PLASTICS IN BUILDINGS

A STUDY OF FINNISH BLOCKS OF FLATS AND DAYCARE CENTRES

Contents

Abstract

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Around one fifth of all plastics are used in construction. The most typical end-uses of plastics include insulation materials, moisture and damp proofing materials, floor coverings and window frames. Plastics are commonly used also as different kinds of profiles and items related to electrical systems, plumbing, and HVAC systems. Furthermore, most paints, glues, boards, roof coverings, mineral-material based insulations, and laminated surfaces include plastics as raw materials or resins. Plastics can help to achieve many essential technical and functional properties that are vital for modern buildings.

However, plastics cause significant environmental and social harms over their life cycles. Still, thorough studies on the quantities and types of plastics in different types of buildings and in different kinds of building parts are rare. This study aimed at helping to fulfil this gap. The main objective was to assess the quantities and types of plastics used in different types of buildings and in different building parts with the help of a review of the literature and selected real building cases.

The main research method was assessing the types and quantities of plastics in building with the help of case studies. The study focused on residential buildings and daycare centres. With reference to the case studies, the main sources of information were the bills of quantities of the particular buildings studied. In addition, information about plastics in buildings was searched from scientific literature and environmental product declaration databases.

The findings of this study show that plastics are found in all parts of buildings. Their weight, however, is less than one per cent, when compared to the total weight of the building. Some of these plastics would be relatively easy to replace, and part of the plastics used could be recycled with existing practices. A remarkable share of plastics are used in glues, paints and resins that cannot feasibly be recycled with existing methods. Further studies on the environmental and economic consequences of replacing or recycling plastics over the full life cycle of a building are needed.

This report is part of the **Plastics Roadmap for Finland**, which aims at a new, sustainable plastics economy.

1 Introduction

1.1 PLASTICS AND THEIR USE IN CONSTRUCTION

Plastics are synthetic, organic polymers [1]. To create polymers, petroleum and other products are heated under controlled conditions and broken down into smaller molecules called monomers. These monomers are the building blocks for polymers. Different combinations of monomers produce plastic resins with different characteristics, such as strength or molding capability [2]. The vast majority of monomers used to make plastics, such as ethylene and propylene, are derived from fossil hydrocarbons [1]. Plastics are typically divided into thermoplastics that can be remoulded into new products after their initial use and thermosets that can be melted and shaped only once [3]. Other classifications may be made on the basis of the chemical structure of plastics, their physical properties or the chemical process required for their manufacturing. Plastics are light, versatile and usually cheap to purchase. Plastics can be made from fossil or non-fossil raw materials. Both fossil and non-fossil plastics may be biodegradable.

Approximately 8,300 Mt of virgin plastics have been produced to date [1]. This amount mainly consists of polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), polyethylene terephthalate (PET), polyurethane (PU), polystyrene (PS), and polyester (PES). It is estimated that some 30% of this material stock is currently in use [1]. About 60% of all plastics produced have been discarded and are accumulating in landfills and in natural environment. The rest has been incinerated or recycled (Figure 1).

Approximately 42% of all non-fibre plastics have been used for packaging. The building and construction sector is the next largest consumer, accounting for 19% of all non-fibre plastics [1]. With regard to some plastic types, construction uses the majority of all production. For example, 69% of all PVC is used in construction. In addition, PEs, PPs, PS-E (polystyrene expandable) and polyurethane are typical plastics used in buildings [3,4].

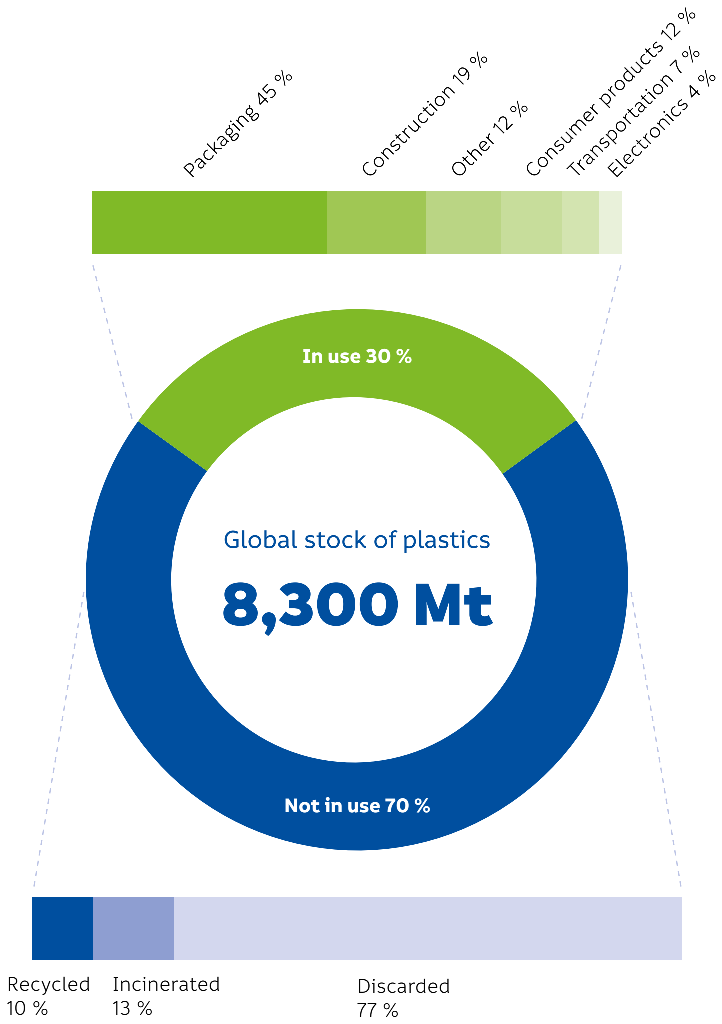
Plastics are used in building products and materials, such as insulation products, products of damp proofing, floorings, and roofing, windows, and laminated surfaces of kitchen and other fitments. Buildings also include several building service installations and devices that contain plastics or are made of plastics, such as pipes. In addition to the plastics found in construction products, the product packaging often contain plastics. Plastics are also used during construction as different kinds of covers, and in tarpaulins. In addition, paints, varnishes, waxes, and glues often have plastics in them. Furthermore, plastics are commonly used in furniture (e.g. cushions, textiles, glues, surface treatments) and in white goods (refrigerators, washing machines, kitchen appliances, media devices etc.). All these add to the total sum of plastics used in the construction sector and in buildings.

1.2 BENEFITS AND CONCERNS ASSOCIATED WITH THE USE OF PLASTICS

Plastics have many advantageous properties that are essential for modern construction technology. They may be light in weight and offer good durability in suitable environments. Plastics help to achieve good thermal, moisture and gas insulation performance, which offer benefits for improving the building physical performance [5]. Their electric insulation properties and fire resistance make plastics important for the production of electric appliances. During construction and renovation processes, plastic tarpaulins and temporary covers help to protect the construction from exposure to weather and dirt.

The plastics industry is an important part of our current economy. The plastics industry is the seventh most value-adding industry in the EU. It consists of almost 60,000 companies with a value of close to EUR 350 billion and that provide some 1.5 million jobs. The contribution to public finances and welfare is estimated to be close to EUR 30 billion [3]. Plastics are important for reaching many of our societies' goals. For instance, vehicles are lighter when plastic components are used to replace heavier components, and this enables fuel savings and lowers related greenhouse gas (GHG) emissions. Plastics in packaging can extend the storage life of many food products, thereby reducing food waste, which is another goal in climate change mitigation. Modern medicine and surgery utilise many features of plastics, from dental care to prosthetics.

FIGURE 1. Production and use of plastics.



However, there are also serious concerns associated with plastics. At present, much attention is paid to plastics, especially because of the rapid increase in their use [6], while at the same time, demands pertaining to circular economies and mitigation of climate change have become more significant.

The relevance of plastic can be studied from the viewpoints of different impacts: environmental pollution and climate change, toxicity, and the scarcity of resources.

Several studies and numerous media articles have illustrated the scale of problem to our environment caused by plastic waste. Micro and nano sized plastics are found in marine life across the oceans, including even isolated areas [7]. It is already unlikely that the condition of the marine environment could recover from its 'plastisphere' condition [8]. In addition, soils around the world suffer from plastic pollution, although this problem is less known [9]. Both marine and soil pollution caused by plastics increase the risks to humans through corresponding food chains. Especially the use of plastics films in intensive farming may pose a threat to the accumulation of plastics in agroecosystems [10]. Plastics seem to have found their way into drinking water around the world[11]. Plastic particles are found in the air that we breathe, and they may carry pollutants with them [12, 13]. Human health risks from plastics can stem from their monomeric building blocks, their additives such as plasticisers, or from a combination of these [2]. Plastics are also floating in the growing cloud of satellite and spacecraft debris that orbits our planet, and it may be impossible to remove them [14]. Worldwide pollution from plastics is estimated to increase by approximately 3% each year [12].

Resource efficiency is another way to examine the issue of plastics. Currently, each tonne of plastics consumes approximately 1.1 tonnes of oil[15]. Given the current production trends, the consumption of fossil oil for plastics would reach 903 million metric tonnes by 2050. This would be 23% of the predicted oil production[16] unless alternative raw materials or recycling are widely applied.

According to Material Economics [4], the consumption of plastics is now increasing at the rate of 10 million metric tonnes per year and the estimated global consumption will reach 800 million tonnes per year by 2050. Recycling rates are still very modest (estimates range from 10 to 30%), but reuse and recycling could supply up to 60% of the demand for plastics by 2050. This would halve the associated GHG emissions. However, recycling does not ultimately remove all plastic waste from circulation, as contamination, additives or wear during their life cycles makes part of plastics less suitable for recycling [17].

Mitigation of climate change can also give relevance to the topic of plastics. According to Global Carbon Project, the remaining 'carbon budget' that can be used without significant risk of causing global warming beyond 2 degrees Celsius ranges from approximately 705 billion metric tonnes [18] to 800 billion metric tonnes of CO_2 [4]. For aiming at the 1.5 degree target, the remaining carbon budget is approximately 550 billion metric tonnes [19]. Continuing the current growth trends of production of plastics, emissions from the production and waste management of plastics alone would range from approximately 226 to 287 billion metric tonnes of CO_2 by 2100 [4].

Depending on the type of plastics, production causes GHG emissions ranging from 1.6 metric tonnes per tonne of plastics to 4.8 tonnes [20]. Furthermore, the hydrocarbon polymer chains in plastics will ultimately be released into the atmosphere when plastics are incinerated for energy or as they decay in nature. Recently, marine plastic litter has been found to emit considerable amounts of strong GHGs (methane and ethylene) when exposed to solar UV radiation [21]. The GHG emissions of some commonly used plastics, based on cradle-to-gate estimations (excluding the manufacture of end products), are listed in Table 1.

TABLE 1. Greenhouse gas estimates for the production of EPS, PU, PP, PE and PVC.

Polymer	Greenhouse gases (kg CO_2e/kg of product, cradle-to-gate)	Source of information
EPS – Expanded polystyrene resin	3.26	PlasticsEurope (2016) [22]
PU – Polyurethane insulation board	2.9	PU Europe (2014) [23]
PP – Polypropylene polymer	1.63	PlasticsEurope (2014b) [24]
PE-HD – High-density polyethylene	1.87	PlasticsEurope (2014a) [25]
PE-LD – Low-density polyethylene	1.80	PlasticsEurope (2014a) [25]
PE-LLD – Linear low-density polyethylene	1.79	PlasticsEurope (2014a) [25]
PVC – Polyvinyl chloride: Suspension PVC (S-PVC)	1.99	PlasticsEurope & ECVM (2015) [26]
Emulsion PVC (E-PVC)	2.56	PlasticsEurope & ECVM (2015) [26]

1.3 MISSING DATA ON CONSTRUCTION PLASTICS

As has become clear, plastics are essential for modern construction but serious environmental and social problems are associated with their use. Interestingly, studies on the quantities and types of plastics in buildings seem to be very rare. Without this knowledge, it would be difficult to manage this material stock in a sustainable manner.

Few research studies have presented information about the types and quantities of plastics in buildings. Information about plastics has been reported as part of overall information about the quantities of different kinds of products in different kinds of buildings. On the basis of a model-house study, Monahan and Powell [27] estimated the quantity of plastics to be 7.4 kg/m^2 (floor area). Ruuska and Häkkinen studied blocks of flats and estimated that the quantity of plastic products is 12–21 kg per 1 m^2 of floor area and the share of plastics is between 0.8 and 2% of all building materials when foundation, piling, soil stabilisation and backfills are not taken into account [28]. Chen et al. [29] studied the quantities of embodied energy in residential buildings in Hong Kong. On the basis of case studies on two 40-storey residential buildings, they showed that PVC for window frames was among the top ten materials used in the erection of buildings. The amounts of PVC in these two buildings were 81 and 77 tonnes, while the overall amounts of the top ten building materials were 17,385 and 10,398 tonnes. Jeffrey [30] claims that plastics typically represent roughly 1% of the total construction and demolition waste, which is another indication of the volume of plastics used in buildings.

However, there is lack of deeper understanding. The aim of this article is not to judge on the use of plastics in construction. Instead, we wish to give a reference for the quantities of plastics found in various buildings and to present our approach to calculating the amount of plastics. Our approach can be utilised and developed further for estimating the benefits, drawbacks and costs of various scenarios for using plastics in construction, including their reuse and recycling potential.

2 Research question and methods

2.1 RESEARCH QUESTIONS

The main objective of this study is to assess the amounts and types of plastics used in buildings. For this purpose, we use a review of the literature and selected real building cases.

Our research questions were as follows:

- How much plastics, and which types, are typically used in buildings?
- How much plastics, and which types, are used in different building parts?
- What share of the plastics used in buildings can be recycled relatively easily?

2.2 METHODS

Our main research method was to assess the types and quantities of plastics in buildings with the help of case studies. We focused on residential buildings and daycare centres. Residential blocks of flats represent the largest share of the building stock in Finland and therefore they are of interest. Daycare centres, on the other hand, as typical municipal buildings may present the possibility of reducing plastics through public procurement criteria. With reference to the case studies, our main sources of information were the bills of quantities of the particular buildings studied.

In addition, we searched the scientific literature for information about plastics in buildings. Relevant articles were searched by using Google Scholar (using as search words, e.g. plastics, the names of different kinds of plastics, building, and construction). This process yielded articles in specific journals. However, the search for literature showed that only a few articles have assessed the types and quantities of plastics in buildings.

In addition, we searched for information about the content and types of polymers in environmental product declaration (EPD) databases. We studied EPDs in The international EPD system [31], EPD Norge [32], and Eco Platform [33].

2.2.1 Description of the buildings studied

The case buildings consist of seven blocks of flats and three daycare centres. All case buildings are real buildings built in Finland during the last twelve years. The case study buildings are presented in Table 2.

TABLE 2. Case study buildings.

Case number	Building type	Completed	Gross floor area (m²)	Frame material
1	Daycare centre	2014	1,177	Wood
2	Daycare centre	2013	1,495	Concrete
3	Daycare centre	2012	1,288	Wood
4–8	Blocks of flats	2015	Total 7,074 Average per building 1,769	Wood
9–11	Blocks of flats	2007	Total 6,753 Average per building 2,251	Concrete

2.2.2 Quantification of plastics in the buildings of the case study

First, we used the bills of quantities (BOQs) provided by the construction companies or the builders to quantify the building materials of each building. The BOQs were converted into bills of materials (BOMs), in which all the construction products were subdivided into their raw materials. We then used the BOMs to identify all products containing plastics and investigated their plastic types. The BOQs used for construction bidding do not always include building service installations and it was not possible to get access to detailed data. In those cases, we based the data on general assumptions about the contents of equipment, energy distribution systems and fire safety appliances.

This investigation was performed using further product data and EPDs.

After the plastics were divided into types, we calculated their weight using typical plastic type densities or the unit weights from technical documentation or building material databases. We then compared the weight of plastics to the other building materials that were used in the same building. Finally, we summarised the results from similar building types and compared the quantity and breakdown of plastic types between the selected building categories.

2.2.3 Applied life cycle scenarios

To illustrate the accumulation of plastics throughout the long technical service lives of buildings, we used study periods of 75 years for residential buildings and 50 years for schools and daycare centres. As the uncertainty of scenarios grows strongly as a function of time, we do not speculate on the accumulation of plastics beyond these time frames. The assumed service lives of plastic products were mainly based on values given for normal or low-burden environments [34].

During the chosen study period, we assumed that some building materials and building service installations would be replaced and that the building would be painted repeatedly. At each round of maintenance, repair, replacement or refurbishment, certain amounts of building materials, including plastics, are removed from the building and new materials, including plastics, are brought in.

2.2.4 Assessment of the potential recycling of plastics

When assessing the potential for recycling, we took into account the following aspects:

- Ease of separating plastics from other materials
- Potential for recycling

As background information for assessing the potential for recycling, we used literature summarised in Chapter 3.2. The potential for recycling is discussed in Chapter 5 on the basis of the assessed results about the quantities and qualities of plastics in the case buildings.

2.3 LIMITATIONS AND UNCERTAINTIES

In this study, we have only considered polymers that are used in construction products and building service appliances (excluding elevators). We have excluded all packaging, household items and furniture because their share would vary from building to building and because they are not usually a result of a building's architectural and engineering design process.

Although the BOQs we used are from real construction projects, they may include mistakes. We have not been able to verify whether the BOQs have been drawn up correctly. Thus, the real amounts of materials in the buildings studied may be slightly different.

It has to be noted that construction projects differ in terms of their coverage. Some projects seem to include more ground and site works than others. Especially the amount of municipal infrastructure and thermal insulation for underground ducts seem to vary. In our study, it was not possible to determine whether the projects are exactly similar and comparable in scope.

For the reasons mentioned above, and as the number of case studies is limited, this study is qualitative in nature. Its results cannot be generalised for larger building stocks in any country. However, the results offer a benchmark for further research, and the method presented here may be usable when other researchers perform similar studies.

2.4. ORGANISATION OF THE STUDY

The study is organised so that Chapter 1 introduces the current state of the art and describes the main idea and importance of this study. Chapter 1 also summarises the sparse information found in recent scientific literature about the types and quantities of plastics in buildings. This chapter (Chapter 2), explains the research questions and the methods used to answer the questions. Chapter 3 describes the use of plastics in different kinds of construction products and recycling potentials. Chapter 4 introduces the case studies and presents the assessment results. Chapter 5 discusses the findings, and Chapter 6 presents the conclusions of the study.

3 Use and recycling of plastics

3.1 USE OF PLASTICS IN BUILDINGS

This chapter summarises the use of different kinds of plastics in building on the basis of the literature and information retrieved from current environmental product declarations.

Building construction and refurbishment utilise plastics as insulation materials, moisture and damp proofing materials, floor coverings, window frames, pipes, ducts, cables, and as different kinds of profiles and items needed for electrical systems, plumbing, and HVAC systems. Plastics (polymers) are also used as components and resins in paints, glues, boards, roof coverings, mineral-material based insulations, and laminated surfaces.

Plastics-based insulation materials include expanded and extruded polystyrene (EPS, XPS), polyurethane (PU) and polyisocyanurate (PIR) [5]. These are mainly made of the polymers in question (see, for example, S-P-00695, [31]). In addition, there can be facing materials and gas residues from manufacturing (see, for example, EPD-PUE-20130285-CBE-EN, [32]). EPS is made from small spheres of polystyrene (from crude oil) containing an expansion agent, e.g. pentane C_6H_{12} [35], while XPS is produced from melted polystyrene by adding an expansion gas, e.g. HFC, CO_2 or C_6H_{12}.

Rigid polyurethane foam (PUR) is one of the most important PU products; in particular, it is usually utilised to produce insulation material for building façades [36]. PUR is formed by a reaction between isocyanates and polyols (alcohols containing multiple hydroxyl groups). During the expansion process, the closed pores are filled with an expansion gas — HFC, CO_2 or C_6H_{12}. PUR may also be used as an expanding foam at the building site, e.g. to seal around windows and doors and to fill various cavities [35].

More than half of all PVC is used in the building industry. 38% of global production is used for pipes, and 20% is used for window profiles [37]. PVC products are produced through polymerisation, where vinyl chloride molecules are linked together to yield polyvinyl chloride, typically a white powder. Further on, pure PVC is mixed with other chemicals such as stabilisers, plasticisers, and colourants to yield a usable plastic with the desired properties [38]. PVC is also used in floorings. In accordance with EPD-ERF-2013111-E [32], the composition of PVC flooring sheets includes 33% PVC and 15.4% recycled PVC flooring. Based on EPD-AMO-20150058-IAA2-EN [32], vinyl cork flooring includes 8.9% PVC and 3.6% adhesive, while the main components are HDF board and cork. In addition, rigid plasticised PVC is commonly used in window profiles and other profiles [39] as well as in roofing sheets [40]. In accordance with EPD-QKE-20150313-IBG1-DE [33], PVC-framing accounts for 28.2% of the overall weight of a window (double-glazed, 1.23 x 1.48 m).

The share naturally varies in accordance with the number of glazes and the size of the window. PVC is used in construction for PVC sidings, gutters, drain pipes, waste and ventilation applications, surface water and storm water applications, and for conduits for electrical and communication applications including cable coating and cable ducts [30,41]. In accordance with S-P-00716, the pipes and conduits are made from unplasticised PVC (PVC-U), which makes up 82% of all raw materials.

Polyethylene (PE) based plastic films are used as moisture barriers and packing materials. For example, plastic sheet for damp proofing of floors, walls and roofs — as reported in NEPD-1230-387-EN [32] — is based on PE. PE is also used in drain pipes [39]. In addition, PE is widely used as an electrical insulator because of its dielectric properties [42].

Polypropylene (PP) is used in some HVAC and plumbing related products, such as in air-conditioning pipes, sewer pipes, and floor drains [41]. For example, pipes used for drain, rain and storm water — reported in NEPD-1507-513-NO [32]— are based on PP. It is also used in components inside washing machines and dishwashers [41].

Polymers are also used in flexible bitumen sheets for roof waterproofing. For example, the bitumen sheets reported in the International EPD System declaration S-P-00414 [31] are based on bitumen and polymers reinforced with polyester fleece or glass mat and possibly finished with PP film, slates etc. The content of polymers [assumed to be styrene-butadiene-styrene (SBS) co-polymers] is 6–10% and reinforcement 2–4%.

Acrylonitrile butadiene styrene (ABS), polycarbonate (PC) and PET are used in household appliances and lighting items [41].

Many building products contain different kinds of resins, in small amounts. Phenolic resin is added to both glass wool and rock wool, to bind the fibres together and improve product properties [35]. Based on EPD Norge data, the content of resin used for glass wool manufacture is <8% (see, for example, NEPD-1533-524), and the content of resin (phenol-formaldehyde-urea copolymer) used for manufacturing rock wool sheets is <6% (see, for example, NEPD00267E [32]).

Resins of different composition are also used in building boards. For example, as declared in NEPD-1326-428, medium-density fibreboards (MDFs) for the roof and walls include wood fibres and roughly 8% resins [urea-formaldehyde (UF), melamine-urea-formaldehyde (MUF)]. In accordance with NEPD00274E, particle boards include 12–15% glues. Correspondingly, building products that include fibre or particle boards — used, e.g. in exterior and interior doors and kitchen fittings — typically contain resins [32].

Laminate floorings contain small amounts of resins. For example, in accordance with EPL-20150021-CBE1-EN, laminate floor covering contains 4–6% resin while the main component is high-density fibre (HDF) board. Linoleum floorings may be covered with acrylic wax for protection (0–1% of weight in accordance with S-P-01218). Parquet floorings include small amounts of glues and lacquer (2% in accordance with EPD-MWS-2060176-CBC1-EN) [33].

The binding materials of paints and lacquers are polymers — such as acrylate co-polymers, epoxy and polyurethane — or natural materials that bind the components together and bind the paint to the surface. According to the model formulations used by Häkkinen et al. [43], the share of the acrylate binding component was 15–20% in water-based stain and 25% in water-based opaque topcoat, while the assessed spreading rates of acrylic dispersions were 2x150ml/m^2 for stain and 2x125 ml/m^2 for opaque.

3.2 RECYCLING POTENTIALS OF PLASTICS USED IN BUILDINGS

This chapter summarises results based on the literature about the recycling potential of plastics typically used in buildings.

The recycling of plastics can be outlined in different ways. A three-step categorisation has been used by Eskelinen et al. [44]. Primary recycling means closed-loop mechanical recycling, which uses plastic waste for original use purpose. Secondary or open-loop mechanical recycling means collection and formation into other plastic products. Mechanical recycling involves the melting of the polymer but not its chemical tranformation. Tertiary recycling is feedstock recycling or chemical recycling, where a certain degree of polymeric breakdown takes place. Chemical recycling takes place in Europe to a much smaller extent than mechanical recycling [41]. The bulk of mechanically recycled plastics is converted into intermediates such as flakes, agglomerates, regrind, pellets, granulates and profilers while the remainder is converted directly into products [45].

Currently in Finland, the main part of separately collected plastic waste is not recycled but used for energy recovery. The most recycled plastics are polyolefins and PET, and the most common uses of recycled plastics include packages, pipes, profiles, and some consumer products such as buckets and hangers [44].

According to Eskelinen et al. [44], the estimated shares of different plastics in building and demolition waste in Finland in 2017 are as follows: PVC 50– 55%; PS 14–19%; PU 3 –8%; and PE-HD 4–9%.

The Waste Framework Directive of the European Union [46] sets a recycling target of 70% for construction and demolition waste, to be achieved by EU Member States by 2020. However, according to AEA and BIO [37] in 2008, 35% of all construction and demolition plastic waste in Europe (EU-27 , Norway and Switzerland) went to energy recovery, only 16% to mechanical recycling, and the rest was sent for disposal. The share of mechanically recycled waste reported by Villanueva and Eder [41] was 20%.

Although the construction sector is the second largest consumer of plastics in Europe (21%), it accounts for 6% of the plastic waste generated per year. The main reason for this is that plastics used in construction often have a significantly longer design life than plastics used for other purposes [37].

The main applications generating waste in the construction and demolition sector are fitted furniture, floor and wall covering (PVC), pipes, ducts, insulation materials (PU) and profiles (PVC) [41]. Villanueva and Elder [41] also report that the polymer types used in construction are often characterised by the need for good resistance to UV-radiation and mechanical impacts. These plastics often have a high content of fillers (over 20–30%) such as talc and limestone, to increase resistanace to abrasion. If plastics include recycled materials, it is common to use a sandwich structure where recycled materials are placed between two layers of virgin material, because the virgin layers have better mechanical and chemical properties.

Thornton [38] states that the different kinds of additives present in different kinds of PVC products make post-consumer recycling of mixed PVC products difficult, and that the recycling process therefor does not yield vinyl products with qualities equivalent to those of the original. According to Janajreh et al. [40], the high hydrogen chloride content and concern over the emission of dioxins and furans hinder the thermochemical conversion of rigid plasticised PVC. They also claim that mechanical recycling of post-consumer PVC waste is an attractive route when feeding from a single homogeneous source — such as the cable industry — rather than from mixed municipal solid waste. They analysed the composition of PVC waste stream from the cable industry and suggest that PVC cable polymer can be reutilised in a nearby sustainable manufacturing. Sadat-Shojai and Bakhshandeh [47] contend that landfilling and composting are not suitable recycling methods for PVC because of the unknown hazards associated with the oxidative degradation of PVC in the environment. Incineration and pyrolysis may also be disfavoured because of the large amounts of hydrogen chloride and other toxic products that are produced. They prefer mechanical recycling if clean PVC with a known composition and previous history is available. Jakubowicz et al. [48] tested the mechanical recycling of old PVC flooring materials obtained from three apartment blocks. The focus of the study was to investigate how ageing processes change the important properties of PVC floorings during their service life and how these changes can influence the suitability of PVC floorings as post-consumer products for recycling. They claim that PVC floorings as plastic waste can be mechanically recycled in the form in which they were recovered without upgrading and without the addition of new plasticiser. Hamad et al. [42] also propose different kinds of mechanical recycling methods for PVC, and Coelho and Brito [49] and Jeffrey [30] report successful cases in different countries. Typical end-uses of recycled PVC waste include window frames, pipes, and flooring [41]. However, Sadat-Shojai & Bakhshandeh [47] claim that although a number of new approaches have been proposed for the separation and recycling of PVC wastes, none are completely satisfactory in terms of economics and/or performance.

Zia et al. [50] studied methods for the recycling and recovery of polyurethane composite. They concluded that especially for rigid PU foam from construction and demolition waste, the recovery of energy can be considered the best disposal option. Thermosetting plastic insulation materials are hard to consider as closed-loop cycling materials [51].

Expanded polystyrene insulation is used regularly in residential developments, resulting also in high volumes of plastic waste [30]. Typical end-uses of recycled PS waste include thermal insulation and electrical appliances [41]. Although a high volume of EPS waste is generated, its relatively low density makes it inconvenient for reuse [52]. Expanded PS foam waste loses its foam characteristics during the recovery process. The recovered material can be re-gassed, but the product becomes more expensive than virgin material [53]. Although recycled EPS foam lacks the same expansion characteristics as virgin foam bead and requires different treatment during processing, it has been used for composite materials [54]. Kan and Demirboğa [54] propose a new technique of processing for waste-expanded polystyrene foams as concrete aggregates, and Amianti and Botaro [55] suggest a new methodology for the production of concrete impregnated with polystyrene.

Typical end-uses of recycled PE-LD waste include cable insulation [41], various kinds of profiles and plastic tiles, and composites such hot-pressed composites of recycled pine wood fibres and recycled PE with mechanical properties suitable for construction applications. as reported by [56].

Polymers are also contained as minor components in several fractions of demolition waste, such as in mineral wool. Väntsi and Kärki [57] report on different possibilities that have been suggested and studied for recycling of mineral wool waste, such as using rock wool waste as aggregate material in cement-based composites, the use of mineral wool as an artificial substrate to grow various plants in cultures without soil, and the use of mineral wool for wood–mineral wool hybrid particleboards.

Systems for collecting plastic waste are currently not envisaged during the design of construction sites, and the management of this waste stream for plastics is still at an early stage [37].

4 Results

4.1 SUMMARY OF PLASTICS IN THE BUILDINGS STUDIED

In this chapter, we first present the overall results and then provide detailed inventories, case by case. The results are further discussed and compared in Chapter 5.

The total consumption of plastics in the buildings studied ranged from 23 to 51 tonnes per building during their life cycle (Figure 2). Residential buildings and wood-framed daycare centre were found to be roughly in the same range, whereas the concrete-framed daycare centre had clearly more plastics on its materials list. Most of the plastics (58–79%) were placed into the buildings during their initial construction phases.

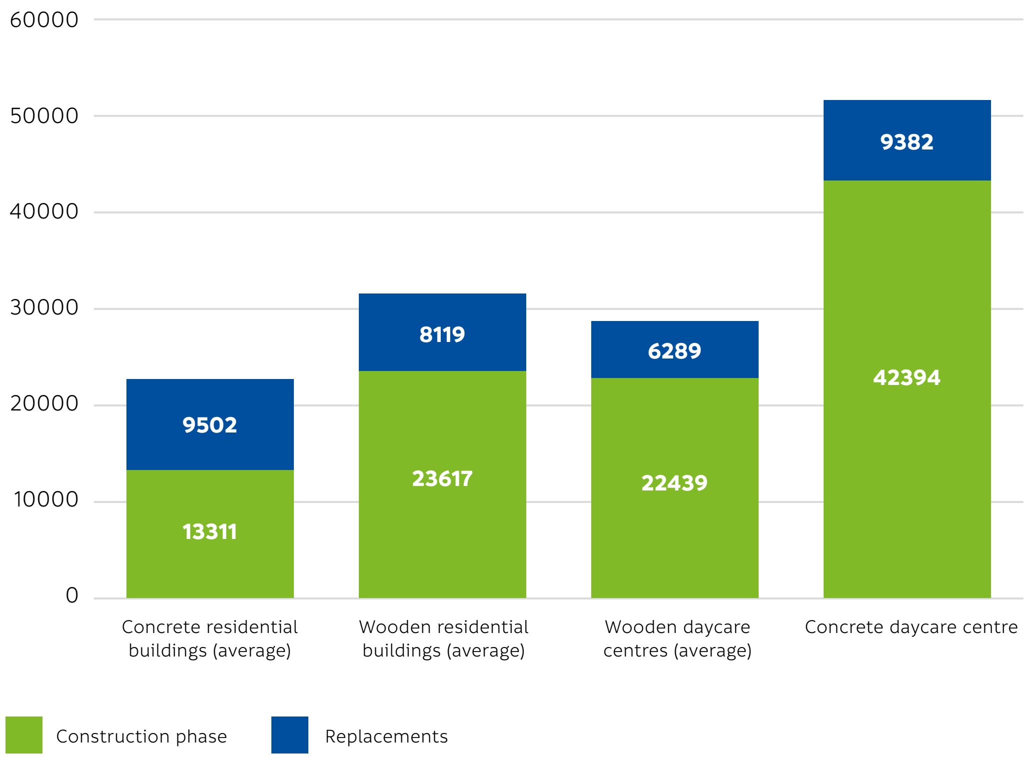
To illustrate the role of plastics further in the buildings studied, we present additional indicators:

- Amount of plastics relative to the floor area of the buildings (Figure 3).
- Distribution of plastics in different parts of the buildings relative to the floor area (Figure 4).
- Weight of plastics in different building parts in relation to the overall weight of all materials in the corresponding building parts (Table 3).

In our examples, there is considerable variation between building types (Figure 3). The share of plastics relative to the floor area was clearly greater in the daycare centres (average 21 kg/m^2 in the construction phase) than in the residential buildings (average 10 kg/m^2 in the construction phase). On average, the amount of plastics relative to the floor area in the residential buildings was only 47% of the amount in daycare centres.

The frame material had some effect on the quantities of plastics in our cases. In the daycare centres, the wood-framed solutions resulted in less plastic during the construction phase than in concrete-framed alternative (18 vs. 28 kg/m^2). The opposite was found for the residential blocks of flats. In our residential cases, the wood-framed examples had more plastics in their structures than the concrete-framed buildings (13 vs. 6 kg/m^2).

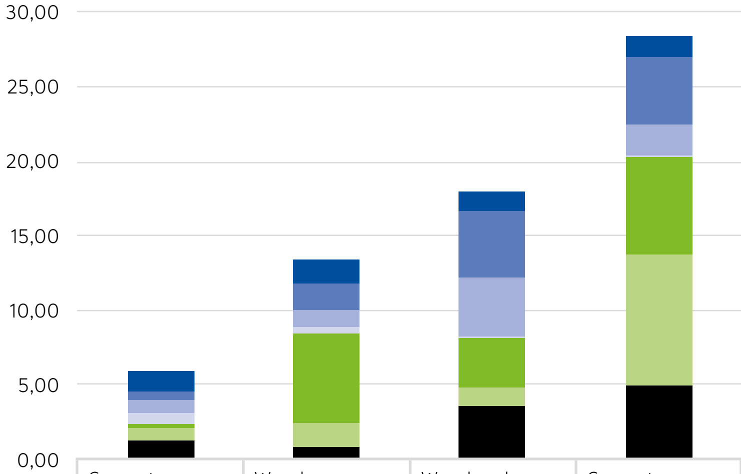
FIGURE 2. Total sum of plastics in the buildings studied (kg)



No clear trend was detected for the distribution of plastics to different building parts. Depending on the building, the amounts of plastics varied considerably. The only clear trend detected was for electrical parts, for which the amount of plastics per m^2 had a similar range in different buildings (Figure 4).

We also compared the weight of plastics in each building part to the weight of all materials in the building part (Table 3). We found that the relative share of plastics is very high in electrical parts and second highest for other building services. This trend was found to be constant in all of the buildings studied. The relative share of plastics in other building part types was less than ten per cent of the total weight of a particular building part type all structural parts and mostly less than one per cent. It should be kept in mind, however, that the total quantities of plastics can be considerably higher in other building part types (Figures 3 and 4).

FIGURE 3. Amount of plastics relative to floor area (kg/gross m²).

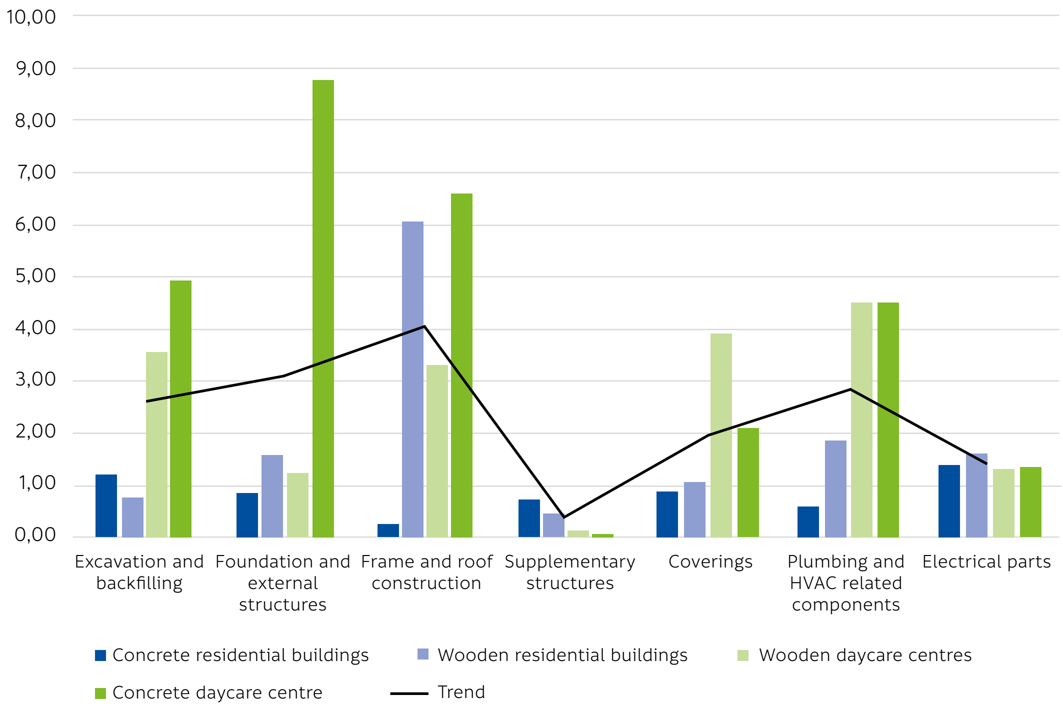


	Concrete residential buildings	Wooden residential buildings	Wooden daycare centres	Concrete daycare centre
Electrical parts	1,39	1,59	1,33	1,35
Plumbing and HVAC components	0,60	1,85	4,51	4,51
Coverings	0,88	1,05	3,91	2,10
Supplementary structures	0,72	0,46	0,14	0,07
Frame and roof construction	0,27	6,06	3,32	6,60
Foundation and external structures	0,84	1,60	1,23	8,78
Excavation and backfilling	1,22	0,76	3,56	4,94

TABLE 3. Weight of plastics in different types of building parts relative to their overall weight.

	Concrete residential buildings	Wooden residential buildings	Wooden daycare centres	Concrete daycare centre
1. Excavation and backfilling	0.04%	0.05%	0.04%	0.18%
2. Foundation and external structures	0.27%	0.46%	0.16%	0.21%
3. Frame and roof construction	0.02%	0.75%	0.81%	0.17%
4. Supplementary structures	0.02%	0.75%	0.78%	0.17%
5. Coverings	1.21%	1.65%	7.48%	0.19%
6. Plumbing and HVAC related components	9.41%	27.7%	8.98%	8.98%
7. Electrical parts	68.35%	63.7%	45.27%	50.11%

FIGURE 4. Variation of plastics in different parts of the studied buildings (kg/gross-m^2).



4.2 CONCRETE RESIDENTIAL BUILDINGS

Tables 4 and 5 present the assessment results for concrete residential buildings. Table 4 shows the use of plastics in different types of building parts, and Table 6 lists the quantity of different types of plastics used during the construction phase and for replacements during the building's service life.

According to the results, concrete residential building contains 0.11% of plastic materials out of the total concrete building mass (Table 4). This represents approximately 6 kg of plastics per gross-m^2 of building. When product replacements are also taken into account, the total quantity of plastics was approximately 10 kg/m^2.

The main plastic types used in concrete buildings were PVC, PP, EPS and PE-HD. These together represented more than 50% of all plastics in the case concrete buildings (Table 5).

TABLE 4. Mass of building structures with plastics and total building mass (concrete residential building, average calculated for three buildings, construction phase).

	Plastics (kg per building)	Share of plastics in each category	Plastics (kg/m²)	Total weight (kg)	Share of plastics out of the mass of the building
1. Excavation and backfilling, including external horizontal frost insulation, external pipes and ducts, and wells	2,750	0.04%	1.22	7,075,277	0.02%
2. Foundation and external structures	1,889	0.27%	0.84	693,891	0.02%
3. Frame and roof construction	604	0.02%	0.27	3,232,138	0.01%
4. Supplementary structures	1,620	0.02%	0.72	658,252	0.01%
5. Coverings	1,978	1.21%	0.88	163,377	0.02%
6. Plumbing and HVAC related components	1,347	9.41%	0.60	14,318	0.01%
7. Electrical parts	3,123	68.35%	1.39	4,569	0.03%
Total	**13,311**		**5.91**	**11,841,822**	**0.11%**

TABLE 5. Main plastics consumed in concrete residential buildings during life time (construction and replacements).

Plastic type	Main use in the buildings	Quantity	Share
PVC	Cables ducts, window frames, PVC flooring	4,129 kg	18%
PP	Pipes, filter fabrics	3,049 kg	13%
EPS	Frost insulations, vertical insulations	2,575 kg	11%
PE-HD	Pipes, wells	2,076 kg	9%
PU	Window paintings, powder paintings	1,907 kg	8%
MUF	Laminate floorings	1,552 kg	7%
Butyl sulphide	Window seals	1,245 kg	5%
SBS	Bitumen roofing	1,218 kg	5%
Polyester	Bitumen roofing, insulations, acoustic boards	1,045 kg	5%
Epoxy resin	Epoxy resin	812 kg	4%
Acrylate	Paints	566 kg	2%
PC	Sockets and lighting items	510 kg	2%
PVB	Laminated glass windows, window walls	442 kg	2%
Silicon	Sealing and jointing materials for windows and doors	400 kg	2%
TPE	Window sealants	348 kg	2%
Phenolic resins	Hard boards	187 kg	1%
Formaldehyde resin	Veneers	120 kg	1%

TABLE 6. Complete list of plastics consumed in the concrete residential buildings studied (construction and replacements).

Plastics type	Construction kg/building	Replacements kg/building	Total kg/ building	Total kg/ gross m²	Share of the total
ABS	1	2	3	0.00	0.01%
Acrylate	151	415	566	0.25	2%
Butyl polysulphide	249	996	1,245	0.55	5%
Epoxy resin	217	596	812	0.36	4%
EPR	51		51	0.023	0.2%
EPS	2,215	360	2,575	1.14	11%
Formaldehyde resin	120		120	0.05	1%
MUF	517	1,035	1,552	0.69	7%
PA	22		22	0.01	0.1%
PC	170	340	510	0.23	2%
PE-HD	1,630	446	2,076	0.92	9%
PE-LD	1	1	2	0.00	0.01%
PE	45		45	0.02	0.2 %
PEX	1		1	0.02	0.002%
Phenolic resin	63	124	187	0.08	1%
Polyester	707	337	1,045	0.46	5%
Polyether	3	6	8	0.00	0.04%
Powder paint	101	364	465	0.21	2%
PP	1,781	1,268	3,049	1.35	13%
PU paint	288	1,154	1,442	0.64	6%
PUR	7	12	19	0.01	0.1%
PVAc glue	112		112	0.05	0.5%
PVB	442		442	0.20	2%
PVC	3,352	776	4,129	1.83	18%
SBS	532	686	1,218	0.54	5%
Silicone	99	301	400	0.18	2%
TPE	70	278	348	0.15	2%
XPS	326		326	0.14	1%
Unspecified	39	6	45	0.02	0.2%
TOTAL (kg)	**13,311**	**9,502**	**22,812**	**10**	**100%**

4.3 WOOD-FRAMED RESIDENTIAL BUILDINGS

Tables 7, 8 and 9 present the assessment results for residential buildings where timber is used for load-bearing structures. Table 7 shows the use of plastics in different types of building parts, and Table 9 lists the quantity of different types of plastics used during the construction phase and for replacements during the building's service life.

The wood-framed residential case buildings contain 0.48% of plastic materials out of the total building mass during the construction phase. This represents 13 kg of plastics per every gross m^2 of building. When the replacements made during service life are taken into account, the total quantity of plastics is 18 kg/m^2.

The main plastic types in the wood-framed case buildings according to their total mass were PVC, PUR, PP, EPS, PE-HD, and EPI. Out of all plastics, together they represent more than 60% of the plastics used during the construction and refurbishment phases.

TABLE 7. Mass of building structures with plastics and total building mass.

	Plastics (kg per building)	Share of plastics in each category	Plastics (kg/m²)	Total weight (kg)	Share of plastics in the mass of the building
1. Excavation and backfilling	1,345	0.051%	0.76	2,663,615	0.03%
2. Foundation and external structures	2,822	0.46%	1.60	615,803	0.06%
3. Frame and roof construction	10,710	0.75%	6.06	1,424,252	0.22%
4. Supplementary structures	806	0.75%	0.46	73,535	0.02%
5. Coverings	1,860	1.65%	1.05	112,895	0.04%
6. Plumbing and HVAC components	3,263	27.7%	1.85	11,801	0.07%
7. Electrical parts	2,812	63.7%	1.59	4,415	0.06%
Total	**23,617**		**13.4**	**4,906,316**	**0.48%**

TABLE 8. Main plastics consumed in the residential wood buildings during life time (construction and replacements).

Plastic type	Main use in the buildings	Quantity	Share
EPI + PU	Cross-laminated timber structures, glues	4,060 kg	13%
PUR	Frame, roof construction, sound insulation	3,828 kg	12%
PVC	Cables, ducts	3,743 kg	12%
PP	Pipes, fabrics	3,450 kg	11%
EPS	Insulation material in floors	2,799 kg	9%
PE-HD	Sprinkler pipes, fabrics used in green roofs	2,253 kg	7%
Polyester	Bitumen fabrics bitumen roofing, insulations boards	1,803 kg	6%
PU	Paints, powder paints	1,490 kg	5%
SBS	Bitumen moisture barriers	1,371 kg	4%
Acrylate	Paintings	1,225 kg	4%
UF and MUF	Resins in chip boards	1,137 kg	4%
Butyl sulphide	Window seals	854 kg	3%
PEX	Pipes	821 kg	3%
XPS	Frost insulations, floor insulations	705 kg	2%
Formaldehyde	Resins in veneers and HDF boards	519 kg	2%

TABLE 9. Complete list of plastics consumed in the wood-framed residential buildings studied (construction and replacements).

Plastic type	Construction kg/ building	Replacement kg/ building	Total kg/ building	Total kg/m²	Share of the total %
ABS	1	2	3	0.0017	0.01%
Acrylate	307	918	1,225	0.69	3.9%
Alkyd + varnish	160	161	321	0.18	1%
Butyl polysulphide	171	683	854	0.48	3%
CR	64	0	64	0.036	0.2%
EPI + PU	4,060	0	4,060	2.30	13%
Epoxy resin	47	129	175	0.069	0.5%
EPR	64	0	64	0.036	0.2%
EPS	2,470	329	2,799	1.58	10%
Formaldehyde resin	249	269	519	0.29	2%
PA	6	0	6	0.0035	0.02%
PC	143	286	428	0.24	1%
PE-HD	1,751	502	2,253	1.27	7%
PE-LD	35	2	37	0.021	0.1%
PEX	702	119	821	0.46	3%
Polyester	1,494	309	1,803	1.02	6%
Polyether	3	6	8	0.0047	0.03%
Polyolefin	4	0	4	0.002	0.01%
Powder paint	124	377	500	0.28	2%
PP	2,381	1,070	3,450	1.95	11%
PRF	35	0	35	0.020	0.1%
PU in paint	198	792	990	0.56	3%
PUR	3,743	85	3,828	2.16	13%
PVAc glue	38	0	38	0.022	0.1%
PVC	2,904	839	3,743	2.12	12%
SBS	664	708	1,371	0.78	4.3%
Silicone	47	188	235	0.13	1%
TPE	48	190	238	0.13	1%
UF + MUF resins	1,137	0	1,137	0.64	3.5%
XPS	564	141	705	0.40	2%
Unspecified	5	14	20	0.011	0.06%
TOTAL	**23,617**	**8,119**	**31,735**	**17.9**	**100%**

4.4 DAYCARE CENTRES

The daycare centres studied represent typical examples of the building category. The frame material for two of them is wood while the frame material for one is concrete.

4.4.1 Wooden daycare centres

In wood-framed daycare centres, the total share of plastics is 0.23% of their weight. This represents 18 kg of plastics per every gross m^2 of building. When the replacements made during service life are taken into account, the total quantity of plastics is 23 kg/m^2.

As to the distribution of masses, most of the plastics are found in ground works, the frame, coverings and HVAC components. Table 10 shows the distribution of plastics in different types of building parts.

TABLE 10. Share of plastics in wood-framed daycare centres (construction phase).

Building part		Plastics (kg per building)	Share of plastics in each category	Plastics (kg/m²)	Share of plastics out of the mass of the building
1	Excavation and backfilling	4,551	0.04%	3.56	
2	Foundation and external structures	1,540	0.16%	1.23	
3	Frame and roof construction	4,168	0.81%	3.32	
4	Supplementary structures	184	0.78%	0.14	
5	Coverings and surfaces	4,796	7.48%	3.91	
6	Plumbing and HVAC components	5,561	8.98%	4.51	
7	Electrical parts	1,639	45.27%	1.33	
	Total	**22,439**		**18.01**	**0.23%**

TABLE 11. Main plastics consumed in wood-framed daycare centres (construction and replacements).

Plastic type	Main use in the building	Quantity	Share
PVC	Floorings, HVAC components	6,185 kg	21%
EPS	Thermal insulations, frost insulations	5,095 kg	18%
PE-HD	Pipes, cables, HVAC installations, electric parts	4,420 kg	15%
SBS	Bitumen roofs	3,347 kg	11%
PES	Floor covers, trims, roofing, HVAC components	2,453 kg	8%
PE-LD	Vapour barriers	1,699 kg	6%
PP	Building service components	1,318 kg	5%
EPDM	HVAC components, playground´s safety surface	1,026 kg	4%
Other plastics	Various building parts	3,648 kg	11%
Total		**29,125 kg**	

TABLE 12. Complete list of plastics used in the wood-framed daycare centres studied.

Plastic type	Construction kg/building	Replacements kg/building	Total kg/ building	Total /m² kg/m²	Share out of the total
ABS	1	1	2	0.00	0.01 %
Acrylate	157	235	392	0.32	1.35 %
EPDM	964	62	1,026	0.81	3.52 %
Epoxy	248	165	413	0.32	1.42 %
EPS	4,920	175	5,095	3.97	17.49 %
Fenolic resin	129	0	129	0.10	0.44 %
Formaldehyde	189	0	189	0.11	0.65 %
MF	34	34	68	0.06	0.23 %
MUF	23	0	23	0.01	0.08 %
Other	71	11	82	0.07	0.28 %
PA	1	0	1	0.00	0.00 %
PC	22	21	43	0.04	0.15 %
PE-HD	4,077	343	4,420	3.56	15.18 %
PE-LD	1,222	477	1,699	1.33	5.84 %
PE-MD	129	0	129	0.10	0.44 %
PES	1,601	852	2,453	1.97	8.42 %
PES resin	476	317	793	0.67	2.72 %
PEX	580	2	582	0.47	2.00 %
PMMA	13	0	13	0.01	0.04 %
PP	1,165	152	1,317	1.06	4.52 %
PPSU	0	0	0	0.00	0.00 %
PRF glue	45	0	45	0.00	0.15 %
PUR	630	43	673	0.53	2.31 %
PVC	3,962	2,223	6,185	5.11	21.24 %
SBS	2,015	1,332	3,347	2.76	11.49 %
XPS	3	1	4	0.00	0.01 %
Total	**22,677**	**6,448**	**29,125**	**23.4**	**100%**

4.4.2 Concrete daycare centre

In the concrete-framed daycare centre, plastics account for 0.2% of the total weight of the building. In terms of mass, most of the plastics were concentrated in the foundations and external structures. This is because the building studied was built on a large concrete slab that required a great amount of thermal frost insulation materials. Thus, this amount of plastics may not be representative of all concrete-framed daycare centres.

TABLE 13. Share of plastics in the concrete-framed daycare centre studied (construction phase).

Building part	Plastics (kg per building)	Share of plastics in each category	Plastics (kg/m²)	Share of plastics out of the mass of the building
1. Excavation and backfilling	7,390	0.18%	4.94	
2. Foundation and external structures	13,131	0.21%	8.78	
3. Frame and roof construction	9,861	0.17%	6.60	
4. Supplementary structures	112	0.17%	0.07	
5. Coverings and surfaces	3,141	0.19%	2.10	
6. Plumbing and HVAC components	6,746	8,98%	4.51	
7. Electrical parts	2,013	50.11%	1.35	
Total	**42,394**		**28.36**	**0.20%**

TABLE 14. Main plastics consumed in the concrete-framed daycare centre studied (construction and replacements).

Plastic type	Main use in the building	Quantity	Share
EPS	Thermal insulations, frost insulations, floor sound insulation	14,493 kg	28%
PU	Thermal insulations in the roof and external walls, plastic floor coverings	10,272 kg	20%
EPDM	Safety surface of a playground area	8,181 kg	16%
PE-HD	Pipes, cables, accessories	6,041 kg	12%
PVC	Pipes, cables	4,271 kg	8%
Epoxy	Flooring	2,573 kg	5%
PP	Building service components, geotextiles	1,154 kg	2%
PES	Building service components	861 kg	2%
Other plastics	Various parts	3,622 kg	11%
Total		**51,470 kg**	

TABLE 15. Complete list of plastics consumed in the concrete-framed daycare centre studied (construction and replacements).

Plastic type	Construction kg/building	Replacement kg/building	Total kg/ building	Total / m² kg/m²	Share out of the total %
ABS	1.5	0.61	2.1	0.00	0.00%
Acrylate	35	82.91	118	0.08	0.23%
EPDM	3,420	4,761.28	8,181	5.47	15.90%
Epoxy	1,544	1,029.20	2,573	1.72	5.00%
EPS	13,711	782.30	14,493	9.69	28.16%
Phenolic resin	544	0.00	544	0.36	1.06%
Formaldehyde	397	65.40	462	0.31	0.90%
MF	41	41.30	83	0.06	0.16%
MUF	65	0.00	65	0.04	0.13%
Other	31	37.16	68	0.05	0.13%
PA	1.6	0.00	1.6	0.00	0.00%
PC	0.0	0.00	0.0	0.00	0.00%
PE-HD	5,626	415.46	6,041	4.04	11.74%
PE-LD	828	10.93	839	0.56	1.63%
PES	725	136.69	861	0.58	1.67%
PEX	704	2.97	707	0.47	1.37%
PP	910	244.29	1,154	0.77	2.24%
PRF glue	11	0.00	11	0.01	0.02%
PU	10,031	241.06	10,272	6.87	19.96%
PVC	2,983	1,288.15	4,271	2.86	8.30%
PPSU	0.34	0.00	0.4	0.00	0.00%
SBS	539	173.07	712	0.48	1.38%
Silicone	2.0	8.00	10	0.01	0.02%
Total	**42,149**	**9,321**	**51,470**	**34.4**	**100 %**

5 Discussion

Although the overall consumption of plastics in the buildings studied ranged from 23 to 51 metric tonnes during their life cycle, the share of plastics in the buildings was low when all types of building parts are taken into account. This is partly because the density of plastics is relatively low (around 1,000 kg/m^3) compared to the main building materials such as concrete (density around 2,400 kg/m^3).

The amount of plastics seems to differ greatly depending on the type of the building and, to a lesser degree, the loadbearing frame material chosen. This is likely to be a result of the greater amount of building service installations and groundwork thermal insulations in a building that has only one storey. In higher residential buildings, the groundwork-related plastics serve a number of storeys and thus their relative share per m^2 remains lower.

We found clearly more plastics in the wood-framed residential buildings than in the concrete-framed examples. This opposite trend was true for the daycare centres. This difference can be partially explained by the different sound insulation solutions used in higher residential buildings, but the limited number of case studies does not support making any generalisations on this. In our case, much of polymers (polymer resins) identified in the wood-framed residential buildings were found in the glues and the sound absorption layers of cross-laminated timber structures.

The distribution of plastics into different types of building parts seems to differ primarily on the basis of the building type. In residential buildings, plastics were found rather equally in all these groups. In the concrete residential buildings, 0.60–1.4 kg per 1 gross m^2 of plastics was used during the construction phase, except for the frame and roof construction, where the amount was only 0.27 kg/m^2 (see Figure 3). In the wood-framed residential buildings, 0.76–1.9 kg per one gross m^2 of plastics was used during the construction phase, again with the exception of the frame and roof construction, where it was as much as 6.1 kg/m^2 (see Table 7). As shown in Table 3, electrical parts had the highest share of plastics.

The result for the daycare centres, however, was different. There, the plastics are distributed unevenly across different types of building parts. On average, most of the plastics in the construction phase were found in frame structures (5.2 kg/m^2) and in HVAC components (5.1 kg/m^2). The supplementary structures of the daycare centres seemed to hold the lowest concentrations of plastics (0.1 kg/m^2).

Comparison of the weight of plastics in different building parts to the overall weight of the same building part reveals a trend. Electrical parts clearly have a very high relative share of plastics. Building services and HVAC components also have a notably high share of plastics. In contrast, the share of plastics in the structural parts is minimal. This may indicate that building service systems hold potential for either for reducing or increasing the recycling rates of plastics.

From the viewpoint of the amounts of plastics, clearly significant additional choices are the selection of insulation materials, floor coverings, roof material and window frame materials. In our case buildings, plastics-based insulations were used in frost insulation, and also in the walls and roofs of one of the cases. The floor coverings varied. PVC floors were used in some daycare centres, whereas in residential buildings, this solution was used only in some minor spaces. Thus, the extended use of PVC sheet floorings in residential buildings would have added meant an 11% increase in the use of plastics in the wooden case building and a 7.6% increase in the concrete case building. Additionally, the use of EPS for above-ground thermal insulations would have increased the share of plastics by 97% in the concrete case building and by 91% in the wooden case building.

The GHG emissions arising from the manufacture of plastics are rather high compared to the typical average values for building products used in construction. Ruuska and Häkkinen [28] estimated that the GHGs in a typical Finnish multi-storey residential buildings during the construction phase are typically around 450 kg/m^2 for concrete element buildings and may range between 250 and 590 kg/m^2 (for wooden buildings and massive buildings when not taking into account external building parts and piling). With regard to the concrete case building, this would mean that, on average, materials have a contribution to GHGs of 0.2 kg per 1 kg of materials, while the emission factors for the production of plastics raw materials range between 1.6 and 3.3 kg GHG/kg (in accordance with Table 1).

Based on our findings, and quite consistently with the results obtained on the basis of our review of the literature, the plastics used the most in the case buildings, when taken together, were PVC, PE-HD, EPS, PP, PU and EPDM. However, their relative shares differed from building to building (Tables 6, 9, 12 and 15).

These plastics are typically used as products or as parts of products in a way that makes it possible to separate the plastic component during demolition, though the separation may be difficult. In our case buildings, these plastic types were used in cables and ducts, pipes and as insulations. EPDM rubber was used to provide a safe surface for a playground area.

TABLE 16. Most dominant plastic types in the buildings studied.

Buildings studied	PVC	EPS	PE-HD	PP	PUR	EPDM	Total share without EPDM
Concrete residential building	18%	11%	9%	13%	0.1%	-	51%
Wooden residential building	12%	10%	7%	11%	13%	-	53%
Wooden day-care centres	21%	18%	15%	5%	2%	4%	63%
Concrete daycare centres	8.3%	28%	12%	2.2%	20%	16%	70%

The review of the literature shows that different kinds of recycling techniques have been investigated, proposed and used. Issues that may hinder recycling or make it more difficult are dirt and impurities because of long service life and/or because of an underground location, an example being frost insulation boards. Difficulties in the separation of material layers may also arise for instance because of glueing, which may become a barrier to feasible recycling. For these reasons, it seems that the management of plastic wastes from demolitions requires much development.

Our findings indicate that a significant share of plastics is used as resins and polymer binders. These appear in paints, glues, rubber and as binding or reinforcing components in boards, bitumen roofing and insulation materials. These plastic materials accounted for 44% of all plastics in concrete residential buildings and 37% in wooden residential buildings. Therefore, when assessing the recycling potentials of plastics in buildings, more attention should be paid to these materials so that solutions other than energy recovery could be found. Different kinds of possibilities should be studied, and guidelines should be developed, making certain to include information about the risks of harmful emissions to the environment. Potential solutions may be based on the use of these materials as aggregates, in hybrid products, and in different kinds of beddings and fillings, as reported for example by Väntsi and Kärki [57].

6 Conclusions

The building and construction sector is the second largest consumption sector of plastics, accounting for 19% of all non-fibre plastics [17]. PVC, PE, PP, EPS, and PU are typical plastics used in buildings [4]. The construction and refurbishment of buildings use plastics as insulation materials, moisture and damp proofing materials, floor coverings, window frames, pipes, cables, and as different kinds of profiles and items associated with electrical systems, plumbing, and HVAC systems. Plastics are also used as components and resins in paints, glues, boards, roof coverings, mineral-material-based insulations, and laminated surfaces.

Although plastics have significant environmental and social impacts, thorough studies on the quantities and types of plastics in different types of buildings and in different types of building parts are rare. The present study aimed at helping to fulfil this gap. The main objective was to assess the quantities and types of plastics used in buildings with the help of a review of the literature and selected real building cases.

Our main findings and conclusions are as follows:

- The percentual share of plastics is rather low, partly because of the light weight of plastics. In our case buildings, the overall share was clearly under 1% when both the construction phase and replacements are taken into account. The overall quantities of plastics ranged from 6 to 28 kg per gross m2.
- Plastics are used in all groups of buildings parts. Our study showed that in residential buildings, plastics are distributed relatively evenly into different types of building parts, whereas in daycare centres plastics seem to accumulate in coverings, underground structures and building service installations.
- The quantity of plastics may vary considerably, depending on the type of frame, insulations and coverings. In our case, changing the insulation material from mineral wool to EPS would have roughly doubled the amount of plastics in the concrete case buildings.
- The relative share of plastics is high in building service systems and especially in electrical parts. The service life of these components is usually shorter than the service life of the building, which means that the materials in these parts return to circulation sooner than other materials. This indicates that there may be recyclng potential in these plastics.

- Quite consistently with results based on the review of literature, the plastics used the most in the case buildings were PVC, PU, PE-HD, PP and EPS. These plastics amount to roughly half of all plastics used in the residential case buildings, 60–70% in the daycare centres. In the wooden daycare centres, the share EPDM of plastics was also high.
- However, a significant share of the plastics used in buildings is used as resins and polymer binders in paints, glues and rubber and as binding or reinforcing components in boards, bitumen roofing and insulation materials. On the basis of the case study results, these account for roughly 40% of all plastics in residential buildings.
- Different kinds of recycling techniques have been investigated and proposed. However, the current recycling rate for mechanical recycling is low (<20%), and most of the plastics in construction and demolition waste goes for energy recovery and disposal. The data on the use of plastics in different kinds of building parts suggest that dirt and impurities — because of a long service life and/or an underground location — and difficulties or hindrances in separation prevent recycling or make recycling difficult. For these reason, the management of plastic wastes from demolitions requires much work. When assessing the recycling potentials of plastics in buildings, much more attention should be paid to plastics used as resins and other components so that solutions other than energy recovery could be found. Different kinds of possibilities should be studied; potential solutions could perhaps be based on the use of these materials as aggregates, in hybrid products, and in various kinds of beddings and fillings.

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References

1 R. Geyer, J.R. Jambeck, K.L. Law, Production, use, and fate of all plastics ever made, Sci. Adv. 3 (2017). http://advances.sciencemag.org/content/3/7/e1700782/tab-pdf.

2 R.U. Halden, Plastics and health risks, Annu. Rev. Public Heal. 31 (2010) 179–194. https://www.annualreviews.org/doi/pdf/10.1146/annurev.publhealth.012809.103714.

3 Plastics Europe, Plastics - the Facts 2017. An analysis of European plastics production, demand and waste data. s.l., 2017.

4 Materials Economic, The Circular Economy - a powerful force for climate mitigation. Transformative innovation for prosperous and low-carbon industry., Helsinki, 2018.

5 S. Schiavoni, F. D'Alessandro, F. Bianchi, F. Asdrubali, Insulation materials for the building sector: A review and comparative analysis, Elsevier, 2016. doi:10.1016/j.rser.2016.05.045.

6 PlasticsEurope 2AD, The New Plastics Economy Rethinking the future of plastics, 2016.

7 M. Haward, Plastic pollution of the world's seas and oceans as a contemporary challenge in ocean governance, Nat. Commun. 9 (2018) 667. doi:10.1038/s41467-018-03104-3.

8 J. Vince, B.D. Hardesty, Plastic pollution challenges in marine and coastal environments: from local to global governance, Restor. Ecol. 25 (2017) 123–128. doi:10.1111/rec.12388.

9 Y. Chae, Y.-J. An, Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review, Environ. Pollut. 240 (2018) 387–395. doi:10.1016/j.envpol.2018.05.008.

10 M. Brodhagen, J. Goldberger, D. G. Hayes, D. Ann Inglis, T. Marsh, C. Miles, Policy considerations for limiting unintended residual plastic in agricultural soils, Environ. Sci. Policy. 69 (2017) 81–84. doi:10.1016/j.envsci.2016.12.014.

11 C. Tyree, D. Morisson, Invisibles. The plastic inside us, (2017).

12 J. Gasperi, S. Wright, R. Dris, F. Collard, C. Mandin, M. Guerrouache, V. Langlois, F. Kelly, B. Tassin, Microplastics in air: Are we breathing it in?, Curr. Opin. Environ. Sci. Heal. 1 (2018). doi:10.1016/j.coesh.2017.10.002.

13 R. Dris, J. Gasperi, M. Saad, C. Mirande, B. Tassin, Synthetic fibers in atmospheric fallout: A source of microplastics in the environment?, Mar. Pollut. Bull. 104 (2016) 290–293. doi:https://doi.org/10.1016/j.marpolbul.2016.01.006.

14 C. Bombardelli, E.M. Alessi, A. Rossi, G.B. Valsecchi, Environmental effect of space debris repositioning, Adv. Sp. Res. 60 (2017) 28–37. doi:10.1016/j.asr.2017.03.044.

15 P.G. Levi, J.M. Cullen, Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products, Environ. Sci. Technol. 52 (2018) 1725–1734. doi:10.1021/acs.est.7b04573.

16 International Energy Agency, Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations., (2017).

17 R. Geyer, B. Kuczenski, T. Zink, A. Henderson, Common Misconceptions about Recycling, J. Ind. Ecol. 20 (2016) 1010–1017. doi:10.1111/jiec.12355.

18 Mercator Research Institute on Global Commons and Climate Change, Remaining Carbon Budget, (2018).

19 IPCC, Special report. Retrieved from An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate , 2018. https://www.ipcc.ch/sr15/.

20 M. Hestin, T. Faninger, L. Milios, Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment. Final Report., 2015.

21 S.-J. Royer, S. Ferrón, S.T. Wilson, D.M. Karl, Production of methane and ethylene from plastic in the environment, PLoS One. 13 (2018) e0200574.

[22] PlasticsEurope, Cradle-to-gate life cycle analysis of expanded polystyrene resin. Final report, 2016. https://www.epsindustry.org/sites/default/files/LCA of EPS Resin LCA 2017.pdf.
[23] PU Europe, Environmental product declaration (EPD) for PU (PUR/PIR) thermal insulation boards and energy saving potential, 2014. http://highperformanceinsulation.eu/wp-content/uploads/2016/08/Factsheet_13-1_Environmental_product_declaration__EPD__for_PU__PUR-PIR__thermal_insulation_boards_and_energy_saving_potential__updated_12-12-14_.pdf.
[24] PlasticsEurope, Polypropylene (PP) Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers, 2014.
[25] PlasticsEurope, High-density polyethylene (HDPE), Low-density polyethylene (LPDE), linear low-density polyethylene (LLDPE). Eco-profiles and Environmental Product Declarations of the European plastics Manufacturers, 2014.
[26] PlasticsEurope, ECVM, Vinyl chloride (VCM) and Polyvinyl chloride (PVC). Eco-profiles and Environmental Product Declarations of the European Plastics manufacturers, 2015.
[27] J. Monahan, J.C. Powell, An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework, Elsevier B.V., 2011. doi:10.1016/j.enbuild.2010.09.005.
[28] A.P. Ruuska, T.M. Häkkinen, The significance of various factors for GHG emissions of buildings, Int. J. Sustain. Eng. 8 (2015). doi:10.1080/19397038.2014.934931.
[29] T.Y. Chen, J. Burnett, C.K. Chau, Analysis of embodied energy use in the residential building of Hong Kong, Energy. 26 (2001) 323–340. doi:10.1016/S0360-5442(01)00006-8.
[30] C. Jeffrey, Construction and Demolition Waste Recycling A Literature Review, Office of Sustainability, Dalhousie University, (2011) 1–35.
[31] Environdec, The International EPD® System, (n.d.). https://www.environdec.com/ (accessed 9 November 2018).
[32] The Norwegian EPD foundation, EPD-Norge, (2018). https://www.epd-norge.no/english/ (accessed 15 December 2018).
[33] Eco Platform, Eco platform, (2018). https://www.eco-platform.org/list-of-all-eco-epd.html (accessed 15 December 2018).
[34] RT, Kiinteistön tekniset käyttöiät ja kunnossapitojaksot. RT 18-10922 (KH 90-00403, LVI 01-10424) (Techical service lives and maintenance periods for properties), (2018).
[35] B.P. Jelle, Traditional, state-of-the-art and future thermal building insulation materials and solutions - Properties, requirements and possibilities, Energy Build. 43 (2011) 2549–2563. doi:10.1016/j.enbuild.2011.05.015.
[36] L. Jiao, H. Xiao, Q. Wang, J. Sun, Thermal degradation characteristics of rigid polyurethane foam and the volatile products analysis with TG-FTIR-MS, Polym. Degrad. Stab. 98 (2013) 2687–2696. doi:10.1016/j.polymdegradstab.2013.09.032.
[37] AEA, BIO, Plastic waste in the environment, Paris, 2011. http://ec.europa.eu/environment/waste/studies/pdf/plastics.pdf.
[38] J. Thornton, Environmental Impacts of Polyvinyl Chloride (PVC) Building Materials, 2004. http://mts.sustainableproducts.com/SMaRT/ThorntonRevised.pdf.
[39] P. Järvinen, Muovit ja muovituotteiden valmistus, Muovifakta, 2017.
[40] I. Janajreh, M. Alshrah, S. Zamzam, Mechanical recycling of PVC plastic waste streams from cable industry: A case study, Sustain. Cities Soc. 18 (2015) 13–20. doi:10.1016/j.scs.2015.05.003.
[41] A. Villanueva, P. Eder, End-of-waste criteria for waste plastic for conversion, 2014. doi:10.2791/13033.
[42] K. Hamad, M. Kaseem, F. Deri, Recycling of waste from polymer materials: An overview of the recent works, Polym. Degrad. Stab. 98 (2013) 2801–2812. doi:10.1016/j.polymdegradstab.2013.09.025.
[43] T. Häkkinen, P. Ahola, L. Vanhatalo, A. Merra, Environmental impact of coated exterior wooden cladding, Espoo, 1999. http://virtual.vtt.fi/virtual/proj6/environ/env_woodclad.pdf.
[44] H. Eskelinen, T. Haavisto, H. Salmenperä, H. Dahlbo, Muovien kierrätyksen tilanne ja haasteet (Recycling of plastics - current situation and challenges), CLIC Innovation, Helsinki, 2016. file:///C:/Users/RTETMH/Downloads/Eskelinen_ym_Muovien_kierratyksen_tilanne_ja_haasteet_11042016.pdf.
[45] J. Aguado, D. Serrano, G. San Miguel, European Trends in the Feedstock Recycling of Plastic Wastes, 2007.
[46] EC, Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste No Title, (2008). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098.
[47] M. Sadat-Shojai, G.R. Bakhshandeh, Recycling of PVC wastes, Polym. Degrad. Stab. 96 (2011) 404–415. doi:10.1016/j.polymdegradstab.2010.12.001.
[48] I. Jakubowicz, L. Martinsson, N. Yarahmadi, PVC floorings as post-consumer products for mechanical recycling and energy recovery, Polym. Degrad. Stab. 79 (2003) 439–448. doi:10.1016/S0141-3910(02)00360-9.

[49] A. Coelho, J. Brito, Economic viability analysis nof a construction and demolition waste recycling plant in Portugal - Part 1: location, materials, technology and economic analysis, J. Clean. Prod. 39 (2013) 338–352.

[50] K.M. Zia, H.N. Bhatti, I. Ahmad Bhatti, Methods for polyurethane and polyurethane composites, recycling and recovery: A review, React. Funct. Polym. 67 (2007) 675–692. doi:10.1016/j.reactfunctpolym.2007.05.004.

[51] J. Kanters, Design for Deconstruction in the Design Process: State of the Art, Build. . 8 (2018). doi:10.3390/buildings8110150.

[52] C. Borsoi, L.C. Scienza, A.J. Zattera, Characterization of composites based on recycled expanded polystyrene reinforced with curaua fibers, J. Appl. Polym. Sci. 128 (2013) 653–659. doi:10.1002/app.38236.

[53] T. Maharana, Y.S. Negi, B. Mohanty, Review Article: Recycling of Polystyrene, Polym. Technol. Eng. - POLYM-PLAST TECHNOL ENG. 46 (2007) 729–736. doi:10.1080/03602550701273963.

[54] A. Kan, R. Demirboğa, A new technique of processing for waste-expanded polystyrene foams as aggregates, J. Mater. Process. Technol. 209 (2009) 2994–3000. doi:10.1016/j.jmatprotec.2008.07.017.

[55] M. Amianti, V.R. Botaro, Recycling of EPS: A new methodology for production of concrete impregnated with polystyrene (CIP), Cem. Concr. Compos. 30 (2008) 23–28. doi:10.1016/j.cemconcomp.2007.05.014.

[56] S. Kazemi, Use of recycled plastics in wood plastic composites - A review, Waste Manag. 33 (2013). doi:10.1016/j.wasman.2013.05.017.

[57] O. Väntsi, T. Kärki, No TitleMineral woola waste in Europe: a review of mineral wool waste quantity, quality, and current recycling methods, J. Mater. Cycles Waste Manag. 16 (2014) 62–72. doi:10.1007/s10163-013-0170-5.

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