Chapter 33
Environmental Impact of a Residential House Using Cardboard Waste as Construction Material

Teofil Câmpean, Nicolae Peiu, Dan-Alexandru Gavrilescu, and Maria Gavrilescu

Abstract Research on waste recycling and developing environmentally friendly materials having good performances and low costs as alternatives to those currently used, in particular in construction and architecture, attempts to minimize the unsustainable use or harmful materials, which also incorporates large amounts of energy. A number of studies demonstrate the use of cardboard waste with sufficient compressive strength offering an alternative for traditional building materials (concrete and steel). In this work the most feasible methods for eco-design and construction of a residential house were analyzed, using corrugated cardboard waste as building material, in the form of old corrugated cardboard panels made without adhesives, by including them between the elements of the supporting structure, made of wood. The analysis shows that the resulted environmental performances recommend the use of recycled corrugated cardboard waste as a construction material with good performance in thermal insulation.

Keywords Eco-designed house · Environmental impact · Insulation · Old cardboard waste

T. Câmpean (✉)
Cristofor Simionescu Faculty of Chemical Engineering and Environmental Protection, SC Rondocarton SRL, Cluj-Napoca, Romania and Gheorghe Asachi Technical University of Iasi, Iasi, Romania
e-mail: teofil.campean@student.tuiasi.ro

N. Peiu
Environmental Protection Agency, Iasi, Romania
e-mail: nicolaesw@yahoo.co.uk

D.-A. Gavrilescu · M. Gavrilescu (✉)
Cristofor Simionescu Faculty of Chemical Engineering and Environmental Protection, Gheorghe Asachi Technical University of Iasi, Iasi, Romania
e-mail: mgav@tuiasi.ro

D.-A. Gavrilescu
e-mail: gda@tuiasi.ro

I. Visa and A. Duta (eds.), *Solar Energy Conversion in Communities*,
Springer Proceedings in Energy, https://doi.org/10.1007/978-3-030-55757-7_33

33.1 Introduction

Circular economy is a model for an economy that is designed to function in harmony with the environment, in which biological materials are designed to return safely to ecological cycles, and technical materials are designed to circulate continuously in the economic system. The ultimate goal is to decouple economic growth from resource consumption [1–3]. This presumes that a continuous economic growth will be possible in the context of resource constraints, while avoiding environmental damage by significantly reducing the extraction of virgin materials, eliminating unnecessary and toxic waste, substantial savings in raw material and energy costs [1]. At the same time, the specialized literature has demonstrated the need to integrate eco-design into product development, to guide and encourage product designers (in the sense of any good/product, process or service) to apply the principles of sustainable development and circular economy in design, also considering environmental issues [4–6]. Despite the apparent availability of studies discussing the adoption of practices, methods and tools for the application of eco-design, some researchers have pointed out that implementation is still in its infancy, especially at the company level [7–9].

Recycled or recovered waste can be reintroduced into the economic circuit as a secondary raw material, generating closed loops in accordance with the principles of the circular economy. Even before the circular economy became the subject of an European Commission legislative package, the paper, board and board packaging industry was one of the pioneers in applying the circular economy model at all stages of a product life cycle: design, production, distribution and use, its recovery. According to figures published by the European Union (EU) before World Recycling Day (18 March 2019), the amount of paper and cardboard packaging currently recovered in Europe has touched a record. In the 28 EU countries, the recovery rate for paper and cardboard packaging waste has reached 85.8%, the highest in EU history and the highest of all packaging materials (metal and glass packaging have rates of recycling of 78.3% and 74.1%, respectively) [10]. Globally, Europe continues to be the world champion in the field of paper recycling, followed by North America.

However, recovered paper and cardboard, which are not yet collected, consist mainly of lower grades with a low potential for papermaking. An important finding is related to the continuous decrease in the quality of recovered paper, from the point of view of paper producers. This trend is also manifesting itself on a European scale and is the consequence of the increasing number of recycling of paper and cardboard, which turns them into non-papermaking forms. Solutions for sustainable use can be found for these categories of paper and cardboard, by applying the principles of the circular economy and tools to facilitate the implementation of these principles.

Starting from the realities of the contemporary world and in accordance with European Directives, particularly those concerning the circular economy, this work focuses on the capitalization of recyclable paper and cardboard materials without papermaking potential to make products, economically profitable and with low environmental impact, on the whole life cycle. An analysis of the opportunities and impacts of using recovered cardboard, without papermaking potential, with sufficient compressive strength as an alternative to traditional construction materials has been performed.

33.2 Paper and Cardboard Recycling in the European Context

In the paper industry, the term waste paper is seldom used, the preferred term being *recovered paper*, which better reflects its value and importance as a raw material. Recovered paper (waste paper) is as important as a raw material for making paper as virgin fibers made from wood. The terms recycled paper and secondary fiber are also often used to refer to this waste stream. Recovered paper and cardboard hold second place in the global amount of waste, representing 17%, after the organic fraction [11]. Recycling of paper and board has proven to be a particularly attractive option, with low environmental impact compared to landfilling [12, 13].

At the beginning of the new millennium, recycled fibers are considered an indispensable raw material to meet the need for fibrous material for the paper industry in both developed and developing countries. Thus, by 2020, a waste utilization rate of about 50% is estimated, which will lead to an almost perfect balance between the consumption of virgin fibers and secondary fibers. Under these conditions, the recycling rate of waste will reach approximately 73% in CEPI member countries in 2020 (Table 33.1) [14]. CEPI considers that the maximum waste recycling rate for the paper industry is 78%, as some grades of paper and cardboard cannot be recycled (toilet paper, used paper and cardboard packaging in sanitary facilities etc.) [15]. In Europe, waste consumption is reported for assortment classes and is distributed as follows: waste corrugated packaging (Old Corrugated Containers, OCC); waste paper for deinking (Deinked Paper, DIP), mixed office paper (MOP), other assortments.

Usually, the recycling process involves sorting the fibers, deinking, removal of filling materials, bleaching etc. On the other hand, the repeated use of recovered paper as a raw material can decreases the quality of paper products [16, 17]. According to the current state of technology, there will always be a certain percentage of paper waste that, for economic and technical reasons, cannot be recycled. A favorable option for

Table 33.1 Quantities of recovered paper used for manufacturing paper and cardboard in CEPI member countries in 2017 [17]

Assortment of recovered paper	Quantity used, million tones	Percentage of total, %
Printing papers (including newsprint)	9.125	18.91
Old corrugated containers and other packaging made from paper and board	34.845	72.21
Other paper and board grades	4.278	8.88
Total	48.258	100.00

non-recyclable paper waste is its use in various composites. In this case, no expensive operations such as cleaning and refining the fibers are required. The alternative use of waste paper is interesting for two reasons. Firstly, secondary fibers are a largely unused resource, and secondly, more importantly, the costs of processing this material are significantly lower than those of producing similar wood-based materials [18].

The use of recovered paper as a material resource for composite type products has been investigated by various institutions and companies in the last 20 years. These products were obtained from different types of recovered paper or in combination with particles or wood fibers and were reinforced with various adhesives, organic or inorganic [19, 20].

Cellulose fibers, the main constituent of paper is a highly efficient insulator and could provide the construction industry with an efficient and environmentally friendly alternative to conventional insulation. The advantages of paper and its by-products and, above all, of cardboard is that they are cheap, light and durable, flexible in shape and color, recyclable and "different" [21, 22]. The discovery of opportunities for the efficient use in construction of materials of this nature, renewable and recyclable to a large extent, can be a step forward in the move towards sustainable development.

As a structural construction element, corrugated cardboard has many advantages. In addition to being a relatively low-priced material, it has significant insulating properties (thermal and acoustic), is easily recyclable and can be made from renewable sources. The most important property of corrugated cardboard, as a construction element, is that it has a high degree of structural strength and rigidity [23, 24].

33.3 The Environmental Impact of a Residential House that Uses Cardboard Waste as a Building Material

Proper design of houses and their ancillary systems can bring numerous benefit for the community, contributing to the eco-efficient functions of the building (including surrounding infrastructure, power and heat generation, wastewater treatment, waste management etc.) and a cleaner and resourceful environment. At the same time, a better community environment can benefit buildings by improving living conditions.

In this section it is analyzed the feasible method by which a residential house can be eco-designed and built using corrugated waste as a building material and the environmental impact associated with such a house.

33.3.1 Brief Description of the Residential House

The transition to a circular economy requires changes in value chains, from product design to new business and market models, from new ways of turning waste into a resource to new ways of consumer behavior. This transition implies full systemic change, eco-innovation and eco-design not only in terms of technology, but also in terms of organizations, society, new methods of financing through sustainable policies [25]. The widespread implementation of ecological solutions is intended to help limit many key issues related to environmental protection, such as climate change, declining natural resources, environmental pollution or biodiversity loss [26].

Eco-design plays an important role in reducing the impact on the environment, being essential for the life cycle of processes, products and services, the decisions taken in the design stage being responsible for the sustainable management of a large part of economic resources and those taken from the environment, necessary to support the entire life cycle of a product, process, service. Some specialists estimate that 80% of the environmental impact is predefined in the product design phase [27, 28]. Therefore, designers are interested and motivated to systematically integrate environmental performance into products and processes from the early stages of their design [29].

A house designed in compliance with eco-design requirements should require as few material resources as little energy and help reduce the impact on the environment. McDonough and Braungart [1] stated that if we could imagine buildings as trees, and cities as forests, then they would produce more energy than they consume and purify their own wastewater. Thus, proper design of houses and their ancillary systems can benefit the community, contributing to eco-efficient building functions (including surrounding infrastructure, power and heat generation, wastewater treatment, waste management etc.) and a cleaner environment with resources. On the other hand, a better community environment can benefit buildings by improving living conditions.

The residential house proposed to be eco-designed using OCC is not a temporary house, but one whose life cycle is expected to last as long as that of a traditional house, 50 years, respectively. For this reason, the use of cardboard, in any form as a structural material was excluded from the beginning. Wood, the closest to paper, was naturally chosen as the structural material. In terms of size, a house with a relatively small size was chosen, with a usable area of 85 m^2 and a ground floor height regime.

The outer walls consist mainly of panels, having the core of old corrugated containers (OCC) waste, with thermal insulation role, the exterior face—made of oriented wood chipboard (OSB), and inner face—made of plasterboard. To protect this core of moisture panels, the OCC panels are protected, both inside and outside with two foils with different purposes. Partition walls were not taken into account.

33.3.2 Life Cycle Assessment of a Residential House

In this analysis the use of Life Cycle Assessment (LCA) methodology for assessing the environmental performance of the compared buildings was made based on the provisions of the standards ISO 14,040:2006, ISO 14,044:2006, and ISO EN 15,978:2011 [30–32]. Life Cycle Assessment is an environmental management tool which, according to International Organization for Standardization (ISO) can be considered “a compilation and evaluation of the inputs, outputs and potential environmental impacts of a product throughout its lifecycle” [30].

The life cycle stages of the residential house consist of: **production, construction, usage, and end-of-life.** In this analysis the use of LCA for the calculation of the environmental performance of the construction materials was mainly made based on the calculation rules established in the standard ISO EN 15,978:2011 [32]. **The functional unit refers to the construction and use by a family of four people, and the final disposal**, after a period of 50 years, of a house on the ground floor with an area of about 85 m^2. **The frontiers of the system include construction, usage and end-of-life** (Fig. 33.1). However, production is an important stage because here an analysis can be made on the environmental quality of construction materials new construction materials can be experienced and evaluated.

Therefore, an analysis of production stage can be made from the beginning, addressing the quality of construction materials from the point of view of environmental protection. For example, a comparison of seven thermal insulation materials has been performed (Fig. 33.2). Using a classical environmental impact assessment methodology known as **cumulative energy demand**, a ranking of all cumulative energies required to produce the same amount (1 kg) of different construction materials shows that, if a panel is produced from virgin fibers, the corrugated board is the thermal insulation material whose production needs more cumulative energy consumed for production than the recycled corrugated waste.

The ReCiPe method (final point, total score, hierarchical version (H)) was chosen for impact assessment in the frame of LCA, because it is a combined one, being able to provide results at both midpoint and endpoint levels [33]. Sima Pro developed by the Dutch company PRé, version 8.2.0.0, was used as software for this tool, for which a license was obtained by the Faculty of Chemical Engineering and Environmental Protection within the “Gheorghe Asachi” Technical University of Iași. The endpoint impact categories covered by this tool are: human health, environmental quality and resource availability (with the meaning of damages) (Fig. 33.3). According to the ISO 14,040 (2006) a complete LCA study comprises four major phases (Fig. 33.4):

– *Goal Definition and Scoping*—include the objective and scope of study, system boundaries and the functional unit;
– *Inventory Analysis*—with a detailed compilation of all environmental inputs (resource and energy flows) and outputs (emissions and wastes);
– *Impact Assessment*—involves evaluation of environmental impacts from the inventory and establish environmental performance of the product;
– *Interpretation*—the results of the inventory are interpreted and used in decision and policy making.

LCA (ReCiPe method) was applied during the three stages of life cycle considered in the study: **construction, use, and end-of-life.** All data required for life cycle inventory were collected from standards, handbooks, technologies, visits on building locations, statistics, databases of the SimaPro software and others.

The construction stage is one of the most important stages in the life cycle of the house, although not the most important. This stage is, of course, preceded by

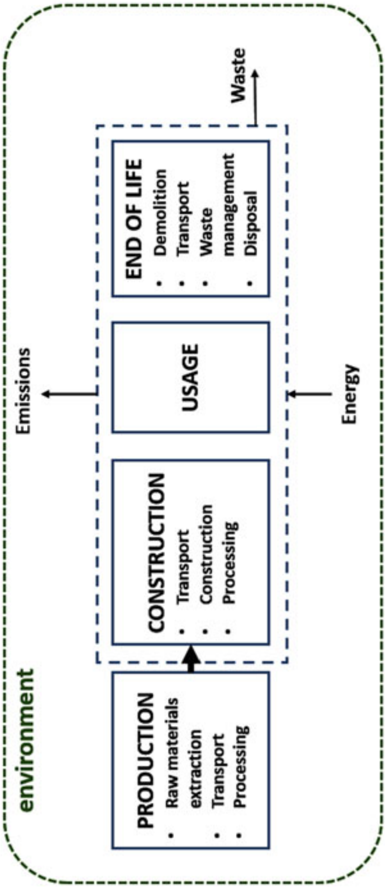

Fig. 33.1 The main stages of the life cycle of a building and the limits of the analyzed system

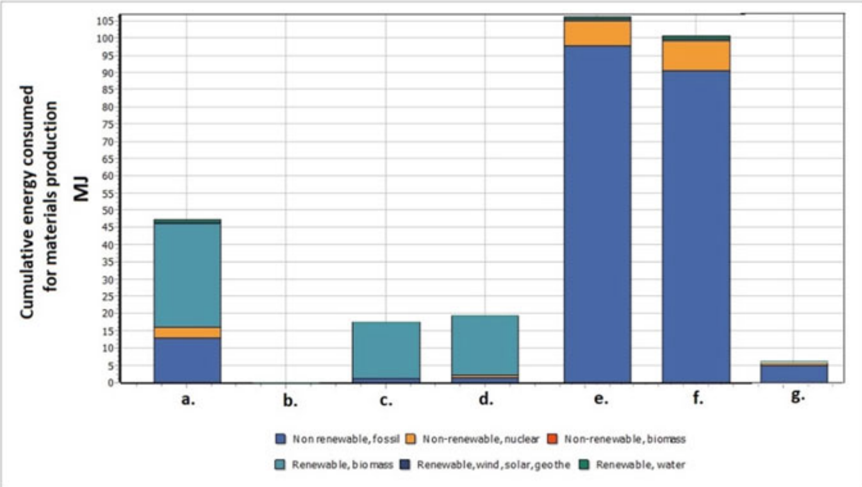

Fig. 33.2 Unit comparison (C.U. = 1 kg) of the main products (construction materials) used for the buildings compared in terms of cumulative energy consumed for their production (MJ); methodology: cumulative (Total) energy demand; total score: **a** virgin fiber corrugated board, **b** recycled corrugated waste, **c** hardwood, **d** softwood, **e** expanded polystyrene PSE, **f** XPS extruded polystyrene, **g** gypsum board

the design, where all the technical details of the future building are developed. According to ISO EN 15,978:2011 [32] this step comprises the following two modules (Fig. 33.1): (i) transporting the raw material from the place of production to the place of construction; (ii) actual construction.

The use/maintenance stage is the longest and most important stage in the entire life cycle of the analyzed house. According to the standard ISO EN 15,978:2011 [32] this step comprises the following seven modules: (i) usage; (ii) maintenance; (iii) repairs; (iv) replacements; (v) renovation; (vi) use of operational energy; (vii) water use. The most important of these modules refers to the operational energy used.

The end-of-life stage is the most difficult to be quantified due to the uncertainty of scenarios evolution and that of waste management technologies resulting from construction and demolition, given the distance within 50 years from the expected period of demolition of the building. According to ISO standard EN 15,978:2011 [32], this step comprises the following four modules: (i) demolition; (ii) transport (to the waste processing site); (iii) waste processing and (vi) final disposal of waste.

Figure 33.5 shows a comparison of the impact on the environment produced in the three stages of the house life cycle, using the ReCiPe impact assessment method. For this analysis, the three impact categories were considered: human health, ecosystem quality and resources availability. In the construction stage, the category of *ecosystem quality* impact has the highest weight, followed by the availability of resources.

In general, the construction activity is considered to be one of the largest contributors to environmental pollution and depletion of resources, producing globally 33%

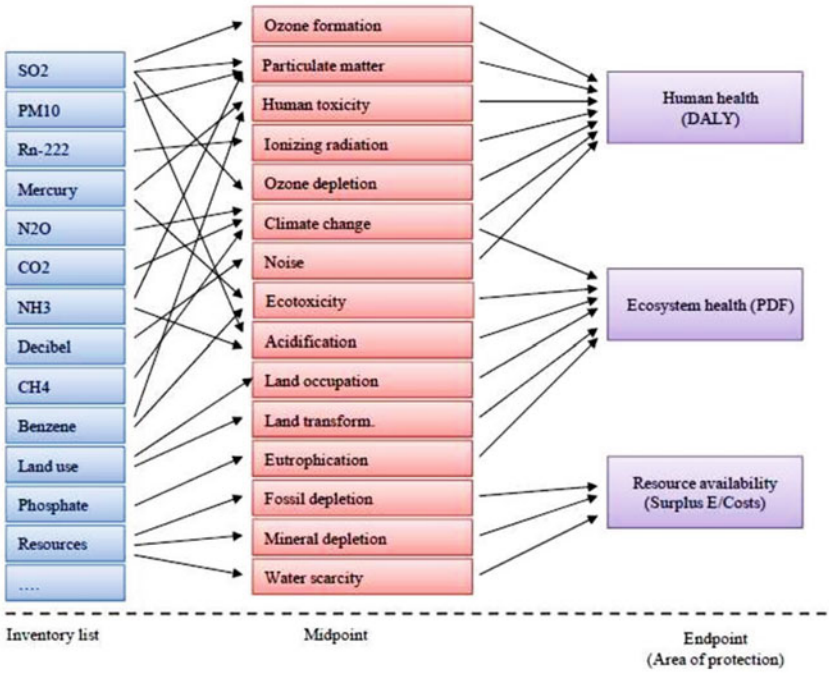

Fig. 33.3 List of impact categories for characterization at midpoint and endpoint level, [34] (under license CC BY-NC-ND, IOP science, https://publishingsupport.iopscience.iop.org/is-permission-required-faqs-using-open-access-content/)

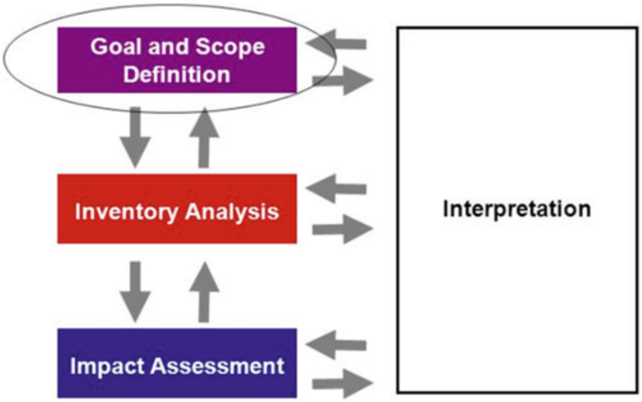

Fig. 33.4 Major phases of life cycle assessment

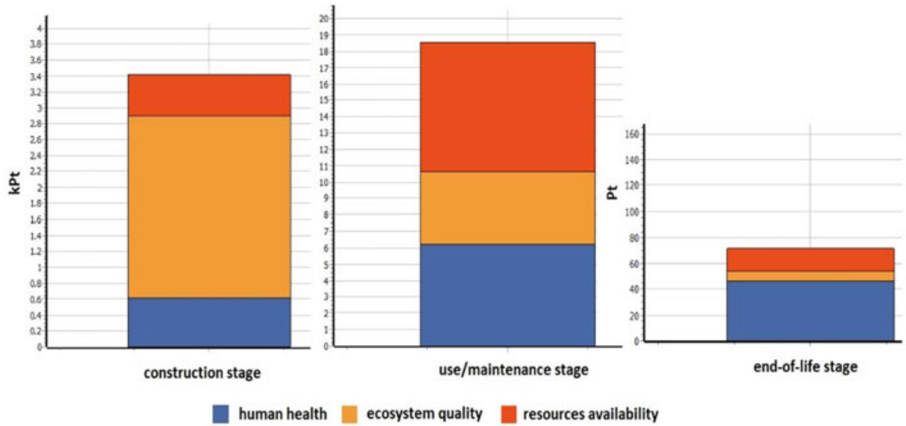

Fig. 33.5 Comparison of the impact produced in the three stages of life cycle of houses (ReCiPe End point methodology hierarchical version, H)

of greenhouse gas emissions and consumes approx. 40% of primary energy [34]. It is expected that this representation will be below the level for the traditional house, because, as can be seen from Fig. 33.2, cumulative energy demand has the lowest value for OCC cardboard waste, used as insulation material in house construction.

33.4 Conclusions

This study aimed at examining the extent to which recyclable corrugated waste without papermaking potential (Old Corrugated Containers, OCC) represents a promising material for the eco-design of a sustainable home (CEP), in terms of environmental performance, analyzed with Life Cycle Assessment (LCA) methodology, a well-structured, standardized and extensive tool used for this purpose especially in Europe, mainly after the launch of the European LCA platform.

The functional unit of the study was the procurement of materials, construction, use and final disposal of a residential house with a period of use of 50 years. ECV focused on all four stages of a building's life cycle: production, construction, usage and final disposal.

Outside the limits of the system analyzed in the production stage, separate investigations were carried out, using Life Cycle Assessment, on the quantities of energy required for the production of corrugated cardboard produced from virgin fiber or cardboard recycled waste. The functional unit chosen for this comparison was 1 kg of the analyzed construction material. Research has shown that the material represented by virgin fiber corrugated cardboard requires one of the highest energy consumption along with extruded or expanded polystyrene. Instead, old corrugated containers (OCC) has the lowest energy consumption, which implicitly means the lowest impact on the environment.

Comparisons made separately for the construction, usage and end-of-life stages show that the human health, environmental quality and resource availability impact categories have different weight in the three stages. In the construction stage, environmental quality has the highest weight. In the usage stage, resource availability is has the highest weight. Human health is the impact category with the highest share in the end-of-life stage.

In the future works, the analysis will be extended, to allow comparisons of environmental impacts and costs generated by a traditional house and a house made of virgin fibers cardboard, with the eco-innovated residential house, which use waste corrugated cardboard without papermaking potential as an insulation material.

References

1. W. McDonough, M. Braungart, A world of abundance. Interfaces **30**, 55–65 (2000)
2. Ellen MacArthur Foundation: Towards the Circular Economy: *Economic and Business Rationale for an Accelerated Transition*, Report vol. 1, (2012). Online at: https://www.ellenmacarthurfoundation.org/business/reports/ce2012
3. F. Preston, A global redesign? *Shaping the Circular Economy, Energy, Environment and Resource Governance, Chatham House, London* (2012). Online at: https://www.biblioteca.fundacionicbc.edu.ar/images/d/d7/Bp0312_preston.pdf
4. F. Brones, M.M. Carvalho, E.S. Zancul, Ecodesign in project management: a missing link for the integration of sustainability in product development? J. Cleaner Prod. **80**, 106–118 (2014)
5. D.C. Pigosso, E.T. Zanette, F.A. Guelere, A.R. Ometto, H. Rozenfeld, Ecodesign methods focused on remanufacturing. J. Cleaner Prod. **18**, 21–31 (2010)
6. S. Sihvonen, J. Partanen, Implementing environmental considerations within product development practices: a survey on employees' perspectives. J. Cleaner Prod. **125**, 189–203 (2016)
7. E.A. Dekoninck, L. Domingo, J.A. O'Hare, D.C.A. Pigosso, T. Reyes, N. Troussier, Defining the challenges for ecodesign implementation in companies: Development and consolidation of a framework, J. Cleaner Prod. **135**, 410–425 (2016). Online at: https://doi.org/10.1016/j.jclepro.2016.06.045
8. M. Rossi, M. Germani, A. Zamagni, Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. J Cleaner Prod. **129**, 361–373 (2016)
9. A.G. Silvius, M. Kampinga, S. Paniagua, H. Mooi, Considering sustainability in project management decision making; an investigation using Q-methodology. Int. J. Proj. Manage. **35**, 1133e1150 (2017). Online at: https://doi.org/10.1016/j.ijproman.2017.01.011
10. Packaging Europe, Paper and cardboard recycling reach record high across Europe, (2019). Online at: https://packagingeurope.com/paper-and-cardboard-recycling-have-reached-record-high-acros/
11. D. Hoornweg, P. Bhada-Tata, *What a Waste—A Global Review of Solid Waste Management, Urban Development and Local Government Unit, World Bank*. (Washington DC, 2012). Online at: https://openknowledge.worldbank.org/handle/10986/17388
12. A. Björklund, G. Finnveden, Recycling revisited—life cycle comparisons of global warming impact and total energy use of waste management strategies. Resour. Conserv. Recycl. **44**, 309–317 (2005)
13. A. Villanueva, H. Wenzel, Paper waste—recycling, incineration or landfilling? Rev. Existing Life Cycle Assessments Waste Manage. **27**, 29–46 (2007)
14. CEPI, CEPI key statistics 2017, (2018). Online at: https://www.cepi.org/system/files/public/documents/publications/statistics/2018/210X140_CEPI_Brochure_KeyStatistics2017
15. EPRC, *European Declaration on Paper Recycling*, 2016–2020, European Paper Recycling Council—EPRC, (2018). Online at: https://www.cepi.org/publication/european-declaration-paper-recycling-2016-2020
16. L. Groom, S. Shaler, L. Mott, Physical and mechanical properties of virgin and recycled wood fibers, In: *Processing of Environmental Quality in Wood Processing*. (Atlanta, 1994), pp. 20–35
17. O. Kordsachia, Remarks on the waste paper problem. Holz-Zentralblatt **81**(82), 1327–1330 (1992)
18. A.H. Grigoriou, Waste paper–wood composites bonded with isocyanate. Wood Sci. Technol. **37**, 79–90 (2003)
19. G. Gerischer, Structural particleboard from waste material. Holzforschung **31**, 129–133 (1977)
20. A. Krzysik, J.A. Youngquist, R.M. Rowell, J.H. Muehl, P. Chow, S.R. Shook, Feasibility of using recycled newspapers as a fiber source for dry-process hardboards. For. Prod. J. **43**, 53–58 (1993)
21. J.F. Latka, Paper in architecture. Research by design, engineering and prototyping, PhD Thesis, Delft University of Technology. (Delft, The Netherlands, 2017)

22. J. Schonwalder, Cardboard as building material, Tentech BV—Engineering consultancy of lightweight structures utrecht, faculty of architecture T.U. (Delft, 2016). Online at: https://www.kcpk.nl/algemeen/bijeenkomsten/presentaties/20160202-9-julia-schonwalder
23. A. Russ, J. Schwartz, S. Bohacek, H. Lubke, V. Ihnat, A. Pazitny, Reuse of old corrugated cardboard in constructional and thermal insulating boards. Wood Sci. **58**, 505–510 (2013)
24. S. Secchi, F. Asdrubali, G. Cellai, E. Nannipieri, A. Rotili, I. Vannucchi, Experimental and environmental analysis of new sound-absorbing and insulating elements in recycled cardboard. J. Build. Eng. **5**, 1–12 (2016)
25. COM 614, *Closing the Loop—an EU Action Plan for the Circular Economy, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*. (European Commission, Brussels, 2015)
26. A. Ociepa-Kubicka, P. Pachura, Eco-innovations in the functioning of companies. Environ. Res. **156**, 284–290 (2017)
27. T.G. Navarro, S.C. Rizo, M.J.B. Ceca, D.C. Ruiz, Designing for the future—application and management of knowledge and information in engineering design, in *DS 35: Proceedings ICED 05, the 15th International Conference on Engineering Design*, 15–18 August. (Melbourne, Australia, 2005)
28. M. Dufrene, A methodological framework to support integrated ecodesign for companies: requirements and conceptualization towards a software platform, PhD Thesis, Université Grenoble Alpes. (France, 2015)
29. M.D. Bovea, V. Pérez-Belis, A taxonomy of ecodesign tools for integrating environmental requirements into the product design process. J. Cleaner Prod. **20**, 61–71 (2012)
30. ISO 14040, *International Organization for Standardization, Environmental Management—Life Cycle Assessment—Principles and Framework*. (2006). Online at: https://www.iso.org/iso/catalogue_detail.htm?csnumber=23151
31. ISO 14044, *Environmental Management—International Organization for Standardization, Life cycle Assessment. Requirements and Guidelines*. (2006). Online at: https://www.iso.org/iso/catalogue_detail?csnumber=38498
32. ISO EN 15978, *Sustainability of Construction Works. Assessment of Environmental Performance of Buildings*. Calculation method. (2011). Online at: https://shop.bsigroup.com/ProductDetail/?pid=000000000030256638
33. M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, R. van Zelm, *ReCiPe 2008 A life cycle impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level*. Ministerie van VROM, Den Haag, 1st edn. (2013). Online at: https://www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf
34. M. Wolfova, A. Estokova, M. Ondova, A. Monokova, Comparing of the external bearing wall using three cultural perspectives in the life cycle impact assessment. IOP Conf. Ser. Mater. Sci. Eng. **385**, 012064 (2018). https://doi.org/10.1088/1757-899X/385/1/012064