a kitchen with furniture that measure a total of, for example, 6 linear metre there are approximately 802.02 kg CO_2e sequestered in the furniture. Given that the growth of a typical forest in temperate conditions is approximately 4.4 cubic metres per year per hectare (Report, 2017) and the average density of wood is 500 kg/m^3 (Furdui, Fekete, 2009), this results in 1.1 tonnes of sequestered carbon, assuming a carbon ratio of 0.5 (Weggler et al., 2012). This represents around 4.033 tonnes of CO_2e.

802.02 kg CO_2e x 12/44 = 218.73 kg C

Considering Equation 1 shown in Chapter 1.1, the amount of carbon sequestered in biomass is estimated to be 50%, hence:

218.73 kg C x 2 = 437.46 kg biomass

437.46 kg biomass / 500 kg/m^3 = 0.8749 m^3

If 4.4 m^3 represents the approximate growth of a typical forest per ha, a value of 0.8749 m^3 equates to a forest area of around 0.198 ha. Therefore, given this rationale, the CO_2e that is contained in this kitchen furniture (of 6 linear metres) is equivalent to the total CO_2 that was sequestered by 0.20 ha of forest in a year.

Knowing the magnitude of equivalent carbon dioxide content in each piece of furniture should be helpful for laypeople to have a better awareness of its impact on climate change mitigation. Here, it is shown that the variability of carbon content per linear metre of kitchen furniture depends to a larger degree on the kitchen design, meaning that furniture composed of smaller cabinets (i.e. length of the cabinet) and more drawers results in a larger number of side walls and therefore a larger amount of biomass used in that furniture, which ultimately gives a larger quantity of CO_2e.

CHAPTER 5 Summary and Conclusion

5.1 Summary and Conclusion

This research aimed to investigate the factors which influence the lifespan of wooden furniture and how this affects the lifecycle of carbon sequestered in it. Furthermore, in order to understand what the drivers are that affect how and when individuals change their furniture, the behaviour of a sample of London residents in relation to carbon storage in wooden furniture was investigated. Approximately 61% of respondents (99 respondents) were female and 39% (62 respondents) were male. Compared to males, females reported stronger worries on climate change effects. Both men and women have in relatively similar percentages rather limited knowledge about carbon sequestration in wooden furniture. The response 'knowledgeable' has a noticeably low frequency amongst both women and men.

Most respondents believe that climate change is happening and are worried about its effects. Therefore, the respondents are generally aware of the effects and consequences of climate change. Furthermore, they expressed a willingness to select climate-friendly raw materials and to keep their current furniture longer in order to help in the fight against climate change. Their concerns about the latter also motivate them to buy used furniture**.**

Parametric and non-parametric correlation tests were used to investigate the behaviour of consumers in relation to the potential of furniture to tackle climate change. The results showed numerous patterns that can describe their behaviour. First, although the vast majority of respondents believe that climate change is actually occurring and are worried about its consequences, their understanding of the potential of wooden furniture in mitigating climate change is limited. They are willing to make changes in their behaviour regarding this matter, although the way furniture can contribute to climate change mitigation is not generally well understood. A better understanding of the contribution of wooden furniture to carbon sequestration was further linked to many behaviour patterns that were beneficial in terms of mitigating climate change.

The majority of respondents do consider which raw materials are used when they choose new furniture or when they take a decision either to sell/donate their old furniture or to send it to landfill, although they have no knowledge about carbon storage in wooden furniture.

Similarly, most respondents prefer solid wood as a wooden raw material, and this is most abundant in their home furniture. As is shown in this study, using timber for wood products and using wood species with significantly higher carbon concentrations is an important way to keep the carbon stored in biomass for a longer time.

Another behaviour that could be observed is the tendency of a large majority of respondents to replace their wooden furniture long before it has reached the end of its useful lifespan. Considering that a portion of the replaced furniture could be recycled or reused again, the wood's useful life could be prolonged and therefore the carbon inside it stored for longer. Extending the lifespan of all wood products such as wooden furniture could make a significant contribution to lowering the concentration of greenhouse gases in the atmosphere.

Using models of wood products, the stock of carbon and fluctuation was estimated and the quantity of carbon that is retained by kitchen furniture was investigated. Given the vast selection of kitchen designs and wooden-based materials that can be used, it was shown that the amount of carbon dioxide equivalent per standardised linear metre of kitchen varies more with the design than with the raw material type used for front doors. Knowing the carbon dioxide equivalent content in each piece of furniture should be helpful for laypeople to have a better awareness of its impact on climate change mitigation.

The mean quantity of carbon stored per one metre of kitchen furniture was 21.89 kg/m for base cabinets and 14.56 kg/m for wall cabinets. Significant were the differences in kitchen design, such as: two base units of 500 mm instead of a single base unit of 1000 mm; one base unit of 400 mm with one door and one drawer; two base units of 500 mm with four drawers each instead of single base unit of 1000 mm; two base units of 400 mm instead of single base unit of 800 mm; one base unit of 600 mm with three drawers instead of with one door; and two wall units of 300 mm instead of one of 600 mm. The raw material used for the front doors, whether it was MDF, oak or chipboard, proved to have less significance.

5.2 Scope for Future Work

The results can be used to carry out information campaigns targeted at different categories of people. Therefore, a recommendation of the study would be to increase awareness among the general public of the potential of wooden furniture to tackle climate change. This study offers some hints on how to increase the effectiveness of awareness campaigns by identifying those categories of people who are least knowledgeable. These are generally people with a lower educational background.

People need to become more aware about the contribution of harvested wood products to the carbon cycle, as keeping carbon stored in wooden furniture for longer is of paramount importance in the fight against climate change. This could lead them to make changes in their behaviour in order to help to decrease the global concentration of the most significant greenhouse gas, carbon dioxide.

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Appendices

Appendix 1: Questionnaire

Dear respondent,

This questionnaire is part of my MPhil degree at Buckinghamshire New University and aims to investigate the factors that influence the lifespan of wooden furniture, with direct effects on the lifecycle of carbon sequestered in it. Carbon dioxide, through the photosynthesis process, is sequestered in plant biomass. It is well known that approximately half of the weight of dried biomass is represented by carbon. Consequently, wood products keep a similar proportion of carbon sequestered in their biomass if this is not burned or decayed.

Your participation in this survey is completely voluntary and all your responses are anonymous. None of the responses will be connected to identifying information. The survey will take approximately 5 minutes to complete.

The information provided by you in this questionnaire will only be used for research purposes. It will not be used in a manner which would allow identification of your individual responses. Anonymised research data will be archived and made available to other researchers on request, in line with current data sharing practices. By completing this survey, you indicate that you understand its purpose and consent to the use of the data as indicated above.

It would be greatly appreciated if you could provide responses to all questions. Thank you in advance for providing this valuable feedback.

Sincerely,

Camelia Marinoiu

1. What is your gender?

- ☐ Male
- ☐ Female
- ☐ Other

2. What is your age?

- ☐ 21 - 25
- ☐ 26 - 35
- ☐ 36 - 65
- ☐ Over 66

3. What is your level of education?

- ☐ Postgraduate
- ☐ Undergraduate
- ☐ A-Level / High school
- ☐ GCSEs / Middle school
- ☐ No completed formal education

4. Which of these describes your personal income last year?

- ☐ £0 to £9999
- ☐ £10,000 to £24,999
- ☐ £25,000 to £49,999
- ☐ £50,000 to £75,000
- ☐ £75,000 and above
- ☐ Prefer not to answer

5. Do you own a property?

- ☐ Yes
- ☐ No

6. In your opinion, is climate change happening?

- ☐ Definitely yes
- ☐ Probably yes
- ☐ Uncertain
- ☐ Probably not
- ☐ Definitely not

7. Are you worried about climate change effects?

☐ Definitely yes
☐ Probably yes
☐ Uncertain
☐ Probably not
☐ Definitely not

8. How knowledgeable are you about carbon storage in wooden furniture?

☐ Very knowledgeable
☐ Knowledgeable
☐ Limited knowledge
☐ No knowledge

9. What category of home furniture have you upgraded most often?

☐ Kitchen
☐ Bedroom
☐ Living room

10. What would be your main reason for a furniture upgrade (or change)?

☐ Worn/deteriorated
☐ Outdated/old fashioned
☐ Improved functionality

11. In your view, what is the most frequent occasion for a furniture upgrade?

☐ Upgrade existing furniture when moving to a new house
☐ Purchase furniture for unfurnished new house
☐ Upgrade of furniture in current house (renovation)

12. How often have you changed your kitchen furniture?

☐ Every 5 years or less
☐ Every 6-10 years

☐ Every 11-30 years
☐ Every 31 years or more

13. How often have you changed your bedroom furniture?

☐ Every 5 years or less
☐ Every 6-10 years
☐ Every 11-30 years
☐ Every 31 years or more

14. How often have you changed your living room furniture?

☐ Every 5 years or less
☐ Every 6-10 years
☐ Every 11-30 years
☐ Every 31 years or more

15. When changing furniture (any kind), what do you usually do with the old items?

☐ Send to landfill
☐ Sell or donate

16. Does the type of raw material (in the old furniture) influence your decision on whether to send it to landfill or sell/donate it?

☐ Definitely yes
☐ Probably yes
☐ Uncertain
☐ Probably not
☐ Definitely not

17. What wooden raw material is most abundant in your current home furniture?

☐ Solid wood
☐ MDF (medium density fibreboard)
☐ Particle board
☐ Don’t know

18. When choosing furniture, are you interested in the raw material?

- ☐ Definitely yes
- ☐ Probably yes
- ☐ Uncertain
- ☐ Probably not
- ☐ Definitely not

19. Which wooden raw material would you prefer?

- ☐ Solid wood
- ☐ MDF (medium density fibreboard)
- ☐ Particle board
- ☐ Not interested in raw material

20. Which is the most important aspect for you when purchasing new furniture?

- ☐ Price
- ☐ Quality
- ☐ Design
- ☐ Practicality

21. If you experienced a significant increase in your income, would you change your furniture more often than you currently do?

- ☐ Definitely yes
- ☐ Probably yes
- ☐ Uncertain
- ☐ Probably not
- ☐ Definitely not

22. If the selection of raw material could help in the fight against climate change, would you consider selecting the most climate-friendly raw material?

- ☐ Definitely yes
- ☐ Probably yes

☐ Uncertain
☐ Probably not
☐ Definitely not

23. If keeping the current furniture longer could help in the fight against climate change, would you keep it just for that reason?

☐ Definitely yes
☐ Probably yes
☐ Uncertain
☐ Probably not
☐ Definitely not

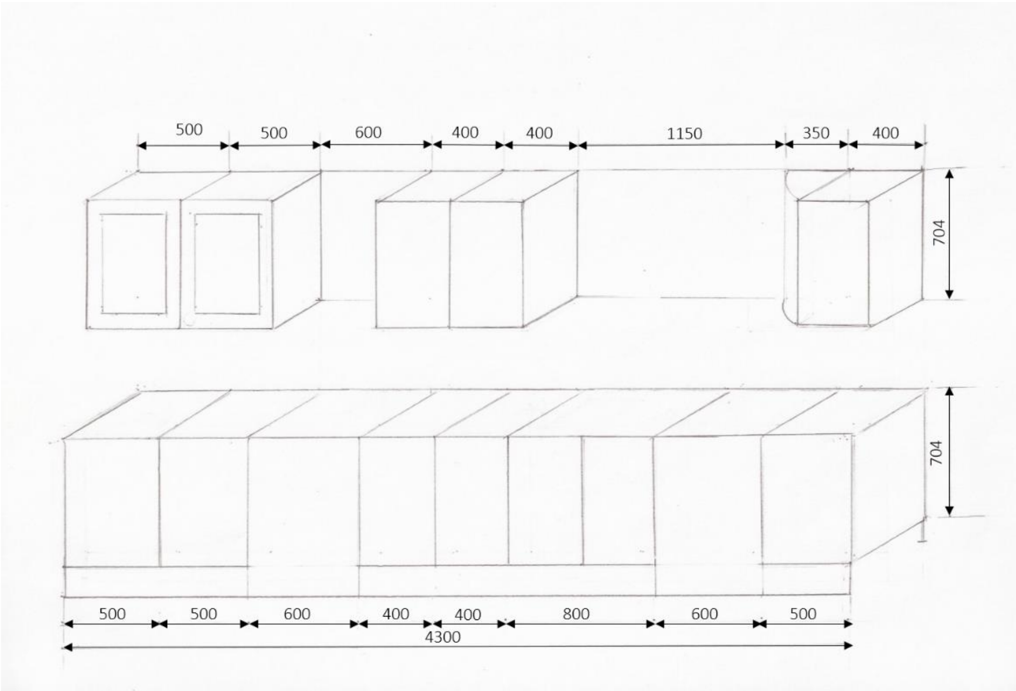
24. If purchasing used furniture could help in the fight against climate change, would you consider buying used furniture?

☐ Definitely yes
☐ Probably yes
☐ Uncertain
☐ Probably not
☐ Definitely not

Appendix 2: Survey sample locations

Appendix 3a: Kitchen models 1-7 (designs with MDF doors)

Model 1



Model 2

Model 1a	Model 2a	Model 3a	Model 4a	Model 5a	Model 6a	Model 7a
Base units L = 8.4 m C(kg)Vω(m^3)	**Base units** L = 3.7 m C(kg)Vω(m^3)	**Base units** L = 3.7 m C(kg)Vω(m^3)	**Base units** L = 3.7 m C(kg)Vω(m^3)	**Base units** L = 3.7 m C(kg)Vω(m^3)	**Base units** L = 3.7 m C(kg)Vω(m^3)	**Base units** L = 3.7 m C(kg)Vω(m^3)
TL6 MDF 2.81 Chip 18.83 6.48 x 10^{-2}	BF 1.79 0.54 x 10^{-2}	BF 1.79 0.54 x 10^{-2}	BF 1.79 0.54 x 10^{-2}	BF 1.79 0.54 x 10^{-2}	BF 1.79 0.54 x 10^{-2}	BF 1.79 0.54 x 10^{-2}
W6/3 MDF 1.03 Chip 13.01 3.97 x 10^{-2}	HL5 MDF 1.90 Chip 5.99 2.34 x 10^{-2}	HL10 MDF 3.79 Chip 8,91 3.75 x 10^{-2}	HL5 MDF 1.90 Chip 5.99 2.34 x 10^{-2}	DL10P MDF 4.88 Chip 5.98 3.17 x 10^{-2}	HL10 MDF 3.79 Chip 8,91 3.75 x 10^{-2}	DL10P MDF 4.88 Chip 5.98 3.17 x 10^{-2}
TEP 4.97 1.5 x 10^{-2}	HL5 MDF 1.90 Chip 5.99 2.34 x 10^{-2}	------	HL5 MDF 1.90 Chip 5.99 2.34 x 10^{-2}	------	------	------
HL6 MDF 2.27 Chip 6.39 2.57	FEP 1.79 0.54 x 10^{-2}	FEP 1.79 0.54 x 10^{-2}	FEP 1.79 0.54 x 10^{-2}	FEP 1.79 0.54 x 10^{-2}	FEP 1.79 0.54 x 10^{-2}	FEP 1.79 0.54 x 10^{-2}

x 10^{-2}						
HL5 MDF 1.90 Chip 5.99 2.34 x 10^{-2}	FEP 1.79 0.54 x 10^{-2}	FEP 1.79 0.54 x 10^{-2}	FEP 1.79 0.54 x 10^{-2}	FEP 1.79 0.54 x 10^{-2}	FEP 1.79 0.54 x 10^{-2}	FEP 1.79 0.54 x 10^{-2}
DL10P MDF 4.88 Chip 5.98 3.17 x 10^{-2}	HL4 MDF 1.51 Chip 5.47 2.08 x 10	HL8 MDF 3.03 Chip 7.87 3.23 x 10^{-2}	DL4P MDF 1.93 Chip 6.3 2.44 x 10^{-2}	HL4 MDF 1.51 Chip 5.47 2.08 x 10^{-2}	DL4P MDF 1.93 Chip 6.3 2.44 x 10^{-2}	DL4P MDF 1.93 Chip 6.3 2.44 x 10^{-2}
HL5 MDF 1.90 Chip 5.99 2.34 x 10^{-2}	HL4 MDF 1.51 Chip 5.47 2.08 x 10	______	HL4 MDF 1.51 Chip 5.47 2.08 x 10^{-2}	HL4 MDF 1.51 Chip 5.47 2.08 x 10^{-2}	DL4P MDF 1.93 Chip 6.3 2.44 x 10^{-2}	DL4P MDF 1.93 Chip 6.3 2.44 x 10^{-2}
HL6 MDF 2.27 Chip 6.39 2.57 x 10^{-2}	HL8 MDF 3.03 Chip 7.87 3.23 x 10^{-2}	HL8 MDF 3.03 Chip 7.87 3.23 x 10^{-2}	HL8 MDF 3.03 Chip 7.87 3.23 x 10^{-2}	HL8 MDF 3.03 Chip 7.87 3.23 x 10^{-2}	HL8 MDF 3.03 Chip 7.87 3.23 x 10^{-2}	HL8 MDF 3.03 Chip 7.87 3.23 x 10^{-2}
BF 1.79 0.54 x 10^{-2}	HL5 MDF 1.90 Chip 5.99 2.34 x 10^{-2}	HL5 MDF 1.90 Chip 5.99 2.34 x 10^{-2}	HL5 MDF 1.90 Chip 5.99 2.34 x 10^{-2}	HL5 MDF 1.90 Chip 5.99 2.34 x 10^{-2}	HL5 MDF 1.90 Chip 5.99 2.34 x 10^{-2}	HL5 MDF 1.90 Chip 5.99 2.34 x 10^{-2}
BF 1.79 0.54 x 10^{-2}	BF 1.79 0.54 x 10^{-2}	BF 1.79 0.54 x 10^{-2}	BF 1.79 0.54 x 10^{-2}	BF 1.79 0.54 x 10^{-2}	BF 1.79 0.54 x 10^{-2}	BF 1.79 0.54 x 10^{-2}
HL4 MDF 1.51 Chip 5.47 2.08 x 10^{-2}	Plinth 2.23 0.67 x 10^{-2}	Plinth 2.23 0.67 x 10^{-2}	Plinth 2.23 0.67 x 10^{-2}	Plinth 2.23 0.67 x 10^{-2}	Plinth 2.23 0.67 x 10^{-2}	Plinth 2.23 0.67 x 10^{-2}
FEP 1.79 0.54 x 10^{-2}	Worktop Chip 22.44 MDF 0.118 6.83 x 10^{-2}	Worktop Chip 22.44 MDF 0.118 6.83 x 10^{-2}	Worktop Chip 22.44 MDF 0.118 6.83 x 10^{-2}	Worktop Chip 22.44 MDF 0.118 6.83 x 10^{-2}	Worktop Chip 22.44 MDF 0.118 6.83 x 10^{-2}	Worktop Chip 22.44 MDF 0.118 6.83 x 10^{-2}
FEP 1.79 0.54 x 10^{-2}	**Total** **80.48 0.24** MDF 11.87 (14.75%) Chip 68.61 (85.25%)	**Total** **74.34 0.22** MDF 11.87 (15.97%) Chip 62.47 (84.03%)	**Total** **81.73 0.24** MDF 12.29 (15.04%) Chip 69.44 (84.96%)	**Total** **77.79 0.23** MDF 12.95 (16.65%) Chip 64.84 (83.35%)	**Total** **79.90 0.24** MDF 12.70 (15.89%) Chip 67.2 (84.11%)	**Total** **78.06 0.23** MDF 13.79 (17.67%) Chip 64.27 (82.33%)
DL4P MDF 1.93 Chip 6.3 2.44						

x 10^{-2}						
HL8 MDF 3.03 Chip 7.87 3.23 x 10^{-2}						
HL10 MDF 3.79 Chip 8.91 3.75 x 10^{-2}						
Plinth 4.60 1.39 x 10^{-2}						
Worktop Chip 49.93 MDF 0.26 15.07 x 10^{-2}						
Total **185.35 0.55** MDF 27.84 (15.02%) Chip 157.51 (84.98%)						

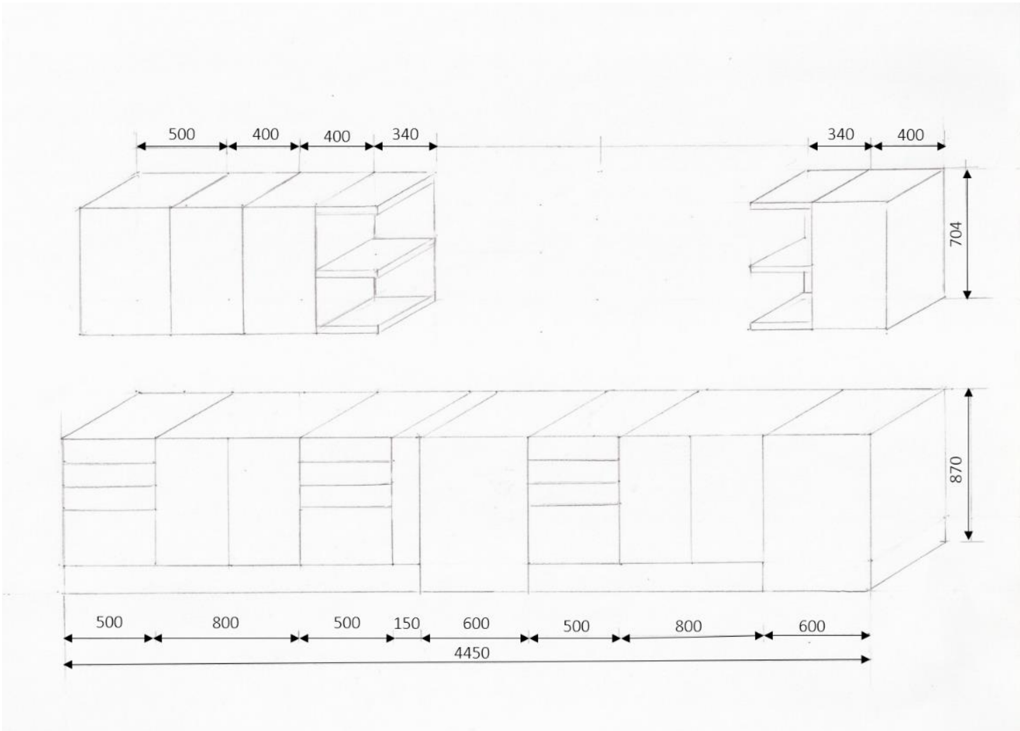
Model 1b	Model 2b	Model 3b	Model 4b	Model 5b	Model 6b	Model 7b
Wall units L = 5.1 m C(kg)Vω(m^3)	**Wall units** L = 2.55 m C(kg)Vω(m^3)	**Wall units** L = 2.55 m C(kg)Vω(m^3)	**Wall units** L = 2.50 m C(kg)Vω(m^3)	**Wall units** L = 2.55 m C(kg)Vω(m^3)	**Wall units** L = 2.55 m C(kg)Vω(m^3)	**Wall units** L = 2.50 m C(kg)Vω(m^3)
W6 MDF 2.27 Chip 6.39 2.57 x 10^{-2}	WF7 1.08 0.33 x 10^{-2}	WF7 1.08 0.33 x 10^{-2}	WF7 1.08 0.33 x 10^{-2}	WF7 1.08 0.33 x 10^{-2}	WF7 1.08 0.33 x 10^{-2}	WF7 1.08 0.33 x 10^{-2}
OU5 5.44 1.65 x 10^{-2}	GLW5 MDF 0.25 Chip 4.08 1.30 x 10^{-2}	GLW5 MDF 0.25 Chip 4.08 1.30 x 10^{-2}	GLW5 MDF 0.25 Chip 4.08 1.30 x 10^{-2}	OU5 5.44 1.65 x 10^{-2}	GLW5 MDF 0.25 Chip 4.08 1.30 x 10^{-2}	OU5 5.44 1.65 x 10^{-2}
GLW5 MDF 0.25 Chip 4.08 1.30 x 10^{-2}	GLW5 MDF 0.25 Chip 4.08 1.30 x 10^{-2}	OU5 5.44 1.65 x 10^{-2}	GLW5 MDF 0.25 Chip 4.08 1.30 x 10^{-2}	OU5 5.44 1.65 x 10^{-2}	OU5 5.44 1.65 x 10^{-2}	OU5 5.44 1.65 x 10^{-2}

GLW5 MDF 0.25 Chip 4.08 1.30 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}
OU5 5.44 1.65 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}
W6 MDF 2.27 Chip 6.39 2.57 x 10^{-2}	W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}	W8 MDF 3.03 Chip 6.27 2.74 x 10^{-2}	W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}	W8 MDF 3.03 Chip 6.27 2.74 x 10^{-2}	W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}	W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}
WF7 1.08 0.33 x 10^{-2}	W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}	------	WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}	------	W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}	WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}
W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}	CCW3 MDF 1.83 Chip 3.13 1.46 x 10^{-2}	CCW3 MDF 1.83 Chip 3.13 1.46 x 10^{-2}	WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}	CCW3 MDF 1.83 Chip 3.13 1.46 x 10^{-2}	WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}	CCW3 MDF 1.83 Chip 3.13 1.46 x 10^{-2}
WEP 1.05 0.32 x 10^{-2}	W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}	W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}	W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}	W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}	W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}	W4 MDF 1.51 Chip 4.09 1.66 x 10^{-2}
WEP 1.05 0.32 x 10^{-2}	WF7 1.08 0.33 x 10^{-2}	WF7 1.08 0.33 x 10^{-2}	WF7 1.08 0.33 x 10^{-2}	WF7 1.08 0.33 x 10^{-2}	WF7 1.08 0.33 x 10^{-2}	WF7 1.08 0.33 x 10^{-2}
WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}	Cornice MDF 2.23 0.62 x 10^{-2}	Cornice MDF 2.23 0.62 x 10^{-2}	Cornice MDF 2.23 0.62 x 10^{-2}	Cornice MDF 2.23 0.62 x 10^{-2}	Cornice MDF 2.23 0.62 x 10^{-2}	Cornice MDF 2.23 0.62 x 10^{-2}
CCW3 MDF 1.83 Chip 3.13 1.46 x 10^{-2}	**Total** **36.91 0.11** MDF 9.09 (24.63%) Chip 27.82 (75.37%)	**Total** **36.12 0.11** MDF 8.85 (24.5%) Chip 27.27 (75.5%)	**Total** **34.47 0.10** MDF 6.97 (20.22%) Chip 27.5 (79.78%)	**Total** **37.23 0.11** MDF 8.6 (23.10%) Chip 28.63 (76.90%)	**Total** **37.12 0.11** MDF 7.62 (20.53%) Chip 29.5 (79.47%)	**Total** **37.59 0.11** MDF 7.69 (20.46%) Chip 29.9 (79.54%)
W8 MDF 3.03 Chip 6.27						

2.74 x 10^{-2}						
WF7 1.08 0.33 x 10^{-2}						
Cornice MDF 3.35 0.93 x 10^{-2}						
Total 68.38 0.20 MDF 15.37 (22.48%) Chip 53.01 (77.52%)						

Appendix 3b: Kitchen models 8-14 (designs with oak doors)

Model 8



Model 9

Model 8a	Model 9a	Model 10a	Model 11a	Model 12a	Model 13a	Model 14a
Base units L = 7.2 m C(kg)Vω(m^3)	**Base units** L = 3.85 m C(kg)Vω(m^3)	**Base units** L = 3.85 m C(kg)Vω(m^3)	**Base units** L = 3.85 m C(kg)Vω(m^3)	**Base units** L = 3.85 m C(kg)Vω(m^3)	**Base units** L = 3.85 m C(kg)Vω(m^3)	**Base units** L = 3.85 m C(kg)Vω(m^3)
HL5 MDF 0.25 Chip 5.99 Oak 2.06 2.44 x 10^{-2}	4DP5 MDF 2.5 Chip 4.95 Oak 2.01 2.73 x 10^{-2}	HL5 MDF 0.25 Chip 5.99 Oak 2.06 2.44 x 10^{-2}	HL5 MDF 0.25 Chip 5.99 Oak 2.06 2.44 x 10^{-2}	4DP5 MDF 2.5 Chip 4.95 Oak 2.01 2.73 x 10^{-2}	HL5 MDF 0.25 Chip 5.99 Oak 2.06 2.44 x 10^{-2}	4DP5 MDF 2.5 Chip 4.95 Oak 2.01 2.73 x 10^{-2}
4DP5 MDF 2.5 Chip 4.95 Oak 2.01 2.73 x 10^{-2}	HL8 MDF 0.41 Chip 7.55 Oak 2.99 3.21 x 10^{-2}	HL8 MDF 0.41 Chip 7.55 Oak 2.99 3.21 x 10^{-2}	HL8 MDF 0.41 Chip 7.55 Oak 2.99 3.21 x 10^{-2}	HL6 MDF 0.30 Chip 6.51 Oak 2.20 2.65 x 10^{-2}	HL6 MDF 0.30 Chip 6.51 Oak 2.20 2.65 x 10^{-2}	HL6 MDF 0.30 Chip 6.51 Oak 2.20 2.65 x 10^{-2}
FEP Chip 1.79 0.54	4DP5 MDF 2.5 Chip 4.95	HL5 MDF 0.25 Chip 5.99	HL5 MDF 0.25 Chip 5.99	HL6 MDF 0.30 Chip 6.51	HL6 MDF 0.30 Chip 6.51	HL5 MDF 0.25 Chip 5.99

x 10^{-2}	Oak 2.01 2.73 x 10^{-2}	Oak 2.06 2.44 x 10^{-2}	Oak 2.06 2.44 x 10^{-2}	Oak 2.20 2.65 x 10^{-2}	Oak 2.20 2.65 x 10^{-2}	Oak 2.06 2.44 x 10^{-2}
FEP Chip 1.79 0.54 x 10^{-2}	HL15 Chip 4.16 Oak 0.61 1.43 x 10^{-2}	HL15 Chip 4.16 Oak 0.61 1.43 x 10^{-2}	HL15 Chip 4.16 Oak 0.61 1.43 x 10^{-2}	HL15 Chip 4.16 Oak 0.61 1.43 x 10^{-2}	HL15 Chip 4.16 Oak 0.61 1.43 x 10^{-2}	HL15 Chip 4.16 Oak 0.61 1.43 x 10^{-2}
HL15 Chip 4.16 Oak 0.61 1.43 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}
HL15 Chip 4.16 Oak 0.61 1.43 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}
FEP Chip 1.79 0.54 x 10^{-2}	4DP5 MDF 2.5 Chip 4.95 Oak 2.01 2.73 x 10^{-2}	4DP5 MDF 2.5 Chip 4.95 Oak 2.01 2.73 x 10^{-2}	HL5 MDF 0.25 Chip 5.99 Oak 2.06 2.44 x 10^{-2}	HL6 MDF 0.30 Chip 6.51 Oak 2.20 2.65 x 10^{-2}	HL6 MDF 0.30 Chip 6.51 Oak 2.20 2.65 x 10^{-2}	4DP5 MDF 2.5 Chip 4.95 Oak 2.01 2.73 x 10^{-2}
4DP5 MDF 2.5 Chip 4.95 Oak 2.01 2.73 x 10^{-2}	HL8 MDF 0.41 Chip 7.55 Oak 2.99 3.21 x 10^{-2}	HL8 MDF 0.41 Chip 7.55 Oak 2.99 3.21 x 10^{-2}	HL8 MDF 0.41 Chip 7.55 Oak 2.99 3.21 x 10^{-2}	HL8 MDF 0.41 Chip 7.55 Oak 2.99 3.21 x 10^{-2}	HL8 MDF 0.41 Chip 7.55 Oak 2.99 3.21 x 10^{-2}	HL10 MDF 0.51 Chip 8.91 Oak 4.11 3.95 x 10^{-2}
HL5 MDF 0.25 Chip 5.99 Oak 2.06 2.44 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}
HC99C MDF 0.43 Chip 9.99 Oak 2.74 3.88 x 10^{-2}	Plinth 2.77 0.84 x 10^{-2}	Plinth 2.77 0.84 x 10^{-2}	Plinth 2.77 0.84 x 10^{-2}	Plinth 2.77 0.84 x 10^{-2}	Plinth 2.77 0.84 x 10^{-2}	Plinth 2.77 0.84 x 10^{-2}
HL6 MDF 0.30 Chip 6.51 Oak 2.20 2.65 x 10^{-2}	Worktop Chip 24.70 MDF 0.13 7.52 x 10^{-2}	Worktop Chip 24.70 MDF 0.13 7.52 x 10^{-2}	Worktop Chip 24.70 MDF 0.13 7.52 x 10^{-2}	Worktop Chip 24.70 MDF 0.13 7.52 x 10^{-2}	Worktop Chip 24.70 MDF 0.13 7.52 x 10^{-2}	Worktop Chip 24.70 MDF 0.13 7.52 x 10^{-2}
HL10	**Total**	**Total**	**Total**	**Total**	**Total**	**Total**

MDF 0.51 Chip 8.91 Oak 4.11 3.95 x 10^{-2}	88.02 **0.26** MDF 8.45 (9.6%) Chip 66.95 (76.06%) Oak 12.62 (14.34%)	**85.7 0.25** MDF 3.95 (4.61%) Chip 69.03 (80.55%) Oak 12.72 (14.84%)	**84.54 0.25** MDF 1.7 (2.01%) Chip 70.07 (82.88%) Oak 12.77 (15.11%)	**85.18 0.25** MDF 3.94 (4.63%) Chip 69.03 (81.04%) Oak 12.21 (14.33%)	**82.23 0.24** MDF 1.69 (2.06%) Chip 68.28 (83.04%) Oak 12.26 (14.90%)	**87.5 0.26** MDF 6.19 (7.07%) Chip 68.31 (78.07%) Oak 13 (14.86%)
HL6 MDF 0.30 Chip 6.51 Oak 2.20 2.65 x 10^{-2}						
FEP Chip 1.79 0.54 x 10^{-2}						
Plinth Chip 4.32 1.31 x 10^{-2}						
Worktop MDF 0.26 Chip 49.94 15.20 x 10^{-2}						
Total **151.44 0.45** MDF 7.3 (4.82%) Chip 123.53 (81.57%) Oak 20.61 (13.61%)						

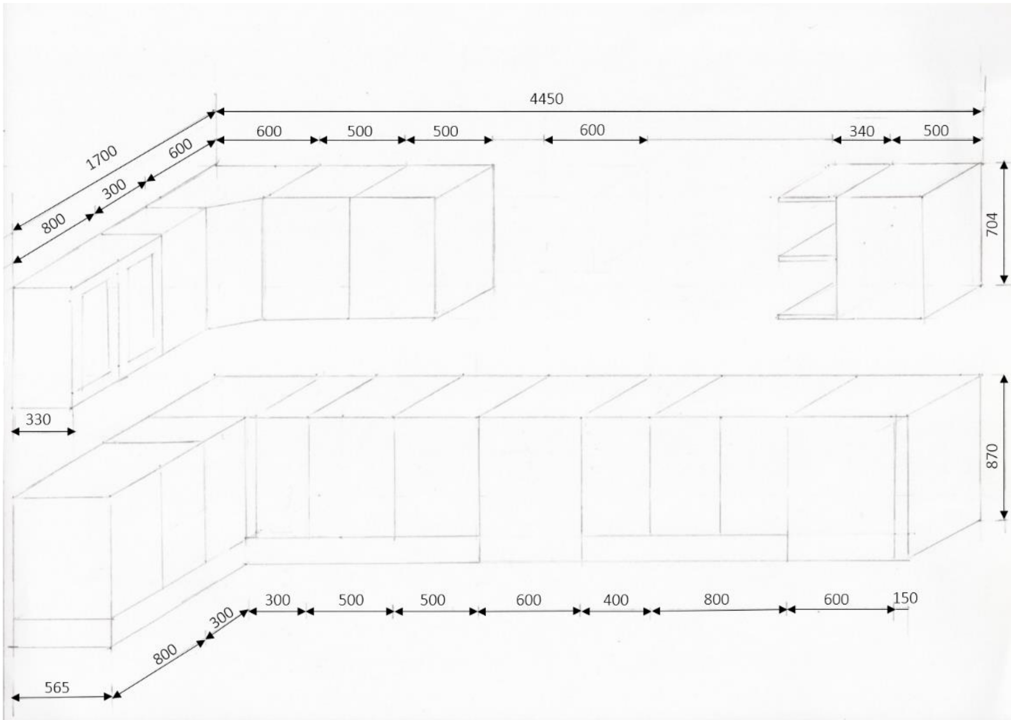
Model 8b	**Model 9b**	**Model 10b**	**Model 11b**	**Model 12b**	**Model 13b**	**Model 14b**
Wall units L = 4.68 m C(kg)Vω(m^3)	**Wall units** L = 2.38 m C(kg)Vω(m^3)	**Wall units** L = 2.54 m C(kg)Vω(m^3)	**Wall units** L = 2.6 m C(kg)Vω(m^3)	**Wall units** L = 2.54 m C(kg)Vω(m^3)	**Wall units** L = 2.54 m C(kg)Vω(m^3)	**Wall units** L = 2.6 m C(kg)Vω(m^3)
WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}
W5 MDF 0.25	W5 MDF 0.25	W6 MDF 0.30	W5 MDF 0.25	W5 MDF 0.25	W8 MDF 0.41	OU5 Chip 5.44

Chip 4.63 Oak 2.06 2.02 x 10^{-2}	Chip 4.63 Oak 2.06 2.02 x 10^{-2}	Chip 5.16 Oak 2.47 2.32 x 10^{-2}	Chip 4.63 Oak 2.06 2.02 x 10^{-2}	Chip 4.63 Oak 2.06 2.02 x 10^{-2}	Chip 6.27 Oak 2.92 2.8 x 10^{-2}	1.65 x 10^{-2}
OU5 Chip 5.44 1.65 x 10^{-2}	W4 MDF 0.20 Chip 4.09 Oak 1.35 1.66 x 10^{-2}	W6 MDF 0.30 Chip 5.16 Oak 2.47 2.32 x 10^{-2}	OU5 Chip 5.44 1.65 x 10^{-2}	W5 MDF 0.25 Chip 4.63 Oak 2.06 2.02 x 10^{-2}	OU5 Chip 5.44 1.65 x 10^{-2}	OU5 Chip 5.44 1.65 x 10^{-2}
Shelf (900) Chip 1.34 0.4 x 10^{-2}	W4 MDF 0.20 Chip 4.09 Oak 1.35 1.66 x 10^{-2}	W6 MDF 0.30 Chip 5.16 Oak 2.47 2.32 x 10^{-2}	W8 MDF 0.41 Chip 6.27 Oak 2.92 2.8 x 10^{-2}	W8 MDF 0.41 Chip 6.27 Oak 2.92 2.8 x 10^{-2}	OU5 Chip 5.44 1.65 x 10^{-2}	W5 MDF 0.25 Chip 4.63 Oak 2.06 2.02 x 10^{-2}
WEP 1.05 0.32 x 10^{-2}	WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	W3 MDF 0.15 Chip 3.54 Oak 1.23 1.44 x 10^{-2}
WEP 1.05 0.32 x 10^{-2}	------	------	------	------	-------	WEP 1.05 0.32 x 10^{-2}
OU5 Chip 5.44 1.65 x 10^{-2}	Window	Window	Window	Window	Window	------
W5 MDF 0.25 Chip 4.63 Oak 2.06 2.02 x 10^{-2}	WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}	WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}	W8 MDF 0.41 Chip 6.27 Oak 2.92 2.8 x 10^{-2}	WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}	WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}	Window
W3 MDF 0.15 Chip 3.54 Oak 1.23 1.44 x 10^{-2}	W4 MDF 0.20 Chip 4.09 Oak 1.35 1.66 x 10^{-2}	W4 MDF 0.20 Chip 4.09 Oak 1.35 1.66 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	W4 MDF 0.20 Chip 4.09 Oak 1.35 1.66 x 10^{-2}	W4 MDF 0.20 Chip 4.09 Oak 1.35 1.66 x 10^{-2}	W8 MDF 0.41 Chip 6.27 Oak 2.92 2.8 x 10^{-2}
CW66 MDF 0.49 Chip 6.38 Oak 1.43 1.44 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}		WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}	WEP 1.05 0.32 x 10^{-2}
W3 MDF 0.15 Chip 3.54	Cornice MDF 2.23 0.62	Cornice MDF 2.23 0.62	Cornice MDF 2.23 0.62	Cornice MDF 2.23 0.62	Cornice MDF 2.23 0.62	Cornice MDF 2.23 0.62

Oak 1.23 1.44 x 10^{-2}	x 10^{-2}	x 10^{-2}	x 10^{-2}	x 10^{-2}	x 10^{-2}	x 10^{-2}
WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}	**Total** **36.31 0.11** MDF 4.3 (11.84%) Chip 25.9 (71.33%) Oak 6.11 (16.83%)	**Total** **38.87 0.11** MDF 3.94 (10.14%) Chip 26.17 (67.33%) Oak 8.76 (22.53%)	**Total** **36.96 0.11** MDF 3.30 (8.93%) Chip 25.76 (69.70%) Oak 7.9 (21.37%)	**Total** **38.56 0.11** MDF 3.95 (10.24%) Chip 26.22 (68%) Oak 8.39 (21.76%)	**Total** **35.56 0.11** MDF 3.45 (9.7%) Chip 27.84 (78.29%) Oak 4.27 (12.01%)	**Total** **37.72 0.11** MDF 3.04 (8.06%) Chip 28.47 (75.48%) Oak 6.21 (16.46%)
Window						
WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}						
W8 MDF 0.41 Chip 6.27 Oak 2.92 2.8 x 10^{-2}						
WEP 1.05 0.32 x 10^{-2}						
Cornice MDF 3.35 0.93 x 10^{-2}						
Total **69.51 0.21** MDF 6.27 (9.02%) Chip 52.31 (75.26%) Oak 10.93 (15.72%)						

Appendix 3c: Kitchen models 15-21 (designs with chipboard doors)

Model 15



Model 16

Model 15a	Model 16a	Model 17a	Model 18a	Model 19a	Model 20a	Model 21a
Base units L = 6.5 m C(kg)Vω(m^3)	**Base units** L = 4.95 m C(kg)Vω(m^3)	**Base units** L = 4.95 m C(kg)Vω(m^3)	**Base units** L = 4.95 m C(kg)Vω(m^3)	**Base units** L = 4.95 m C(kg)Vω(m^3)	**Base units** L = 4.95 m C(kg)Vω(m^3)	**Base units** L = 4.95 m C(kg)Vω(m^3)
FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}
PD6P MDF 2.41 Chip 7.72 2.75 x 10^{-2}	HL8 MDF 0.41 Chip 11.21 3.51 x 10^{-2}	HL5 MDF 0.25 Chip 7.75 2.42 x 10^{-2}	HL4 MDF 0.20 Chip 6.87 2.13 x 10^{-2}	HL5 MDF 0.25 Chip 7.75 2.42 x 10^{-2}	4DP5 MDF 2.5 Chip 6.67 2.71 x 10^{-2}	4DP5 MDF 2.5 Chip 6.67 2.71 x 10^{-2}
HL8 MDF 0.41 Chip 11.21 3.51 x 10^{-2}	HC99C MDF 0.69 Chip 12.06 3.85 x 10^{-2}	HL3 MDF 0.15 Chip 5.88 1.82 x 10^{-2}	HL4 MDF 0.20 Chip 6.87 2.13 x 10^{-2}	WR15 Chip 5.50 1.67 x 10^{-2}	HL3 MDF 0.15 Chip 5.88 1.82 x 10^{-2}	WR15 Chip 5.50 1.67 x 10^{-2}
HC99C MDF 0.69 Chip 12.06 3.85 x 10^{-2}	HL5 MDF 0.25 Chip 7.75 2.42 x 10^{-2}	HC99C MDF 0.69 Chip 12.06 3.85 x 10^{-2}	HC99C MDF 0.69 Chip 12.06 3.85 x 10^{-2}	WR15 Chip 5.50 1.67 x 10^{-2}	HC99C MDF 0.69 Chip 12.06 3.85 x 10^{-2}	WR15 Chip 5.50 1.67 x 10^{-2}
HL15 Chip 4.68 1.42 x 10^{-2}	HL5 MDF 0.25 Chip 7.75 2.42 x 10^{-2}	HL8 MDF 0.41 Chip 11.21 3.51 x 10^{-2}	4DP5 MDF 2.5 Chip 6.67 2.71 x 10^{-2}	HC99C MDF 0.69 Chip 12.06 3.85 x 10^{-2}	HL6 MDF 0.30 Chip 8.38 2.62 x 10^{-2}	HC99C MDF 0.69 Chip 12.06 3.85 x 10^{-2}
WR15 Chip 5.50 1.67 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	HL5 MDF 0.25 Chip 7.75 2.42 x 10^{-2}	4DP5 MDF 2.5 Chip 6.67 2.71 x 10^{-2}	HL4 MDF 0.20 Chip 6.87 2.13 x 10^{-2}	HL4 MDF 0.20 Chip 6.87 2.13 x 10^{-2}
FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	4DP5 MDF 2.5 Chip 6.67 2.71 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	HL4 MDF 0.20 Chip 6.87 2.13 x 10^{-2}
FEP Chip 1.79 0.54 x 10^{-2}	HL4 MDF 0.20 Chip 6.87 2.13 x 10^{-2}	HL6 MDF 0.30 Chip 8.38 2.62 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}
WR15 Chip 5.50 1.67 x 10^{-2}	HL8 sink MDF 0.41 Chip 11.21 3.51 x 10^{-2}	HL8 sink MDF 0.41 Chip 11.21 3.51 x 10^{-2}	HL4 MDF 0.20 Chip 6.87 2.13 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	HL4 MDF 0.20 Chip 6.87 2.13 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}
HL15 Chip 4.68 1.42 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	HL8 sink MDF 0.41 Chip 11.21 3.51 x 10^{-2}	HL4 MDF 0.20 Chip 6.87 2.13 x 10^{-2}	HL8 sink MDF 0.41 Chip 11.21 3.51 x 10^{-2}	PDP6 MDF 2.41 Chip 7.72 2.75 x 10^{-2}

HC99C MDF 0.69 Chip 12.06 3.85 x 10^{-2}			FEP Chip 1.79 0.54 x 10^{-2}	HL8 sink MDF 0.41 Chip 11.21 3.51 x 10^{-2}	FEP Chip 1.79 0.54 x 10^{-2}	HL8 sink MDF 0.41 Chip 11.21 3.51 x 10^{-2}
HL8 sink MDF 0.41 Chip 11.21 3.51 x 10^{-2}				FEP Chip 1.79 0.54 x 10^{-2}		FEP Chip 1.79 0.54 x 10^{-2}
BHF Chip 3.57 1.08 x 10^{-2}	Plinth Chip 3.87 1.17 x 10^{-2}	Plinth Chip 3.87 1.17 x 10^{-2}	Plinth Chip 3.87 1.17 x 10^{-2}	Plinth Chip 3.87 1.17 x 10^{-2}	Plinth Chip 3.87 1.17 x 10^{-2}	Plinth Chip 3.87 1.17 x 10^{-2}
Plinth Chip 3.31 1 x 10^{-2}	Worktop Beech 36.20 10.16 x 10^{-2}	Worktop Beech 36.20 10.16 x 10^{-2}	Worktop Beech 36.20 10.16 x 10^{-2}	Worktop Beech 36.20 10.16 x 10^{-2}	Worktop Beech 36.20 10.16 x 10^{-2}	Worktop Beech 36.20 10.16 x 10^{-2}
Worktop Beech 51.82 14.54 x 10^{-2}						
Total **143.30 0.42** MDF 4.61 (3.22%) Chip 86.87 (60.62%) Beech 51.82 (36.16%)	**Total** **106.29 0.31** MDF 2.21 (2.08%) Chip 67.88 (63.86%) Beech 36.20 (34.06%)	**Total** **105.93 0.31** MDF 2.21 (2.09%) Chip 67.52 (63.74%) Beech 36.20 (34.17%)	**Total** **109.98 0.32** MDF 4.45 (4.05%) Chip 69.33 (63.03%) Beech 36.20 (32.92%)	**Total** **116.01 0.34** MDF 6.55 (5.65%) Chip 73.26 (63.15%) Beech 36.20 (31.20%)	**Total** **109.62 0.32** MDF 4.45 (4.06%) Chip 68.97 (62.92%) Beech 36.20 (33.02%)	**Total** **116.04 0.34** MDF 6.41 (5.52%) Chip 73.43 (63.28%) Beech 36.20 (31.20%)

Model 15b	**Model 16b**	**Model 17b**	**Model 18b**	**Model 19b**	**Model 20b**	**Model 21b**
Wall units L = 4.68 m C(kg)Vω(m^3)	**Wall units** L = 4.68 m C(kg)Vω(m^3)	**Wall units** L = 4.68 m C(kg)Vω(m^3)	**Wall units** L = 4.68 m C(kg)Vω(m^3)	**Wall units** L = 4.68 m C(kg)Vω(m^3)	**Wall units** L = 4.68 m C(kg)Vω(m^3)	**Wall units** L = 4.68 m C(kg)Vω(m^3)
WEP 1.08 0.33 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}
W6 MDF 0.30 Chip 7.28 2.29	GLW4 MDF 0.20 Chip 3.82 1.21	W6 MDF 0.30 Chip 7.28 2.29	W8 MDF 0.41 Chip 8.76 2.76	WPR5 Beech 1.13 Chip 5 1.83	W4 MDF 0.20 Chip 5.33 1.67	W4 MDF 0.20 Chip 5.33 1.67

x 10^{-2}	x 10^{-2}	x 10^{-2}	x 10^{-2}	x 10^{-2}	x 10^{-2}	x 10^{-2}
GLW4 MDF 0.20 Chip 3.82 1.21 x 10^{-2}	GLW4 MDF 0.20 Chip 3.82 1.21 x 10^{-2}	W5 MDF 0.25 Chip 6.38 2 x 10^{-2}	W3 MDF 0.15 Chip 4.59 1.43 x 10^{-2}	W6 MDF 0.30 Chip 7.28 2.29 x 10^{-2}	GLW4 MDF 0.20 Chip 3.82 1.21 x 10^{-2}	W4 MDF 0.20 Chip 5.33 1.67 x 10^{-2}
GLW4 MDF 0.20 Chip 3.82 1.21 x 10^{-2}	W3 MDF 0.15 Chip 4.59 1.43 x 10^{-2}	CW66 MDF 0.49 Chip 7.6 2.43 x 10^{-2}	CW66 MDF 0.49 Chip 7.6 2.43 x 10^{-2}	CW66 MDF 0.49 Chip 7.6 2.43 x 10^{-2}	W3 MDF 0.15 Chip 4.59 1.43 x 10^{-2}	W3 MDF 0.15 Chip 4.59 1.43 x 10^{-2}
W3 MDF 0.15 Chip 4.59 1.43 x 10^{-2}	CW66 MDF 0.49 Chip 7.6 2.43 x 10^{-2}	WPR5 Beech 1.13 Chip 5 1.83 x 10^{-2}	WPR5 Beech 1.13 Chip 5 1.83 x 10^{-2}	W6 MDF 0.30 Chip 7.28 2.29 x 10^{-2}	CW66 MDF 0.49 Chip 7.6 2.43 x 10^{-2}	CW66 MDF 0.49 Chip 7.6 2.43 x 10^{-2}
CW66 MDF 0.49 Chip 7.6 2.43 x 10^{-2}	W5 MDF 0.25 Chip 6.38 2 x 10^{-2}	W5 MDF 0.25 Chip 6.38 2 x 10^{-2}	WPR5 Beech 1.13 Chip 5 1.83 x 10^{-2}	W4 MDF 0.20 Chip 5.33 1.67 x 10^{-2}	W6 MDF 0.30 Chip 7.28 2.29 x 10^{-2}	W4 MDF 0.20 Chip 5.33 1.67 x 10^{-2}
W5 MDF 0.25 Chip 6.38 2 x 10^{-2}	W5 MDF 0.25 Chip 6.38 2 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	W6 MDF 0.30 Chip 7.28 2.29 x 10^{-2}	W3 MDF 0.15 Chip 4.59 1.43 x 10^{-2}
WEP 1.05 0.32 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	------	------	------	WEP 1.08 0.33 x 10^{-2}	W3 MDF 0.15 Chip 4.59 1.43 x 10^{-2}
------	------	Window	Window	Window	------	WEP 1.08 0.33 x 10^{-2}
WEP 1.05 0.32 x 10^{-2}	Window	GLW4 MDF 0.20 Chip 3.82 1.21 x 10^{-2}	WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}	W3 MDF 0.15 Chip 4.59 1.43 x 10^{-2}	Window	------
WPR5 Beech 1.13 Chip 5 1.83 x 10^{-2}	WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}	GLW4 MDF 0.20 Chip 3.82 1.21 x 10^{-2}	W5 MDF 0.25 Chip 6.38 2 x 10^{-2}	W5 MDF 0.25 Chip 6.38 2 x 10^{-2}	W6 MDF 0.30 Chip 7.28 2.29 x 10^{-2}	Window
W6 MDF 0.30 Chip 7.28 2.29 x 10^{-2}	W5 MDF 0.25 Chip 6.38 2 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	WEP 1.08 0.33 x 10^{-2}	W4 MDF 0.20 Chip 5.33 1.67 x 10^{-2}
Window	WEP 1.08 0.33 x 10^{-2}					W4 MDF 0.20 Chip 5.33 1.67 x 10^{-2}

WES MDF 0.61 Chip 3.45 1.21 x 10^{-2}						WEP 1.08 0.33 x 10^{-2}
	Cornice MDF 2.23 0.62 x 10^{-2}	Cornice MDF 2.23 0.62 x 10^{-2}	Cornice MDF 2.23 0.62 x 10^{-2}	Cornice MDF 2.23 0.62 x 10^{-2}	Cornice MDF 2.23 0.62 x 10^{-2}	Cornice MDF 2.23 0.62 x 10^{-2}
Cornice MDF 3.35 0.93 x 10^{-2}	**Total** **50.29 0.15** MDF 4.63 (9.21%) Chip 45.66 (90.79%)	**Total** **48.57 0.15** MDF 3.92 (8.07%) Chip 43.52 (89.60%) Beech 1.13 (2.33%)	**Total** **50.42 0.15** MDF 4.14 (8.21%) Chip 44.02 (87.31%) Beech 2.26 (4.48%)	**Total** **51.75 0.16** MDF 3.92 (7.58%) Chip 46.7 (90.24%) Beech 1.13 (2.18%)	**Total** **50.59 0.15** MDF 4.17 (8.24%) Chip 46.42 (91.76%)	**Total** **55.43 0.17** MDF 4.17 (7.52%) Chip 51.26 (92.48%)
Total **59.38 0.18** MDF 5.85 (9.85%) Chip 52.46 (88.35%) Beech 1.13 (1.80%)						

Appendix 3d: Legend for kitchen model tables

C = carbon content (kg)

V_ω = the volume of the solid wood product at that moisture content (m^3)

Base unit

TL6	= base unit vertically with 2 doors	W6/3	= base unit for fridge
TEP	= a tall end panel	HL15	= base unit 150 mm
WR15	= base unit 150 mm with shelves	HL 3	= base unit 300 mm
HL4	= base unit 400 mm	HL5	= base unit 500 mm
HL6	= base unit 600 mm	HL8	= base unit 800 mm for sink
HL10	= base unit 1000 mm with two doors	HL10	= base unit 1000 mm for sink
DL4P	= base unit 400 mm with door and drawer	BF	= base fillers
4DP5	= base unit 500 mm with 4 drawers	PD6P	= base unit 600 mm with 3 drawers
DL10 P	= base unit 1000 mm with two drawers	HC99C	= corner unit
HC99C	= corner unit 900 x 900 mm – left	HC99C	= corner unit 900 x 900 mm – right

Wall unit

W3	= wall unit 300 mm	W4	= wall unit 400 mm
W5	= wall unit 500 mm	W6	= wall unit 600 mm
W8	= wall unit 800 mm	GLW4	= wall unit 400 mm with glass
GLW5	= wall unit 500 mm with glass	WPR-5	= wall unit 500 mm for plates
OU5	= wall unit 500 mm only with shelf	WF7	= wall fillers
WEP	= wall end panel	WES	= corner wall unit 340 mm with shelf
CCW3	= corner wall unit 350 mm with semi-round door		
CW66	= corner unit		