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Substitution effect of Finnish wood products according to dominant tree species

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Abstract

Finland has committed under Paris Agreement to limit global temperature rise to well below 2 ˚C compared to pre-industrial levels, and to reach carbon neutrality by 2035. Finnish forests have a key role in reaching these targets. Firstly, forests contribute to climate change mitigation by sequestrating carbon dioxide (CO_2) from the atmosphere through photosynthesis. Secondly, forest is a valuable resource pool of renewable low carbon material that has several advantageous attributes. Long-lived harvested wood products (HWP) function as external carbon pools supporting continuous growth of biomass in the forest, and substitute for fossil-intensive material. Processing of wood material result in substantially smaller life-cycle emissions compared to its energy intensive substitutes concrete, aluminium and steel. The substitution potential of wood use is particularly significant in construction sector that caused one third of both national and global GHG emissions in 2018.

In this study the substitution effect of Finnish wood products by dominant tree species was assessed by combining information on current consumption with substitution factors (SF) for structural construction, non-structural construction and energy usage from previous studies. The aim was to identify those factors that influence the substitution potential most extensively and estimate the overall climate effect of mechanical forest industry in the light of current production levels and consumption trends. Current production volumes of mechanical forest industry are averages from LUKE statistical service from 2015-2018. Proprietary information on wood use in Finland was obtained from Forecon report on use of sawn wood and wood-based panels.

Contrary to previous ones, this study provides substitution factors by tree species, which has been an unidentified area of research to date. The results show that with current consumption trends, the substitution effect for pine, spruce and birch were 1.37, 1.27 and 1.04 tC / tC, respectively. This implies that every ton of carbon used in wood product result to an emission reduction of 1.04-1.37 (3.8–5 t CO_2) carbon tons. Sensitivity analyses showed that the SFs for coniferous trees were highly sensitive for changes in the use of *general sawn wood,* which represents the largest singular product group. The substitution effect of birch was determined by its use in short-lived products.

The overall substitution effect of current consumption of sawn wood and wood-based panels equals to 3.3 Mt C (12,1 $MtCO_2$). The results imply that the external carbon stock in produced wood products (2.5 Mt C, or 9.2 $MtCO_2$) and its substitution effect (3.2 Mt or 12.1 $MtCO_2$) could increasingly offset the reduction in forest carbon stock (6 Mt C or 22 $MtCO_2$) due to raw-material acquisition, if forests are managed sustainably and wood is used primary for production of long-lasting wood products.

Keywords
Substitution effect, mechanical forest industry, wood construction

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Tiivistelmä

Suomi on sitoutunut Pariisin ilmastosopimuksen myötä rajoittamaan maapallon lämpötilan nousun reilusti alle kahteen celsiusasteeseen suhteessa esiteolliseen aikaan, sekä saavuttamaan hiilineutraaliuuden vuoteen 2035 mennessä. Suomen metsillä on merkittävä rooli näiden tavoitteiden saavuttamisessa. Ensinnäkin metsät torjuvat ilmastonmuutosta sitomalla yhteyttämisprosessissa hiilidioksidia (CO_2) ilmakehästä. Toiseksi metsät ovat uusiutuvan, monikäyttöisen ja vähähiilisen raaka-aineen lähde. Pitkäikäiset puutuotteet (HWP) toimivat ulkopuolisina hiilivarastoina tukien biomassan jatkuvaa kasvua metsissä. Lisäksi ne korvaavat useita fossiilisintensiivisiä materiaaleja. Puumateriaalin jalostamisesta aiheutuu merkittävästi vähemmän elinkaaripäästöjä verrattuna sen energiaintensiivisiin substituutteihin kuten betoniin, alumiiniin ja teräkseen. Puun käytön substituutiopotentiaali on erityisen merkittävä rakennussektorilla, josta aiheutui kolmannes niin kansallisista kuin kansainvälisistä kasvihuonekaasupäästöistä vuonna 2018.

Tässä tutkimuksessa suomalaisten pääpuulajien korvaavuusvaikutusta arvioitiin yhdistämällä tietoa vallitsevista kulutustrendeistä aikaisemmasta tutkimuksesta saatuihin substituutiokertoimiin liittyen kantaviin ja kantamattomiin rakenteisiin, sekä energiakäyttöön. Tavoitteena oli tunnistaa merkittävimmät substituutiopotentiaaliin vaikuttavat tekijät ja arvioida mekaanisen metsäteollisuuden ilmastovaikutusta nykytuotannon ja vallitsevien kulutustrendien valossa. Tuotannon volyymeinä käytettiin Luonnonvarakeskuksen tilastotietojen keskiarvoja vuosilta 2015-2018. Puun käyttöä arvioitiin Foreconin salassa pidettävästä raportista liittyen sahatavaran ja puulevyjen käyttöön Suomessa.

Aikaisemmista tutkimuksista poiketen, tämä tutkimus tarjoaa puulajikohtaiset substituutiokertoimet kotimaisille pääpuulajeille. Aihetta ei ole aikaisemmin tutkittu. Tulokset osoittavat, että nykyisten kulutustrendien vallitessa männyn, kuusen ja koivun substituutiovaikutus on suuruudeltaan järjestyksessä 1,37; 1,27 ja 1,04 tC / tC. Tämä tarkoittaa, että jokaisesta puutuotteen sisältämästä hiilitonnista aiheutuu 1,04-1,37 (3,8–5 t CO_2) hiilitonnin suuruinen päästövähennys.

Herkkyysanalyysit osoittivat, että havupuiden substituutiokerroinarvot olivat herkkiä käytön muutoksille puutuoteryhmässä nimeltä *yleinen sahatavara*, joka edusti suurinta yksittäistä puutuoteryhmää. Koivun substituutiokertoimen määritti puulajin runsas käyttö lyhytikäisissä tuotteissa.

Sahatavaran ja puulevyjen nykykulutuksen yhteenlaskettu substituutiovaikutus on 3,3 Mt C (12,1 $MtCO_2$). Tuloksista selviää, että metsän ulkopuolinen hiilivarasto tuotetuissa puutuotteissa (2,5 Mt C, tai 9, 2 $MtCO_2$) yhdessä tuotteiden korvaavuusvaikutuksen (3,2 Mt tai 12,1 $MtCO_2$) kanssa voisi enenevissä määrin korvata raaka-aineen hankinnasta aiheutuneen vähennyksen metsän hiilivarastossa, mikäli metsiä hoidetaan kestävästi ja puuta jalostetaan ensisijaisesti pitkäikäisiksi tuotteiksi.

Avainsanat
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List of acronyms

AFOLU	Agriculture, Forestry and Other Land Use sector
C	Carbon
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide Equivalent
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas
Gt	Gigaton, billion tons
HWP	Harvested Wood Product
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life-cycle Assessment
LCI	Life-cycle Inventory
LUC	Land-Use Change
LUKE	Natural Resources Institute Finland
LULUCF	Land Use, Land-Use Change and Forestry
Mt	Megaton, million tons
SF	Substitution factor
UNEP	United Nations Environment Program

1. Introduction

1.1. Forests and climate

Finland has committed under Paris Agreement (UNFCC, 2015) to limit global temperature rise to well below 2 ˚C compared to pre-industrial levels. The new government of Finland set the target for reaching carbon neutrality by 2035 (Finnish Government, 2019). Finnish forests have a key role in reaching both national and European targets.

Firstly, forests contribute to climate change mitigation by sequestrating carbon dioxide (CO_2) from the atmosphere through photosynthesis. Finnish forest area represents some 10% of the total European forest area and it forms an important carbon sink as well as raw material reservoir. In 2018 the net carbon sink of forested land equalled to 20.8 megatons (Mt)CO_2-eq (Statistics Finland, 2019). That includes the changes in carbon stock in living biomass as well as in soil. In comparison, the concurrent total national greenhouse gas emissions (LULUCF sector excluding) accounted for 56.5 MtCO_2-eq (Statistics Finland, 2019).

Finnish forestry is assumed sustainable as forest is growing more than it is harvested. 85% of national forests have a certificate of ecologically, socially and economically sustainable forestry (PEFC), and harvesting levels are currently some 80% of maximum sustainable level. According to the latest Finnish National Forest Inventory (NFI 12) the annual timber growth exceeds removals by 107 million (M)m^3. The Natural Resources Institute Finland (LUKE) estimates the maximum sustainable cutting potential for 2015-2024 to be 85 Mm^3 per year, and to further increase after that period of time. In 2018 78.1 Mm^3 was harvested (LUKE, 2019b).

In Europe, sustainable forest management is increasing the forest area. The annual growth rate of forest area has been 0,8 million hectares over the last 20 years and forest area is expected to expand (Forest Europe, 2015). This is mostly due to afforestation and natural forest expansion.

Over the period of 2011-2015 the world's forests were a net carbon sink of 2.1 $GtCO_2$. According to FAO (2015) the global forest carbon stock (incl. above- and below-ground biomass) accounted for 296 Gt of biogenic carbon. In comparison the global GHG emissions reached a record high of 53.5 $GtCO_2$-eq (carbon dioxide equivalent, including land-use change) in 2017 (UNEP, 2018). Several authors claim that focus of global climate change mitigation should primary be on reducing GHG emissions and not on compensating existing emissions by increasing carbon sinks (for example Werner et al. 2005). However, the comparison of carbon sinks and emission volumes highlights the potential of forest carbon sinks in climate mitigation. Global forests are an important global carbon pool that is threatened by unsustainable forest management and deforestation mainly in the tropical forests.

Secondly, forest is a valuable resource pool of renewable low carbon material that has several advantageous attributes. Harvested wood products (HWP) function as external carbon pools. They support continuous growth of biomass in the forest and substitute for energy-intensive materials. Half of wood's dry weight is biogenic carbon that mostly remains in HWP until disposal. Wood products can be recycled or used for energy purposes after service life. It can in principle be considered a carbon neutral material, as the post-use combustion emits the same amount of carbon dioxide once absorbed from the atmosphere. However, this carbon neutrality is only temporary. The assumption also disregards all life-cycle emissions but gives a rough idea of the advantages of wood material. The biogenic carbon in HWP is considered as a negative emission within LULUCF (Land Use, Land-Use Change and Forestry), and it compensates some of the life-cycle emissions of wood materials. According to Statistics Finland's preliminary data (2019), harvested wood products represented a carbon sink of 4 $MtCO_2$-eq in 2017. The HWP carbon sink includes all wood and paper products and is affected by changes in production volumes and the estimated life span of different HWP. The current HWP carbon sink in Finland equals to one fifth of that in forested land, and hence represents already an important carbon pool.

A comparison of previously mentioned national and global emissions is summarized in table 1. Positive numbers are GHG sources. Negative values represent carbon sinks and stocks converted into CO_2. The magnitude of global emissions is expressed in gigatons whereas national emissions are in megatons.

Table 1. Examples of global and national emissions from years 2011-2018

Global emissions ($GtCO_2$-eq)	Forest carbon stock, 2015	-296
	Forest carbon sink 2011-2015	-2,1
	GHG emission record, 2017	53,5
Finnish emissions ($MtCO_2$-eq)	LULUCF sector in total, 2018	-14,2
	Forest carbon sink, 2018	-20,8
	HWP carbon sink, 2017	-4
	GHG-emissions (LULUCF excl.), 2018	56,5

In Finland forest industry is the largest singular producer of bioenergy using mainly forest and industry residues. In 2018 the national energy generation consumed 19.9 million solid cubic meters of solid wood fuels generating 38.4 terawatt-hours of energy (LUKE, 2019). Though used primarily within forest sector, the produced bioenergy equals to almost 60% of total electricity generation in 2018. In 2018 solid wood fuel consumption remained unchanged compared to the previous year and represented an all-time record in solid wood fuel use. Solid wood fuels consumed in 2018 constituted most importantly of bark (38%) and forest chips from small-size trees (20%) and logging residues (14%). Production of wood products results in increased availability of biofuels from biomass by-products (Eriksson et al., 2009). Of the previously mentioned wood fuels bark and logging residues are by-products from raw material acquisition and processing of sawn logs. All side streams of sawmills can be used to produce pulp or used as fuels (Hassan et al., 2018).

Increasing use of forest biomass will lead to a lower average carbon stock in forests. However, the supply of forest biomass for substitution of fossil energy and carbon intensive material provides a continuing long-term climatic benefit. Substituting wood for coal, oil and natural gas in the energy sector, and concrete, aluminium and steel in material production can result in substantial GHG emission reductions (Sathre and O'Connor, 2010; Gustavsson et al., 2015). Wood product substitution is increasingly recognized as an important element of climate change mitigation. The IPCC (2014b, p.838) states that the integrated optimization of carbon stocks in forests and in long-lived

HWP’s together with efficient use of side-streams and residues can result in the highest GHG benefit in agriculture, forestry and other land sector (AFOLU).

1.2. Construction sector

Substitution potential of wood use is particularly significant in the construction sector, which is one of the largest wood consuming, as well as energy intensive, industries worldwide. The manufacturing and construction industry accounted for roughly one third of both global and national combustion emissions in 2017 (IEA, 2018). The main source of industry emissions is material processing of which 44% is arising from iron, steel and non-minerals (most importantly cement) (IPCC, 2014b, p. 746). The share of concrete related emissions in annual global GHG emissions is 9 %. Likewise, iron, aluminium, copper and four other metals are responsible for 7% of annual global GHG emissions (OECD, 2018). The global steel sector emissions were estimated to be 2.6 $GtCO_2$ in 2006, whereas process-related emissions alone from cement manufacturing accounted for 1.4 $GtCO_2$ in 2010 (IPCC, 2014b, p. 749). The previously mentioned emissions alone equal to global forest carbon sink of almost two years.

Concrete is the most important substitute of wood and holds the largest substitution potential by wood use. Compared to metals, the climate impact per kilogram of concrete is small, but the consumed masses are manifold. Non-metallic minerals are the largest component of global material use and have faced the largest growth in relative terms between the years 1970 (production 9.2 billion) and 2017 (43.8 billion tons). The OECD (2018) projects the use of non-metallic minerals in construction materials to grow from 35 Gt in 2011 to 82 Gt in 2060. This growth is likely to rise from developing countries due to growth in population size and urban areas. Likewise, in the OECD countries the use on non-metallic minerals is likely to increase more than any other material groups.

Wood use in construction provides multiplicative effects on net carbon balance through product and energy substitution. Use of wood material results in lower energy usage and CO_2 emissions compared to alternative materials such as concrete, aluminium and steel (Pingoud and Perälä, 2002; Lippke et al., 2004; Sathre and O’Connor, 2010). A New Zealand study suggests that an increase of 17% in wood usage in national building industry could result in a 20% decrease in carbon emissions arising from the manufacturing of building materials (Buchanan and Levine, 1999). Besides material substitution and capacity to store carbon the climate mitigation potential of long-lived HWP includes several attributes that can decrease carbon footprint of construction sector. In addition to low process energy requirement, manufacturing of wood material does not emit carbon along industrial processes – the calcination reaction alone during cement manufacturing accounts for some 50% of the total emissions of cement production and cannot be decreased through improved technology (IPCC, 2014b, p.758). Instead by-products derived from forestry and sawmill industry can be used to replace fossil fuels. HWPs function as external carbon stocks allowing forest to continuously increase its renewable biomass. External carbon pools in HWP's are transitory, as carbon will eventually return to the atmosphere after product's service life, but the substitution benefit is permanent. Furthermore, cascading use of wood material provides the benefit of secondary substitution when both material and fuel substitution are utilized (Dornburg, 2004).

Wood material has long traditions in Finnish building construction. Almost all recreational homes, and nearly 80% of detached houses, have a wooden frame. Wood accounts for some 40% of all building materials used by the Finnish building construction sector (OSF, 2019). A study by Vares et al. (2017) examined the carbon stock of built environment in Finland in 2016. The scope of the study included all existing wooden residential buildings, industrial buildings and warehouses; office, public and traffic buildings; agricultural buildings as well as wooden infrastructural construction, yard houses, small wooden constructions and civil engineering. The overall carbon stock of built environment accounted for 83.7 $MtCO_2$-eq. The carbon stock of the build environment in 2016 equalled to the average annual increment of almost three years in the 2010s in Finland (Statistics Finland, 2019). Wood construction is generally considered ecological also by the public, and it has been increasing in recent years. According to a building construction survey conducted in 293 Finnish municipalities, residential multi-storey and rowhouse wood building constructions are estimated to increase during years 2018-2020 (Rakennustutkimus RTS Oy, 2018). The estimated increase of the 186 planned multi-storey buildings is twice as much as the number of those built during years 2010-2018. Simultaneously the use of logs and massive wood in row house building is estimated to quadruple. The future of wood construction in Finland looks optimistic but is subject to changes in the economy.

1.3. Carbon accounting

One of the key topics during the Finnish Parliament elections campaigning in spring 2019 were national carbon sinks and future harvest levels. Forest carbon sink decreases directly after harvesting, but substitution of energy intensive materials by wood use provides a long-term climate benefit. In general, the climate change mitigation potential of forests is well recognised, but the climate change mitigation potential of wood product substitution is far less familiar to the general public (Ranacher et al., 2017). In order to justify increased harvesting levels, it is vital to understand the overall impact of forestry on carbon balance.

Half of wood's dry weight is biogenic carbon that has been absorbed from the atmosphere during growth. Wood material can be considered as external carbon stocks because the carbon remains in HWP until disposal. The biogenic carbon returns to the atmosphere as carbon dioxide when wood is disposed and is again re-absorbed by photosynthesis. The longer the wood product's service life is, the longer the HWP carbon stock exists. Carbon sequestration during growth is an advantage for wood material as it offsets some of the life-cycle emissions. Standard EN 16485 sets guidelines for accounting carbon stocks and emissions relating to HWP's (BSI, 2014a). Key condition for regarding carbon stocks as negative GHG emission in life-cycle assessment (LCA) is that the wood is originated from sustainably managed forest (BSI, 2014a) The overall carbon balance is determined by the relation of CO_2 emissions and the remained biogenic carbon in wood material. Carbon accounting can be used to determine the carbon foot print of a certain product or service.

Carbon dioxide is the most substantial greenhouse gas and has accounted for 80-85 percent of all emissions in Finland during years 1990-2018. (Statistics Finland, 2019). It is the largest component of anthropogenic greenhouse gas strengthening the *greenhouse effect,* but not the most intensive. Other GHGs such as methane (CH_4), nitrous oxide (NO_4) and tropospheric ozone (O_3) have larger relative climate effect (IPCC, 2014a, p.87). Greenhouse gases are often measured based on their Global Warming Potential (GWP) using equivalents of CO_2 as a reference. As sample, the GWP of methane during 100-year time horizon is 28 indicating that the impact of atmospheric methane is 28 times greater than that of carbon dioxide (IPCC, 2014a, p.87).

1.4. Wooden construction

Life-cycle emissions of wood-based building materials arise most significantly from raw material acquisition and transportation. Harvesting immediately decreases the carbon sinks in the forest by the carbon content in the harvested wood. Transportation is also a substantial source of emissions in countries where distances are long. However, transportation emissions of wood-based building materials are smaller compared to several substitutes due to relatively light weight (Häkkinen and Wirtanen, 2006). Domestically logs are used exclusively by the sawmills, that produce energy from raw material side streams generating renewable energy surplus. Processing of wood material is not as energy intensive as its alternative as it does not require high temperatures like metals. The remained biogenic carbon in HWP contributes to life-cycle emissions as a negative emission. Some life-cycle assessment studies include maintenance and repairing related emissions, which in reality are often minor. After demolition the biogenic carbon returns to the atmosphere through combustion or decay without creating additional emissions. This is based on assumption of sustainable forest management: in sustainably managed forest harvested wood is gradually replaced by new vegetation. In Finland and other European countries, the disposal of wooden demolition material by landfilling is prevented by EU regulation (EU Waste Framework Directive 2008/98/EC). Without decaying at landfills demolition wood causes only $C0_2$ emissions from combustion followed by energy recovery. However, if a wooden building is replaced with another of the same kind, carbon stock will remain the same (Vares et al., 2017).

1.5. Research aims

The objective of this study is to assess the substitution effects of dominant tree species in Finland at the sectoral level for end-products of the mechanical forest industry. The aim is to assess the substitution effect of domestic pine, spruce and birch saw logs with current consumption trends. The study seeks to answer following questions:

- What is the magnitude of GHG substitution effect of saw logs of Finnish dominant tree species (SF_{TS})?
- What determines the substitution efficiency of Finnish dominant tree species?
- What is the quantity of the overall substitution effect of Finnish mechanical forest industry?

2. Previous literature

Previous substitution effect studies were primarily analysed from Sathre and O'Connor's (2010) meta-analysis, that was until fall 2018 the single most inclusive study on current knowledge of the topic. The study integrated data from 21 international studies on wood products substituting in place of non-wood material. The studied functional units included residential and office buildings, single-family houses, solid wood flooring, window frames, utility poles, roof beams and doors. Two studies covered national construction sectors in Finland (Pingoud and Perälä, 2000) and Switzerland. Several studies were conducted in Nordic countries (9/21), other represented countries were USA, Australia and New Zealand (Buchanan and Levine, 1999). All studies on building construction (altogether 10 studies) considered concrete as the main or one of the substitutes for wood. Half of the studies on building construction regarded steel substitution in addition to concrete. Life span for wood framed apartments and single-family houses was set to 100 years in most studies. All studies included use of demolition waste recovery for energy proposes after service life. The use of logging, processing, construction and demolition residues for energy supply was included in the studies to varying degrees. All Swedish studies regarded all above-mentioned residues as fuel, whereas several studies did not discuss any residues. Some studies included cement process reaction (calcination) and carbonation in carbon emission computation. None of the studies included in the meta-analysis consider the direct impact of harvesting on carbon balance. The collected substitution factors ranged from a low of -2.3 to a high of 15, with most lying in between 1 and 3. The average substitution factor value was 2.1 meaning that for each ton of carbon (tC) in wood products substituting for non-wood material a GHG emission reduction of 2.1 tC (or 3.9 t CO_2eq) occurs.

Leskinen et al. (2018) published a review based on 51 studies and provided information on 433 separate substitution factors. The purpose of the study was to present the most updated knowledge on GHG effect of various wood products and to identify the limitations of current substitution studies. Leskinen et al. (2018) noted what could also be observed from separate substitution studies: carbon accounting is highly dependent on variations in system boundaries. Substitution potential of wood is influenced by the functionality it is used for and the material wood is substituting for. This is due to correlation between substitution factor values and carbon intensity of the replaced

material - climate benefit from carbon intensive coal substitution can increase up to 1 kg C/kg C compared to natural gas or oil (Sathre and O'Connor, 2010). SF's are based on prevalent product design, technologies and energy supply. Future development in mentioned areas of compared materials will lead to changes in substitution efficiency. Substitution factors are therefore not static, but subject to large variation.
Several papers reviewed in this study highlight the need to improve carbon accounting methods by including the substitution effect as well as cascading effect of wood use. Previous studies have focused on construction and little is known about substitution effects of textiles – even less about biochemicals. Most available studies are conducted in Northern America and the Nordic countries hampering geographical representativeness (Leskinen et al., 2018).

Finnish studies on substitution effect of wood use has similarly covered well the construction sector. Koskela et al. (2011) notes that following the principles of life-cycle assessment in environmental impact evaluation is common in the construction industry. There is a consensus that the biogenic carbon stock should offset some the accounted life-cycle emissions of wood products. However, according to the researchers there is a lack of a commonly shared method to accurately measure and report the environmental impact of the biogenic carbon stock in wood material and its release after disposal. Similarly, the environmental impact of land use change and the temporal scope of carbon emissions should be evaluated consistently when assessing life-cycle emissions (Koskela et al., 2011). Ruuska et al. (2013) concluded that material production accounts for a substantial share of buildings GHG life-cycle emissions and highlighted the importance to consider differences between alternative construction materials. Pingoud and Perälä (2000) studied greenhouse impacts of wood construction. The study in question is the only Finnish study included in Sathre and O'Connor's (2010) meta-analysis reviewed here above. Pingoud and Perälä pointed out that the climate change mitigation potential of wood use is based on energy intensive material and fossil fuel substitution rather than using wood products as external carbon stocks. Vares et al. (2017) further denoted that a wooden 4-storey residential building will reduce material based GHG emissions by 40-44 % compared to concrete element building and increase external carbon stock by 174-547 %. The largest increase could be achieved by using massive wood construction products (CLT) in space elements.

Häkkinen and Wirtanen (2006) studied production and transportation stage emissions of two functionally equivalent office buildings one of them being wood framed with wooden cladding. They found 40% smaller CO_2 emissions arising from the studied life-cycle stages of construction materials for the wooden building compared to the alternative concrete building. This was explained by the lightness of used wood frame that accounted for 2000 tons and resulted in consumed 3 500 GJ of non-renewable energy during the studied life-cycle stages. The same function in concrete building weight almost 5000 tons and consumed 7 400 GJ of non-renewable energy during the same life-cycle stages. Soimakallio et al. (2016) studied the overall net carbon emissions of wood utilization in Finland considering all industry interactions within the forest industry. The researchers discovered that extending the system boundaries to include substitution effect of all biomass-based products and industrial side-streams reduced significantly the net carbon emissions of wood utilization. However, the substitution effect was not large enough to offset the combined emissions from raw material acquisition, fossil fuel inputs and other embodied emissions in the scope of production trends in reference year 2010. Seppälä et al. (2019) noted the deficiency of current substitution studies of not taking into account the impact of harvesting on forest carbon sink, wood-based products and fuels. They noted that wood-products may be assumed to mitigate climate change only if the substitution effect is greater that the decrease in carbon stock of extended system boundaries. Seppälä et al. (2019) concluded that 'during the next 100 years increased harvesting of domestic wood will not cause climate benefit if the substitution effects of wood products and fuels correspond to the current situation and forest growth does not substantially increase from the assumed level'.

In addition to meta-analyses and Seppälä et al., other applications of substitution factors from previous literature have not been identified in the scope of this literary review. The substitution effect of Finnish logs as raw material for long-lived building material has until today remained an unidentified research area. Similar studies from other countries have also not emerged during literary review.

3.Methods and data

3.1. Life-cycle assessment (LCA)

LCA is a method to quantitatively assess the environmental impacts of a certain product from raw material acquisition to manufacturing and further from usage to disposal. Global standards 14040 and 14044 by International Organization for Standards (ISO) provide guidelines for life-cycle assessment. This cradle-to-gate approach quantifies all impacts using a category indicator depending on the studied system. There are two approaches to life-cycle inventory (LCI) i.e. quantification of inputs and outputs during all life-cycle stages, which precedes the assessment of life-cycle impacts. Attributional LCA aims at identifying the share of global emissions that results from a certain product. Consequential LCA on the other hand attempts to quantify those global emissions that occur as a result of a change most commonly in demand. Such change could be for example an increase in demand, and consequential LCA would attempt to provide information on the environmental impact that result from the altered required amount of different outputs (Sonnemann and Vigon, 2011). Weidema et al. (2017) argue that LCA should include the impact of change in order to reflect social responsibility, as the interlinked nature of global economy in reality precludes organizations to delimit responsibility to certain specified activities. This implies that LCA should not only assess the direct impacts from supply and value chains, as greater responsibility for producing goods should be taken towards the downstream of the value chain and include the whole product life-cycle.

When examining climate impact of a certain product or service, a commonly used indicator is emissions in kg of CO_2. This is commonly referred to as kgCO_2-eq indicating the reference level of carbon dioxide. However, when quantifying the substitution potential of wood use, the avoided emissions are most commonly expressed in mass units of carbon per mass units of carbon in wood product (often t C/t C). Carbon dioxide can be converted into carbon by dividing its value with the ratio of molecular weights of carbon dioxide and carbon (44/12) (BSI, 2014b). This conversion allows the biogenic carbon stock to be taken into account as negative emissions when assessing climate impact of wood materials.

3.2. Substitution factors

Substitution factors (SF) can be used to evaluate the climate change mitigation potential of wood products as they refer to the avoided emissions by wood use. They are indicators of efficiency with which the use of biomass reduces net greenhouse gas emissions compared to a functionally equivalent alternative (Leskinen et al., 2018). Most substitution studies to date are based on comparison of LCAs that consider GHG emissions from all life-cycle stages of a certain product and the remained carbon content in the end product. Other than CO_2 emissions are converted to CO_2 equivalents based on their GWP. In most cases the reported factor values are positive for wood products indicating that they cause less GHG emissions that non-wood alternatives.

Given a wood-based alternative and a non-wood-based alternative, Sathre and O'Connor (2010) expressed the SF equation as follows:

$$SF = \frac{\mathrm{GHG}_{\mathrm{non-wood}} - \mathrm{GHG}_{\mathrm{wood}}}{\mathrm{WU}_{\mathrm{wood}} - \mathrm{WU}_{\mathrm{non-wood}}} \tag{1}$$

$\mathrm{GHG}_{\mathrm{non\text{-}wood}}$ and $\mathrm{GHG}_{\mathrm{wood}}$ are life-cycle emissions resulting from the use of wood and an alternative material. $\mathrm{WU}_{\mathrm{wood}}$ and $\mathrm{WU}_{\mathrm{non\text{-}wood}}$ refer to the amount of wood used in assessed materials. GHG emissions are expressed in mass units of C, and wood use in mass units of C in the wood material.

The comparison of life-cycle GHG emissions between two products require that they have the same functionality as equal masses of different materials do not fulfil the same function. For that matter substitution factors are always functional unit specific. In construction a functional unit can refer to a certain building component, complete building or a specific human-built function. As an example, the average SF of 1.3 tC /tC for non-structural construction by Leskinen et al. (2018) includes substitution factor values for wood use in windows, doors, cladding, flooring, civil engineering etc. Substitution factors from previous studies can be used to assess the substitution impact by multiplying product volumes by product specific SF value. The term substitution factor is often used interchangeably with displacement factor meaning the same. In this study terms substitution factor and substitution effect are used exclusively.

The primary SF values for long-lived wood products used in this study are from Leskinen et al. (2018). The selected substitution factors describe the substitution effect of wood in structural (1.3 tC/tC) and non-structural elements (1.6 tC/tC) in building construction. The selection of examined functions is based on domestic use of Finnish logs: logs are used by the sawmill industry that produces raw material for the construction sector. Substitution factor for energy usage was used from a study by Lippke et al. (2010). The substitution efficiency of 0.4 tC/tC for energy wood represents a relatively low level of substitution effect. Using a lower substitution factor for short-lived wood products was considered justified as the substitution potential is likely to decrease during upcoming years due to restrictive emission requirement for energy sector. The GHG impact of each tree species is based on current consumption trends. The production volumes are mainly from LUKE's forest product statistics, and the use is estimated from Forecon report (2018) on utilization of Finnish sawn goods and wood-based panels. The substitution effect was estimated by combining information on the quantity of wood products that are produced for each function with function specific SF.

Mechanical forest industry uses logs exclusively and the final use is estimated in Finnish conditions. In the scope of this research exports were omitted, and all production was assumed to be consumed domestically. Therefore, the results of this study should be applied only to Finnish conditions.

3.3. Data

The study was conducted by quantitative means. Production volumes of sawn wood and wood-based panels were collected from Natural Resources Institute Finland's (LUKE) forest product statistics. The averages used in final computation were based on data from years 2015-2018. LUKE's forest product statistics do not contain information on industries with only one operator. Therefore, the production and raw material usage of particle board and fibreboard was estimated by combining interviews and other statistics. Utilization of raw material was of interest as the distribution of different tree species in end-production was often unclear and derived from that in raw material.

The use of produced sawn wood was firstly assessed by focusing on such engineered wood products that were known to be used entirely in either primary functional unit. Such production was examined by interviewing representatives of the selected industries. Raw material usage and production of glulam and cross-laminated timber were inquired from the Finnish Glulam Association[1] and the market leader of domestic CLT markets, Hoisko[2]. The use of above-mentioned engineered wood products is unambiguously in structural elements.

The use of most wood product groups was relatively straightforward to estimate as several of them was used unambiguously for one functional unit only (table 2.). The group of *general sawn wood* deviated from other product groups as it is used in all three examined functions, and the use of different coniferous tree species in different elements is often not specified. The functional units of newbuilding construction in Forecon report (2018) were classified following Leskinen et al.'s (2018) example to structural and non-structural elements as follows: outdoor and indoor wall cladding, ceiling and flooring, doors, windows and civil engineering were included in non-structural construction; structural systems in walls, flooring and roof were included in structural construction. Wood utilization in renovation and other than reported construction were omitted as they can be subject to either structural or non-structural construction. The division of used tree species in each function was estimated from its share on domestic sawn wood production.

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[1] Personal communication, Tero Vesanen, Executive Manager, Finnish Glulam Association, 11.2.2019

[2] Personal communication, Jukka Peltokangas, Research and Development Manager, Hoisko, 4.3.2019

Table 2. Average production and estimated use of wood in function units

	Product	**Production (t m^3)**	**Use in function unit (t m^3)**		
			Structural construction	**Non-structural construction**	**Short-term use**
Pine	Sawn wood	5551	2960	2222	320
	Glulam	160	160		
	Fibreboard	23	13	9	1
	General sawn wood	5319	2787	2213	319
Spruce	Sawn wood	5800	4052	1182	339
	Glulam	316	316		
	CLT	12	12		
	Fibreboard	24	14	9	1
	Particleboard	97	46	44	7
	General sawn wood	5124	3664	1129	331
	Plywood	805	275	157	358
Birch	Sawn wood	44		44	
	Plywood	385	134	76	175

The Forecon report (2018) did not comment on used tree species in its functional units. To generate some variance between the use of pine and spruce, some functions were considered only on either's benefit. Windows and doors were assumed to be of pine and external panelling of spruce. These assumptions were based on raw material usage of one of the leading Finnish window and door manufacturer[3], and traditions in Finnish wood construction.

The end-use on wood-based panels was estimated from Forecon report's (2018) panel statistics. It presented the usage of different wood-based panels in carpentry, short-term use (moulds and other use during construction), new construction and renovations. Carpentry is included in non-structural construction whereas short-term use is excluded from both primary functions. The share of wood used short-term was significant and therefore a third substitution factor was chosen to indicate the substitution potential of wood products in energy sector. New construction and renovations were assumed to focus

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[3] Personal communication, Pekka Kiviniemi, Purchasing Manager, Inwido Finland Oy, 12.3.2019

entirely on structural construction. This is merely because wood panels are more often used as structural elements on walls and flooring, than in cladding.

Since the existing substitution factors indicate the substitution effect by each ton of carbon in wood, the tree species specific carbon content and dry weight of total end-production was computed using carbon content and dry mass conversion factors from previous literature (Karjalainen et al., 1992, Karjalainen and Kelomäki, 1993).

Sensitivity analyses for coniferous trees included two scenarios based on traditional usage and a compromise. The scenario for birch usage included only long-term use. Scenarios are as follows:

- Traditional: *general sawn wood* in primary functional units are used 80/20 (pine) and 40/60 (spruce) in structural and non-structural construction.
- Compromise: *general sawn wood* in primary functional units are used 50/50 (pine) and 50/50 (spruce) in structural and non-structural construction
- Long-term birch products: short term plywood usage is omitted. Plywood is used in non-structural elements exclusively.

4. Results

With current consumption the largest factual substitution effect results from use of spruce in structural construction being 1.12 Mt C (Table 3.). The smallest substitution effect arises from short-term use of birch plywood. Both values are explained by the quantity of tree species in specific functional unit. In general, the substitution potential of birch logs is currently small due to close values in total carbon content and factual substitution effect. This results from low variance of volumes in examined functional units. In addition to substitution effect of each functional unit, the carbon content is also presented in table 3. As shown in equation 1., the C content is used in denominator when dividing the factual substitution effect to discover the SF_{TF}.

Table 3. Carbon content and substitution effect by dominant tree species and function units

	Function unit	Mass (Mt)	C Content (Mt)	Substitution effect (Mt)
Pine	Structural construction	1,15	0,60	0,78
	Non-structural construction	0,87	0,45	0,72
	Short-term use	0,12	0,06	0,03
Total		2,15	1,11	1,53
Spruce	Structural construction	1,67	0,86	1,12
	Non-structural construction	0,52	0,27	0,43
	Short-term use	0,27	0,14	0,06
Total		2,45	1,27	1,61
Birch	Structural construction	0,07	0,03	0,04
	Non-structural construction	0,06	0,03	0,05
	Short-term use	0,09	0,04	0,02
Total		0,21	0,11	0,11

The substitution effect of Finnish tree species varied from a low of 1.03 t C/t C for birch to a high of 1.37 t C/t C for pine (Table 4.). This suggests that for each ton of carbon in used wood product an emission reduction ranging from 1.04-1.37 t C. (3.8–5 t CO_2) is achieved. The value of 1.03 for birch is determined by the use of plywood in short-lived products. Birch plywood is used in functions that demand excellent strength, stiffness and resistance to creep (Finnish Forest Industries, 2002). Such functions include concrete formwork systems, packaging and scaffolding materials as well as floors, walls and roofs in transport vehicles. In this study all wood-based panels were assumed to have similar usage regardless of tree species. The assumption was considered justified as the share of birch in wood-based panel industry is minor and exact information on raw material usage was not available.

Sensitivity analyses showed that the SF_{TF} of coniferous trees are highly sensitive to changes in the use of *general sawn wood* in primary functional units. This is because the group of *general sawn wood* represent some 80% of total production of sawn timber. Results are displayed in table 4. In the baseline scenario representing current consumption pine is used 56/44 in structural and non-structural element. The same division for spruce is 76/24. In Finnish wood construction pine has been traditionally considered less suitable for cladding than spruce and the best alternative for structural elements. If pine in long-lived *general sawn wood* were to be used 80/20 in structural and non-structural elements, the substitution effect would drop to 1.30 tC/tC. This is due to increased volumes in structural construction with lower substitution factor. Similarly, the 40/60 division of spruce in long-lived *general sawn wood* to structural and non-structural elements resulted in substitution factor value of 1.35 tC/tC. If coniferous long-lived *general sawn wood* would be used 50/50 in structural and non-structural elements, substitution effect would be 1.38 tC/tC for pine and 1.32 tC/tC for spruce.

The scenario for birch excluded short-term use of birch plywood. The share of birch plywood in short-term use was originally overstated due to the high reference level of plywood use in general, which consist mainly of pine plywood. If birch plywood was not used for short-term purposes, the substitution factor value would rise to 1.43 tC/tC.

Table 4. Substitution effect in examined scenarios by each ton of carbon used in wood and overall expressed in CO2.

Tree species	**Scenario**	**Substitution effect**	
		t C / t C	**$MtCO_2$**
Pine	Baseline	1,37	5,6
	Traditional	1,30	5,3
	50/50	1,39	5,7
Spruce	Baseline	1,27	5,9
	Traditional	1,35	6,3
	50/50	1,33	6,2
Birch	Baseline	1,02	0,4
	Short-term use excluded	1,43	0,6

Converted into carbon dioxide, the average annual substitution effect of produced sawn goods and wood-based panels in structural and non-structural elements was in the baseline scenario all together 5.6, 5.9 and 0.4 $MtCO_2$ for pine, spruce and birch, respectively. In traditional scenario the substitution effect was 5.3 $MtCO_2$ for pine and 6.3 $MtCO_2$ for spruce. The 50/50 scenario resulted in a substitution effect of 5.7 $MtCO_2$ for pine and 6.2 $MtCO_2$ for spruce. If birch plywood was used only for long-term purposes, the overall substitution potential would increase to 0.6 $MtCO_2$. On average, the annual volume of produced HWP comprises carbon as follows: 1.1 Mt for pine, 1.27 Mt for spruce and 0.11 Mt for birch. Converted into CO_2 this equals carbon stocks of 4.1, 4.7 and 0.4 $MtCO_2$.

5. Discussion

The objective of the study was to assess the substitution effect of Finnish logs according to dominant tree species. The study is based on current consumption trends and existing substitution factors. The obtained results imply that the overall substitution effect of mechanical wood industry in Finland is notable. Contrary to existing ones, this study provides substitution effect values for pine, spruce and birch logs by each ton of carbon contained in timber, which to date has been an unidentified area of research.

As the primary SF's from Leskinen et al. (2018) used in this study are averages based on numerous studies relating to structural and non-structural construction elements, it is uneasy to identify the exact sources of uncertainty behind them. However, the literature review showed that in general the most important attributes hampering applications of exiting SFs relate to their system boundaries and are highly sensitive to future development in product design, technologies and energy supply. A decrease in either product's manufacturing emissions, will decrease the other one's substitution potential. In the future such development in construction sector is likely to result most importantly from restrictive emission requirement for energy sector, that will most likely decrease the relative emissions of energy intensive materials.

In addition to those relating to SFs form previous studies, uncertainties and assumptions about current consumption trends will contribute to the results of tree species specific substitution factors (SF_{TS}). The exact volumes of pine and spruce in structural and non-structural construction was not straightforward to estimate due to lack of up-to-date studies. The latest published end-use study on Finnish sawn wood was conducted in the 1990's after economic depression. Furthermore, the exact used coniferous raw material in wood product is commonly not specified as pine and spruce are technically and seemingly quite similar. The baseline scenario was however seen as the best estimate of current usage of coniferous trees in building construction. The use of spruce in structural elements has increased significantly over recent decades. One of the leading Finnish housing company[4] reported using mainly spruce with a share of 95% in company's

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[4] Personal communication, Tero Vesanen, Executive Manager, Finnish Glulam Association, 11.2.2019

production. Leading CLT massive wood producer[5] informed using 99% of spruce as raw material. This suggests that the conception of spruce primarily as outdoor cladding material is out-dated. Likewise, pine is no longer a dominant material in structural construction. The actual usage of birch might be closest to alternative scenario, where birch plywood is not used for short-term products. Birch wood is more expensive and aesthetically more appreciated than coniferous sawn wood. Short-term usage in high-strength demanding moulds is in practice relatively minor. Without knowledge on exact volumes in birch plywood moulds, short-term usage could rightly be omitted.

The annual average in 2015-2018 of used raw material in sawmill industry was in total 27.8 Mm^3. That includes 11.5 Mm^3 of pine, 14.4 Mm^3 of spruce and 1.1 Mm^3 of birch saw logs. The reduction in forest carbon stock by previously mentioned harvesting volumes equals to 10.2, 10.7 and 1.2 $MtCO_2$, respectively. All together the removal of 27.8 Mm^3 of saw logs results in a decrease of 6 MtC in forest carbon stock. Wood products can be assumed to have a positive net climate impact over time, if the substitution effect is greater than the reduction in forest carbon stock and wood-based products over a defined period of time (Seppälä et al., 2019). The results of this study imply that the overall substitution effect of 3.3 MtC (12,1 $MtCO_2$) together with the external carbon stock of 2.5 MtC (9,2 $MtCO_2$) in produced sawn goods and wood-based panels could already offset the original decrease of 6 MtC (22 $MtCO_2$) from raw material acquisition in forest carbon stock to a decent extent.

Future research should seek to specify the substitution effect in Finnish conditions to eliminate significant variation and uncertainty relating to current substitution factors. SFs from previous literature are not optimal to be applied to Finnish wood products due to differences in production technology and capacity as well as industrial infrastructure. Compared to ones in many other countries Finnish forest industry is exceptional with the ability to maximise the capitalization of industrial side-streams. The substitution effect of Finnish sawn goods and wood-based panels might in reality be even better than suggested here. The effect of harvested biomass on forest carbon pool should also be included in the scope of wood product substitution studies. Even minor changes in SF_{TFS} can have significant impact on avoided emissions. As can be seen from table 4. An improvement

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[5] Personal communication, Jukka Peltokangas, Research and Development Manager, Hoisko, 4.3.2019

of 0,02 in SF_{TF} of coniferous trees, can result to an increase of 0,1 Mt in substitution effect. The amount equals to half of the annual CO_2 emissions caused by Finnish agriculture sector on average during recent years (Statistics Finland, 2019).

Product specific substitution factors could provide valuable information for consumers, businesses and other stakeholders when used in sustainability reporting. Currently there is a lack of a common and consistent method for assessing the overall climate impact of products and services, as well as businesses. Substitution factors provide a single value that determines the superiority of alternatives in the same reference group in sense of emissions. The deployment of SFs among businesses could motivate companies to develop resource efficiency in different functions and units in order to promote social responsibility and improve competitiveness.

6. Conclusions

In 2018 mechanical forest industry consumed some 40% of harvested industrial roundwood which means that two fifths of annual roundwood removal are transformed locally into relatively long-lived wood materials (LUKE, 2018). Even larger climate benefit could be obtained if production of HWP would shift increasingly into primarily producing sawn goods and wood-based panels. This would also increase forest carbon stock through sturdiness of wood as small-diameter trees are used only in chemical forest industry to produce paper and other short-lived HWPs. Carbon stock in building construction in Finland has increased by 23% during years 2000-2016 (Vares et al., 2017) and will further increase if future wood building plans were to be executed.

Prioritizing material use of biomass in Finnish bioeconomy has significant advantages, if the production and usage of domestic long-lived products are supported. This would increase the carbon stock in HWP's and the resource efficiency of Finnish bioeconomy if short-term use of wood is reduced. The overall substitution effect could also result in a significant climate benefit on national level if wood was increasingly used to substitute energy-intensive construction materials. In addition to climate benefit the local production and use of domestic renewable raw material in construction includes significant economic advantages such as employment benefit and value-added production.

Political and global drivers are increasing the demand of wood. The European Commission's Bioeconomy Strategy (2012) highlights the potential of engineered wood in construction sector while building a carbon neutral economy. One of the mentioned key areas in long-term vision of deploying and scaling up the bioeconomy is the substitution of non-sustainable materials in construction by wood.

The climate change mitigation potential of wood materials in construction will increase in the upcoming decades due to growth of urban areas, provided that wooden multi-storey construction increases. This is acknowledged also by the IPCC, as it emphasizes an integrated strategy for climate change mitigation that involves reducing the use of fossil energy and fossil-based materials while enhancing carbon sinks in the LULUCF sector (IPCC, 2018).

The Finnish bioeconomy sector has a highly developed infrastructure that supports efficient and sustainable use of forest biomass and industrial side-streams. Kallio et al. (2018) examined the impacts of potential harvest limitations in Europe. They discovered that a decrease in harvesting by 100 million m^3 in Finland and other European countries would result in a harvest leakage rate of 80% as roundwood removals would shift to other regions. Kallio et al. noted that the climate mitigation benefit obtained through increased carbon sinks (i.e. reduced harvests) in the EU would finally be modest due to increased harvesting in countries with less sustainable forest management. Decreasing production in Finland would also result in increased emissions elsewhere due to weaker possibilities to capitalize industrial side-streams. Eventually decreased supply of roundwood will lead to increased prices and to decreased production of forest product. This would further result in inter-sectoral carbon leakage through increased demand of carbon intensive wood substitutes (Kallio et al., 2018). Importing wood-based building materials in order to execute the existing wood construction plans would significantly increase life-cycle emissions even though most of them would arise outside Finland. Transportation emissions would increase the carbon footprint of building construction even if material were delivered inside the Europe. Palomäki (2018) studied the climate impact of CLT massive wood elements and discovered that transporting CLT elements from central Europe would double the carbon footprint of exterior wall construction.

The Finnish Bioeconomy Strategy (Ministry of Employment and the Economy, 2014) aims at Finland becoming a world pioneer of bioeconomy. Its object is to build a low-carbon, resource-efficient society and a sustainable economy through the efficient use of biomass. The core idea of bioeconomy is a gradual replacement of fossil-based products and fuels with forest biomass (Priefer et al., 2017). The main aim of the national bioeconomy strategy is to generate wealth by increasing the bioeconomy businesses by using bio-based natural resources to produce products and services with high added value (Ministry of Employment and the Economy, 2014). It is thereby of national interest to increase the extent of value added by primarily producing long-lived wood products. As forest carbon sinks are subject to EU regulation, the potential of Finnish mechanical forest industry in providing substitutes for several energy-intensive materials is important to be acknowledged also on international level. In order to combine sustainable forest management with efficient raw material use in Finland and in Europe, a coherent understanding of its integrated climate impact is essential to achieve. In order to reach the ambiguous target of limiting the global temperature rise to well below 2 ° C degrees, a global climate policy with nationally differentiated targets ought to be deployed.

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APPENDIX 1.

Table 5. Annual use of sawn wood in construction on average during years 2017-2018 (Forecon, 2018)

Functional unit	**Volume (m^3)**	**Tree species**	
		Pine	Spruce
External cladding	73		73
Internal cladding	128	128	
Windows and doors	391	391	
Civil engineering	227	115	111
Structural construction	655	333	321
Short-term use	649	331	319
total	2124	1298	825

Table 6. Annual use of wood-based panels on average during years 2017-2018 (Forecon, 2018)

Functional unit	**Volume (m^3)**		
	Particleboard	Fibreboard	Plywood
New construction	17	35	8
Renovation	37	26	9
Construction carpentry	51	40	10
Moulds + worksite use	8	6	23
total	112	107	50