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Wood as a building material in the light of environmental assessment of full life cycle of four buildings

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HIGHLIGHTS

- LCA study of four functionally equivalent single-family houses were performed.
- As a renewable material, wood is ideal for sustainable buildings.
- Benefits of using wood appear in almost all stages of buildings' life cycles.

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ABSTRACT

This paper presents the results of the research project financed by the Polish Ministry of Science and Higher Education (N N309 078138) and coordinated by the Wood Technology Institute in Poznan. One of the key points of this project was LCA study of four detached single-family dwellings in the context of intensification of wood usage. Four functionally equivalent buildings with different material structure, building technology and energy standards have been subjected to Life Cycle Assessment (LCA) environmental impact analysis. The study has taken into account a full life cycle of the buildings, including the following stages: production of building materials, prefabrication, transport to the building site, building, use, demolition, transport of waste and final disposal of waste. Wood and wood-based materials, are the only ones from among the analysed building materials, that have shown an environmental benefit both from the "cradle-to-gate" (stage 1) and "gate-to-grave/reincarnation" (stage 7) perspective.

1. Introduction

In EU countries, despite the traditions of building with stone and concrete, an increased interest with wood and wood-based materials can be seen. The possibilities of using wood in the building industry are numerous. One of the more prominent directions, is the production of light and strong construction elements. Wooden buildings can be seen more and more often in the landscape of Polish cities, towns and villages. Wood facades are becoming a visible sign of an increased popularity of using wood in the building industry. Special aesthetic and technical qualities of wood favour an increasing dominance of this material in the production of floors and decks. More and more interior architects choose wood as an attractive material for the production of interior woodwork and furniture. Solid wood and wood-based materials are perfectly suited for building single-family detached houses featuring either traditional or modern architecture. In the last couple of years, more and more housing estates have been built in Poland, including multi-dwelling units whose walls, ceilings and roofs have been prefabricated from wood and wood-based panels. Designers of aquatic centres, sports arenas, entertainment arenas, churches, hotels and inns are increasingly more keen on using this material.

The role of wood in the modern economy is becoming more and more important, which results from the fact that it combines many qualities that are crucial from the ecological and technological point of view, among which we can include [1–7]:

- it is both light and mechanically strong,
- it has a good thermal conductivity coefficient,
- it is warm to the touch,
- it does not change its dimensions when temperature changes,
- it deadens noise well,
- it is resistant to the effects of destructive chemical substances,
- before it gives in to the destructive forces, it issues a "warning" by creaking, providing time for evacuation,
- it absorbs the humidity in highly humid conditions, and releases it in very dry conditions, positively influencing the microclimate of rooms,

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- it is both durable and resistant to the effect of destructive biological factors,
- it is a renewable material,
- it shows a beneficial, carbon balance and embodied energy indicator, in comparison to other building materials,
- it can be easily worked mechanically and it can be modified, as well as relatively easily and inexpensively transformed into other useful building, insulation or finishing materials.

The opponents of using wood in the building industry mention arguments concerning weaknesses of wood as the building material, which include: flammability, relatively low durability, high hygroscopicity and susceptibility to the effect of fungi, moulds and insects. However, the majority of these issues can currently be overcome by using, e.g. appropriate impregnates and preservatives.

Within the context of the sustainable development, the ecological aspects of building materials and entire buildings has become increasingly more important. The environmental assessments carried out within the scope of the building industry can pertain to three types of objects: only Building Materials (BM) [8–11], Component Combination (CC) [12–14] or the Whole Process of the Construction (WPC) [15,16]. Such studies can incorporate various scopes or include only a part of the life cycle, e.g. the production of building materials (cradle-to-gate) or the disposal of building waste (gate-to-grave/reincarnation), but they can also assume the perspective of a full life cycle. In literature we can find analyses of environmental impact dedicated to wood treated as both a building material [17,18] and waste [19]. Also, certain individual publications can be found concerning the environmental assessment of wood as a building material carried out in the light of full life cycles of buildings [20].

The main goal of the study presented in this paper was to analyse and assess potential environmental advantages of using wood in construction of houses. Making by one group of researchers a comparison between four functionally equivalent houses can be recognised as a strong point of the study, because the initial assumptions, data quality, system boundaries were similar for all analysed objects. These buildings were assumed to have the same energy requirements for 100 years use stage in corresponding pairs (conventional and passive). Having the same energy requirements, usage of different construction materials can differentiate environmental burdens arising from the other stages, mainly from production of building materials and final disposal of demolition waste. It was assumed that wood, as a renewable and carbon neutral material, might diminish these burdens in the most significant way.

2. LCA study

Four model single-family residential buildings for a 4-person family with the usable area of 98.04 m^2 have constituted the objects of the study. These buildings differed in material structure, building technology and the energy standard. The following objects have been analysed: a conventional masonry building (A1), a passive masonry building (A2), a conventional wooden building (B1) and a passive wooden building (B2) (Fig. 1). The term wooden building should be understood as a building with maximisation of the use of wood everywhere where it is technologically and functionally justified. All analysed objects constituted single-storey buildings with the following functional program: hall, toilet, living room with a dining area, kitchen, 2-person bedroom, two 1-person rooms, bathroom and laundry room. A separate architectonic design has been prepared for each of the above mentioned buildings. The material use, operational parameters, installations and the use of energy carriers have been calculated individually for each of the buildings, however, in the case of variants A2 and B2 this has been done while taking into account the requirements for passive buildings [21,22]. The buildings have been situated in such a way in relation to the sides of the world so as to maximise the benefit from the solar radiation (large windows in the south wall), which is of special importance in the case of passive buildings.

Buildings serve various functions, among which we can include: occupancy, shielding, hygienic, aesthetic and construction function. Within the scope of the conducted studies, the occupancy and shielding functions have been assumed to constitute the main functions, and on such a basis the functional unit of the studies has been defined: *ensuring 98.04 m^2 of residential area fit to be used for a period of 100 years and ensuring the occupants and items protection from the harmful effect of external factors.* Table 1 provides the characteristics of the construction system and the method of foundation of the analysed buildings. All the analysed buildings have load-bearing structure in a longitudinal arrangement. The masonry buildings are assumed to use load-bearing wall built in a single-layer SOLBET masonry technology in a case of conventional house (A1) and in a double-layer masonry technology in a case of passive house (A2). The wooden buildings (B1, B2) are designed as having load-bearing walls built using a light framework. Traditional wood roof with a collar beam are assumed for masonry buildings while ceiling and pitched roof constructed using lattice trusses are destined to wooden houses. The differences lie also in a construction of foundations (Table 1).

2.1. Material structure of the analysed buildings

The division of the selected buildings into masonry (A1, A2) and wooden (B1, B2), and into conventional (A1, B1) and passive (A2, B2) required architects to assume different design solutions that resulted in a varied material structure of analogous house modules. Table 2 shows individual modules of the analysed buildings according to the weight of building materials within their scope. Table 2 presents the "gross" values constituting the weight of materials delivered directly to the building site or for prefabrication (namely the material loss occurring during the transport and building processes performed on the building site have been taken into account). As Table 2 shows, building materials necessary for constructing masonry buildings weigh 217,986.7 kg (A1) and 244,282.3 kg (A2) and are considerably heavier than materials required for constructing wooden buildings 150,993.8 kg (B1) and 91,623.8 kg (B2). The passive masonry building (A2) as "the heaviest" was 12% heavier than the conventional masonry building (A1),

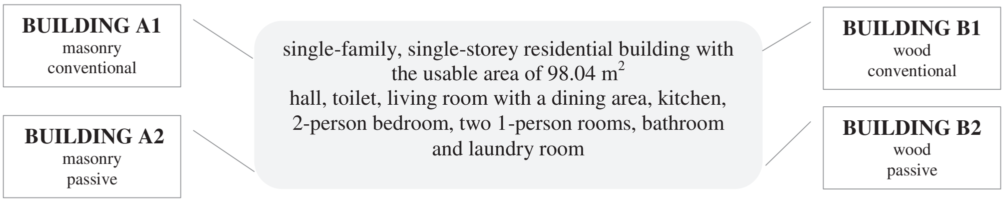

Fig. 1. Variants of four model buildings selected for analysis. *Source:* [23].

Table 1
Construction system and the method of foundation of the analysed buildings.

building	description
Building A1(masonry, conventional)	Load-bearing structure in a longitudinal arrangement. Load-bearing walls built using single-layer SOLBET masonry. Beam and block ceiling. Traditional wood roof with a collar beam. Building foundation laid on a continuous footing. Continuous footing made of concrete (thickness 30 cm), laid directly on the bearing soil.
Building A2(masonry, passive)	Load-bearing structure in a longitudinal arrangement. Load-bearing walls built using double-layer masonry. Beam and block ceiling. Traditional wood roof with a collar beam. Building placed on the concrete foundation slab (thickness 25 cm) laid on the bearing soil via thermal insulation boards (XPS).
Building B1(wooden, conventional)	Load-bearing structure in a longitudinal arrangement. Load-bearing walls built using a light framework. Ceiling and pitched roof constructed using lattice trusses. Building placed on the concrete continuous footing (thickness 30 cm) founded directly on the bearing soil.
Building B2(wooden, passive)	Load-bearing wall structure in a longitudinal arrangement. Load-bearing walls built using a light framework. Ceiling and pitched roof constructed using lattice trusses. Building placed on the concrete foundation slab (thickness 20 cm) laid on the bearing soil via thermal insulation granules (foam glass granulate).

Source: [23].

Table 2
Weight of individual construction modules of the analysed buildings.

Building module	Building A1(masonry, conventional)		Building A2(masonry, passive)	
	Amount (kg)	Share (%)	Amount (kg)	Share (%)
Roof/ceiling	51,854.5	23.8	52,673.8	21.6
Internal walls	8,627.1	4.0	13,812.4	5.7
Foundations/floor	120,863.8	55.4	142,168.0	58.2
Gables	2,864.6	1.3	5,330.7	2.2
Windows/doors	1,330.3	0.6	1,500.1	0.6
Installations	1,454.5	0.7	911.0	0.4
External walls	29,966.0	13.7	26,860.4	11.0
Bathroom	1,026.0	0.5	1,026.0	0.4
Total	217,986.7	100.0	244,282.34	100.0
Building module	Building B1(wooden, conventional)		Building B2(wooden, passive)	
	Amount (kg)	Share (%)	Amount (kg)	Share (%)
Roof/ceiling	8,072.9	5.3	9,717.3	10.6
Internal walls	2,621.5	1.7	2,616.6	2.9
Foundations/floor	130,250.1	86.3	66,845.4	72.7
Gables	440.4	0.3	507.3	0.6
Windows/doors	1,258.9	0.8	1,397.4	1.5
Installations	1,848.1	1.2	911.0	1.0
External walls	5,479.3	3.6	8,933.2	9.7
Bathroom	1,022.6	0.7	1,022.6	1.1
Total	150,993.8	100.0	91,950.7	100.0

Source: [23].

62% heavier than the conventional wooden building (B1) and 167% heavier than the passive wooden building (B2).

In the case of the analysed masonry buildings (A1, A2), the use of wood and wood-based materials has been provided only in the roof structure (coniferous timber), whereas in the case of the wooden houses (B1, B2), wood has also been used as roofing (shake), facade (facade board), floor (floorboard), internal window sills and walls (OSB, MDF, HDF and cellulose) (Table 3).

Table 4 characterises the analysed buildings in respect of the share of individual groups of building materials. As we can see, concrete, natural stone materials, building ceramics and mineral binding materials (cement, lime, gypsum, mortars and grouts) dominate in the case of the masonry buildings (A1, A2). In the masonry buildings, the percentage share of wood and wood-based materials amounts to 1.7–1.9%, which comprises a little over 4 t of roof structure elements. In the case of wooden buildings, concrete also dominates, but a higher share of wood materials becomes visible too (13.6 t in B1 and 18.7 t in B2). Save for the wooden structure of the roof, in this case, additionally wood or wood-based materials have been used in the roof (shake), facade (facade board), floor (floorboard), internal window sills and walls (OSB, MDF, HDF and cellulose). In the wooden buildings, floorboard has been provided on the floor (ceramic tile only in the bathroom), thus a considerable drop in the share of ceramics in the wooden houses in comparison to the masonry houses. Furthermore, in the masonry houses, ceramics includes clinker, which is used for external window sills (in wood houses they are made of aluminium sheet) and expanded clay aggregate, which is used for the elements of ceiling system (structural clay tiles, tie beam profiles, and control and supplementary elements). As non wooden materials having significant weight in wooden buildings, the presence of sand bed (qualified as stone materials) can be seen for building B1, and increased amount of glass (foam glass in the foundations) for building B2.

2.2. Life cycle inventory – the consequences of maximising wood use in the analysed buildings

A different material structure and building technology have influenced each stage of the life cycle of the analysed buildings. From the point of view of the second phase of LCA studies, the life cycle inventory, the maximisation of wood and constructing wooden buildings B1 and B2 using a light frame has had the following inventory consequences in relation to their masonry counterparts (Table 5):

Table 3
Differences in the use of wood and wood-based materials among the analysed buildings.

Element	Masonry houses		wooden1 houses	
	A1 conventional	A2 passive	B1 conventional	B2 passive
Roofing, roof	Concrete roof tiles	Concrete roof tiles	Wood shake	Wood shake
Roof structure	Coniferous timber	Coniferous timber	Coniferous timber	Coniferous timber
Ceiling structure	Cellular concrete blocks	Calcium silicate blocks	OSB, fire-resistant plasterboard	OSB, fire-resistant plasterboard
Ceiling insulation	EPS	EPS	Wood wool	Cellulose
External wall structure	Cellular concrete blocks	Calcium silicate blocks	OSB, fire-resistant plasterboard	OSB, fire-resistant plasterboard
External wall insulation	EPS	EPS	Wood wool	Cellulose
Internal wall structure	Cellular concrete blocks	Calcium silicate blocks	OSB, fire-resistant plasterboard	OSB, fire-resistant plasterboard
Gables' construction	Cellular concrete blocks	Calcium silicate blocks	OSB, fire-resistant plasterboard	OSB, fire-resistant plasterboard
Internal window sills	PVC	PVC	Softwood	Softwood
Floor finish	Ceramic tile	Ceramic tile	Hardwood floorboard	Hardwood floorboard
Window frames	PVC	PVC	Wood	Wood
Façade	External plaster, façade paint	External plaster, façade paint	Softwood façade board	Softwood façade board

Source: [23].

Table 4
Use of various groups of building materials in the analysed buildings.

Group of building materials	Building A1(masonry, conventional)			Building A2(masonry, passive)		
	Amount (kg)	Share (%)	Ranking	Amount (kg)	Share (%)	ranking
Concrete	107,038.8	49.1	1	101,069.4	41.4	2
Natural stone materials	74,121.0	34.0	2	104,257.4	42.7	1
Building ceramics	16,452.9	7.5	3	16,452.9	6.7	3
Mineral binding materials, as well as grouts and mortars	10,640.4	4.9	4	8,268.4	3.4	4
Wood/wood-based materials	4,050.8	1.9	5	4,103.4	1.7	5
Metals	3,906.9	1.8	6	5,232.7	2.1	6
Plastics	1,320.2	0.6	7	3,864.6	1.6	7
Glass	277.0	0.1	8	854.5	0.3	8
Preservatives and paints	178.6	0.1	9	179.8	0.1	9
Plasterboards	0.0	0.0	10	0.0	0.0	10
Total	217,986.7	100.0		244,282.3	100.0	
Group of building materials	Building B1(wooden, conventional)			Building B2(wooden, passive)		
	Amount (kg)	Share (%)	Ranking	Amount (kg)	Share (%)	Ranking
Concrete	60,165.5	39.8	2	54,034.6	58.8	1
Natural stone materials	68,633.4	45.5	1	0.0	0.0	10
Building ceramics	797.7	0.5	8	797.7	0.9	6
Mineral binding materials, as well as grouts and mortars	1,422.9	0.9	5	712.7	0.8	7
Wood/wood-based materials	13,629.5	9.0	3	18,738.3	20.4	2
Metals	1,132.5	0.8	6	1,460.5	1.6	5
Plastics	1,082.8	0.7	7	607.0	0.7	8
GLass	277.0	0.2	9	11,745.8	12.8	3
Preservatives and paints	198.7	0.1	10	200.4	0.2	9
Plasterboards	3,653.9	2.4	4	3,653.9	4.0	4
Total	150,993.8	100.0		91,623.8	100.0	

Source: [23].

- increased use of renewable resources with a neutral carbon balance (in masonry houses A1 and A2 about 2% of the weight of all materials, in conventional wooden house B1 9%, whereas in B2 over 20%),
- decreased weight of used building materials,
- almost two-fold increase of paint and preservative use related to the need of impregnating wood both on the building site and during use (renovation and conservation, replacement and repairs), and the introduction of the required regular reconditioning and maintenance of wood elements during the period of use (floor varnishing, painting windows, painting doors and painting the facade board),
- decreased, because of a lower load weight, transport indicators related to the transport of building materials from the production/sale location to the building site (in the case of the lightest building B2 it is a 75% reduction in comparison to the transport indicators of the masonry buildings).
- introduction of an additional process – partial prefabrication of internal and external walls – during the life cycle of the wooden buildings,
- six-fold decrease of the building time thanks to the prefabrication of walls,
- six-fold decrease of water consumption and almost seven-fold decrease of electric energy consumption on the building site (in the case of wood houses power tools such as saws, nail guns or staple guns are used more often, but concrete mixers or plastering machines are used less frequently). The frequency of construction workers' transportation decreases as well,
- reduced time and consumption (on average by 38%) of energy during the demolition of buildings,
- reduced transport indicators for the transport of demolition waste (on average by 50%) because of a lower shipping weight,

Table 5
Inventory consequences related to the maximisation of wood use in buildings B1 and B2 in comparison to their masonry counterparts.

Inventory Criterion		Change	Building A1(masonry, conventional)	Building A2(masonry, passive)	Building B1(wooden, conventional)	Building B2(wooden, passive)
Share of wood as a renewable resource in the total weight of building materials	%	↑	1.9	1.7	9.0	20.4
Total weight of building materials used on the building site	kg	↓	217,986.7	244,282.3	150,993.8	91,623.8
Use of paints and wood impregnates, and wood-based materials	kg	↑	241.8	243.1	460.1	465.8
Total transport indicator (tonnage * distance) for delivering building materials to the building site	tkm	↓	32,480	32,532	23,857	8,127
Construction time performance (including seasoning)	mths	↓	18	18	3	3
Water consumption on the building site	kg	↓	2,577.3	2,032.6	431.7	340.2
Electric energy consumption on the building site (power tools, mixers and plastering machines)	kWh	↓	923.9	688.7	118.6	120.8
Electric energy consumption during demolition	kWh	↓	377.5	253.1	195.3	197.5
Total transport indicator (tonnage * distance) for transporting demolition waste to the disposal sites	tkm	↓	3,254.4	3,603.8	2,196.7	1,232.7
Amount of waste generated on the building site after the demolition of the building (the portion of materials that have been accumulated during use)	kg	↓	222,319.4	247,845.4	152,652.9	93,684.9

Source: [23].

- decreased overall weight of waste for final disposal, both from the building site and after the demolition, provided that there is a higher amount of paints and wood impregnates constituting difficult waste.

Among the above mentioned consequences there has been no reference made to the energy requirement of the buildings, because the distinction between masonry and wooden buildings (A vs. B) had no influence on energy consumption during the period of use. This issue had been reflected in the second distinction between conventional and passive buildings (1 vs. 2). In terms of energy consumption during use stage, conventional masonry building had its counterpart in conventional wooden building and passive masonry building in passive wooden building.

2.3. Life cycle impact assessment – the environmental consequences of maximising wood use in the analysed buildings

Above, the differences, from the inventory point of view, between the masonry and the wooden buildings that have become visible in the LCA studies has been discussed. As it can be seen, the increase of the amount of wood and wood-based materials and the use of a light structure of load-bearing walls subject to prefabrication, has an inventory-wise effect, in general, on every single stage of the life cycle of buildings. Here, the results of the environmental impact assessment and the environmental consequences resulting from the maximisation of wood use in buildings B1 and B2 in comparison to their masonry counterparts shall be assessed. LCIA analyses have been carried out in SimaPro Analyst 7.3 using Impact 2002+ method constituting a combination of four LCIA methods: IMPACT 2002+ [24], Ecoindicator 99/E [25], CML [26] and IPCC. On the most accumulated level, the value of environmental impact is expressed with ecoindicator and measured in environmental points [Pt]. The result of the accumulated ecoindicator can be “decomposed” into smaller elements: damage categories (human health, ecosystem quality, climate change, resources) and impact categories (carcinogens, non-carcinogens, respiratory inorganics, ionising radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nitrification, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy, mineral extraction). In such a case, the weighted results of impact or damage indicators are concerned and they will also be expressed in environmental points [Pt] (endpoints level). Because Impact 2002+ is a combined method, identical damage or impact categories can also be analysed on more disaggregated levels: normalisation and characterisation (midpoints level). In the latter case, the results of impact category indicators will be expressed in midpoint units, e.g. kg CO_2 eq for global warming, kg C_2H_3Cl eq for carcinogens, kg CFC-11 eq for ozone layer depletion. Regardless of the level of analysis, the rule stating that the higher the positive indicator result is, the higher the negative impact on the environment, remains effective. A negative indicator result will be interpreted as a benefit to the environment. This article shall present the results of ecoindiator [Pt] and weighted results of impact category indicators [Pt].

In the studies that have been conducted, the passive masonry house (A2), whose entire life cycle generates negative environmental impact equal to 270.6 Pt, has turned out to be the worst environmentally-wise (Table 6). In the case of passive wood house B2 and conventional masonry house A1, the results are quite similar, around 250 Pt (A1 = 249.1 Pt; B2 = 257.1 Pt). The life cycle of conventional wood house B1, whose indicator result is 230.7 Pt and is lower by 7.3%, 14.7% and 10.2% than the results for A1, A2 and B2, respectively, has turned out to be the best. The impact shown above relates to the functional unit assumed in the study, therefore the production and transport of the amount of materials necessary to construct a building with the usable area of 98.04 m^2, constructing such a building, using it for a 100 years (including replacements, repairs, renovations and waste disposal), demolition as well as transport and management of the generated demolition waste.

Results presented in Table 6 show that the wooden buildings show lower environmental impact than their masonry counterparts in the majority of life cycle stages. In the case of use, the environmental impact is dominated with energy issues, and higher indicator results for passive houses (despite the lower energy requirement) are the effect of heating the buildings using electric radiators and a high ecological rucksack related to the production of electric energy in Poland (90% based on hard coal and brown coal). However, because this is not a question directly correlated with the use of wood as a building material, it has been excluded from the scope of this article. A lower environmental impact of transport processes, building activities and demolition results directly from the inventory consequences that have been described previously. A lower shipment weight resulting from lighter building materials used in houses B1 and B2 results in, in comparison to A1 and A2, a reduction of the ecoindicator for the transport of building materials (stage 2) by 23.5% (B1) and by 58.5% (B2). Also, a four-fold lower impact related to the building activities (stage 3)

Table 6
Environmental impact of individual life cycle stages of buildings A1, A2, B1 and B2 as the result of the accumulated ecoindicator [Pt, %].

Life cycle stage	Building A1(masonry, conventional)		Building A2(masonry, passive)		Building B1(wooden, conventional)		Building B2(wooden, passive)	
	(Pt)	(%)	(Pt)	(%)	(Pt)	(%)	(Pt)	(%)
Stage 1 – production of building materials	16.8	6.8	20.4	7.5	6.3	2.8	13.0	5.1
Stage 2 – transport of building materials	1.7	0.7	1.7	0.6	1.3	0.6	0.7	0.3
Stage 3– construction process	1.6	0.6	1.6	0.6	0.4	0.2	0.4	0.2
Stage 4 – use	229.5	92.1	249.0	92.0	223.2	96.7	245.1	95.3
Stage 5 – demolition	0.22	0.1	0.2	0.1	0.15	0.08	0.16	0.08
Stage 6 – transport of demolition waste	0.17	0.1	0.18	0.1	0.11	0.04	0.06	0.04
Stage 7 – final disposal of demolition waste	−0.88	−0.4	−2.37	−0.9	−0.81	−0.34	−2.36	−0.9
Total	249.1	100.0	270.6	100.0	230.7	100.0	257.1	100.0

Source: SimaPro Analyst v.7.3.0/Impact 2002+.

Table 7
Environmental impact of stage 1 – production of building materials, buildings A1, A2, B1 and B2 – weighted results of impact category indicators.

Impact Category	Building A1(masonry, conventional)		Building A2(masonry, passive)		Building B1(wooden, conventional)		Building B2(wooden, passive)	
	(Pt)	(%)	(Pt)	(%)	(Pt)	(%)	(Pt)	(%)
Carcinogens	0.3	1.7	0.5	2.2	0.2	3.0	0.3	2.4
Non-carcinogens	0.5	3.2	0.6	3.1	0.4	6.5	0.5	4.2
Respiratory inorganics	6.9	41.1	7.4	36.5	2.9	46.1	4.2	32.0
Ionising radiation	0.02	0.1	0.03	0.1	0.013	0.2	0.1	0.4
Ozone layer depletion	0.0004	0.003	0.0367	0.180	0.0002	0.0	0.0006	0.004
Respiratory organics	0.005	0.03	0.01	0.05	0.004	0.1	0.005	0.04
Aquatic ecotoxicity	0.01	0.1	0.02	0.1	0.01	0.2	0.02	0.1
Terrestrial ecotoxicity	1.0	5.9	1.1	5.3	0.7	11.9	1.0	7.6
Terrestrial acidification and nitrification	0.1	0.3	0.1	0.3	0.03	0.5	0.1	0.5
Land occupation	0.3	1.9	0.3	1.6	0.5	8.5	0.6	4.8
Aquatic acidification	–	–	–	–	–		–	–
Aquatic eutrophication	–	–	–	–	–		–	–
Global warming	3.9	23.2	4.8	23.5	−0.5	−7.4	1.3	9.9
Non-renewable energy	3.7	22.0	5.4	26.7	1.9	30.2	4.9	38.0
Mineral extraction	0.1	0.4	0.1	0.3	0.02	0.4	0.02	0.1
Total	16.8	100.0	20.4	100.0	6.3	100.0	13.0	100.0

Source: SimaPro Analyst v.7.3.0/Impact 2002+.

can be seen, which is 1.6 Pt for the masonry buildings, whereas it equals 0.4 Pt in the case of the wooden ones. It is a direct effect of a lower consumption of electric energy and water on the building site of the wooden buildings (a lower water consumption also reduces the amount of wastewater generated by building activities). Moreover, the construction of the wooden buildings is related to a lower impact of the transport of construction workers. A lower electric energy consumption during demolition also translates into a lower environmental indicator result for the demolition of the wooden buildings. Similar to the transport of building materials, the transport of demolition waste is more favourable environmentally-wise in the case of B1 and B2, which is the consequence of the lower weight of materials.

Results for stages 1 and 7 require a separate commentary. What environmental impact is generated by wood and wood-based materials used in the analysed buildings remains the key question. If we look at the indicator results for stage 1 *production of building materials*, and if we analyse the impact using “cradle-to-gate” perspective (Table 6), we can see that that the wooden houses turn out significantly better: A1 = 16.8 Pt, A2 = 20.4 Pt, B1 = 6.3 Pt and B2 = 13.0 Pt. Furthermore, if we take into account a higher weight percentage share of wood and wood based materials in the whole buildings (B1 (9%) and B2 (20.4%) in comparison to masonry houses A1 (1.9%) and A2 (1.7%)), we should expect the existence of an interrelation between the use of wood and the reduction of the result of the environmental indicator. Below, in Tables 7 and 8, the results enabling a more in-depth analysis of this issue have been presented. Table 7 shows the environmental impact of stage 1 – production of building materials with a division into impact categories (as weighted indicator results), whereas Table 8 shows the environmental impact of the production of individual groups of materials. The intention has been to make the form of Table 8 analogous to Table 4 which showed types of materials according to their weight. However, a complete harmonisation has turned out to be impossible because of the multi-material and complex structure of certain elements, i.e. ceiling system in the masonry houses, electrical cables, gas boiler, window and door frames. Therefore, in Table 4 they have been separated and assigned by weight, whereas in Table 8 the environmental indicators obtained for such elements have not been separated and they have been isolated as an individual category.

Wood and wood-based materials constitute the only group of building materials used for the construction of all analysed houses for which the indicator result shows an environmental benefit (Table 8). In the technological “history” of wood and wood-based materials there have been certain interferences that have had a negative impact on the environment, but the final negative indicator result has proved that in the case of analysed houses they have been lower than the environmental benefit. Here, the main source of the environmental benefit is the impact category *global warming* (Table 7). It results from the favourable carbon footprint of wood, which in the process of growth and photosynthesis “sucks up” carbon dioxide from the atmosphere. The result of the accumulated ecoindicator for the production of 1 m^3 large-size softwood

Table 8

Environmental impact of stage 1 *production of building materials*– according to the type of building materials.

Group of building materials	Building A1(masonry, conventional)			Building A2(masonry, passive)		
	indicator result (Pt)	Share (%)	Ranking	Indicator result (Pt)	Share (%)	Ranking
Concrete	3.9	23.0	3	1.8	8.7	4
Natural stone materials	0.1	0.5	9	1.0	4.9	6
Building ceramics (excluding expanded clay aggregate from the ceiling system)	4.0	23.6	2	4.0	19.5	3
Mineral binding materials, as well as grouts and mortars	0.8	4.9	5	0.7	3.4	7
Wood/wood-based materials (excluding doors)	−0.1	−0.5	10	−0.1	−0.4	10
Metals (excluding ceiling system, gas boiler, window/door frames and cables)	1.3	7.8	4	1.5	7.2	5
Plastics (excluding window/door frames, cables and gas boiler)	0.8	4.7	6	4.4	21.4	2
Glass	0.2	0.9	9	0.5	2.3	8
Preservatives and paints	0.2	1.1	7	0.2	0.9	9
Other/multi-material (complete ceiling system, electrical cables, gas boiler, window and door frames)	5.7	34.0	1	6.6	32.2	1
Total	16.8	100.0		20.4	100.0	
Building module	Building B1(wooden, conventional)			Building B2(wooden, passive)		
	Indicator result (Pt)	Share (%)	Ranking	Indicator result (Pt)	Share (%)	Ranking
Concrete	0.7	11.7	5	1.1	8.3	4
Natural stone materials	0.1	1.2	9	–	–	–
Building ceramics (excluding expanded clay aggregate from the ceiling system)	0.9	13.9	4	0.9	6.8	5
Mineral binding materials, as well as grouts and mortars	1.0	15.9	3	0.5	3.7	7
Wood/wood-based materials (excluding doors and cellulose)	−0.5	−7.8	10	−0.2	−1.5	10
Metals (excluding ceiling system, gas boiler, window/door frames and cables)	1.5	24.0	2	1.2	9.1	3
Plastics (excluding window/door frames, cables and gas boiler)	0.4	5.9	6	0.2	1.8	8
Glass	0.2	2.5	7	5.9	45.6	1
Preservatives and paints	0.2	3.5	8	0.2	1.7	9
Other/multi-material (complete ceiling system, electrical cables, gas boiler, window and door frames)	1.8	29.2	1	2.6	20.1	2
Wood/wood-based materials (cellulose)	–	–	–	0.6	4.4	6
Total	6.3	100.0		13.0	100.0	

Source: SimaPro Analyst v.7.3.0/Impact 2002+.

is -0.011 Pt, which shows that the environmental benefit taking place only within the scope of *global warming* exceeds the negative impact caused by other environmental interferences related to the forest processes and subsequent processing of wood. For the impact category *global warming* itself, the weighted indicator result for 1 m^3 large-size softwood is −0.072 Pt, and if we take into account the characterising level, it is around −715 kg CO_2 eq. During forest processes, CO_2 is being emitted (transport processes, cutting with chainsaw, transforming the land surface), but it is significantly lower (98.7 kg per 1 m^3 large-size softwood) in comparison to the amount of CO_2 absorbed during photosynthesis (926 kg per 1 m^3 large-size softwood). The negative indicator result is characteristic not only of the wood itself, but also of wood-based materials, such as OSB or wood wool. Therefore, this group of materials takes the last, 10th place in the ranking of all materials listed in Table 8, as the one having the smallest environmental impact.

For house B1, the negative indicator results for stage 1 within the same impact category *global warming* show (Table 7) that in the case of this house the emission of greenhouse gasses related to the production of all building materials is lower than the positive "photosynthesis" effect of wood used for building such a house. In the case of house B2, also significantly based on wood materials, the indicator result for *global warming* is positive, which results from the fact that the environmental benefit from using wood is equalised by a considerable emission of greenhouse gasses occurring during the production of other building materials. This is mainly due to the emissions taking place during the production of electric energy and heat energy used for producing foam glass used in building B2 as a construction and insulation material for the foundations.

According to the indicators provided in Table 8, the indicator result within the scope of wood materials for house B2 equals −0.2 Pt, however, cellulose, used as an insulation material in external walls and the ceiling, which is also based on wood material, has not been included on purpose. Because as it can be seen in data provided in Table 8, cellulose eventually shows a positive ecoindicator result (a negative environmental impact) and the environmental rucksack related to the production of cellulose used both in external walls and the ceiling equals 0.57 Pt, which constitutes 4.4% of total impact within the scope of *production of building materials* for house B2. The main sources of impact comprise environmental rucksacks related to electric energy and heat energy (natural gas) as well as sulphuric acid and boric acid, used for producing cellulose. If we add the indicator result for wood materials (−0.2 Pt) and cellulose (0.57 Pt) the final result would equal 0.4 Pt (2.9%), which would move the *wood and wood-based materials* to the last but one position (in such a case plastics would be ranked higher with the indicator result of 0.2 Pt). Nevertheless, it is worth mentioning, that they would still constitute a group of materials with the lowest negative environmental impact.

Above, the results of environmental impact of individual material groups from the perspective of stage 1 *production of building materials* have been presented. Below, in order to obtain a complete picture, the indicator results for stage 7 *final disposal of demolition waste* shall be presented. Because in this case it has been possible to accurately separate waste materials, Table 9 corresponds to Table 4 (with one difference, namely that Table 4 relates to stage 1 and shows "gross" building material amounts, but the indicators in Table 9 below relate to stage 7, thus to the "net" amount to which materials accumulated during use have been added). For the sake of cohesion with the discussion concerning stage 1, in the case of house B2, cellulose has been isolated as a separate category of wood-based material.

The information contained in Table 8 enable a comparison and assessment of individual groups of building materials from the "cradle-to-gate" perspective and show the amount of environmental impact generated during the "technological history" of all

Table 9
Environmental impact of stage 7 *final disposal of demolition waste*– according to groups of waste materials.

Waste material group	Building A1(masonry, conventional)		Building A2(masonry, passive)	
	Final waste disposal (Pt)	Ranking	Final waste disposal (Pt)	Ranking
Concrete	0.4	1	0.3	2
Natural stone materials	0.3	2	0.4	1
Building ceramics	0.1	3	0.1	3
Mineral binding materials, as well as grouts and mortars	0.1	4	0.04	4
Wood/wood-based materials	−0.1	7	−0.1	7
Metals	−0.8	9	−0.9	8
Plastics	−0.7	8	−2.1	9
Glass	−0.03	6	−0.1	6
Preservatives and paints	0.01	5	0.01	5
Plasterboards	–	–	–	–
Total	−0.9		−2.4	
Waste material group	Building B1(wooden, conventional)		Building B2(wooden, passive)	
	Final waste disposal (Pt)	Ranking	Final waste disposal (Pt)	Ranking
Concrete	0.2	2	0.2	1
Natural stone materials	0.2	1	–	–
Building ceramics	0.003	6	0.003	5
Mineral binding materials, as well as grouts and mortars	0.01	5	0.004	4
Wood/wood-based materials (excluding cellulose)	−0.2	8	−0.1	6
Metals	−0.8	10	−0.9	9
Plastics	−0.3	9	−0.3	8
Glass	−0.03	7	−1.1	10
Preservatives and paints	0.02	3	0.02	2
Plasterboards	0.01	4	0.01	3
Wood/wood-based materials (cellulose)	–	–	−0.2	7
Total	−0.8		−2.4	

Source: SimaPro Analyst v.7.3.0/Impact 2002+.

materials in the amount necessary for the construction of buildings A1, A2, B1 and B2. This table shows wood and wood-based materials as the most advantageous environmentally-wise (even after considering the positive indicator result for cellulose in the case of house B2), because photosynthesis occurs at the stage of “cradle” and an environmental benefit takes place. An analogous division into waste materials has been provided in Table 9, also the amount of environmental impact related to the disposal of such an amount of waste generated upon the demolition of buildings has been shown. In accordance with the assumed scenarios of final disposal, there is more environmentally beneficial waste (with a negative indicator result) and, aside for wood and wood-based materials, it also includes: metals, plastics and glass. It should be added that Table 9 shows the final result corresponding to a given material group. Negative indicator results for metals and plastics result from the environmental benefit related to recycling, but not every metal or plastic waste has been recycled. Sometimes, if it has been thought justified, e.g. because of it being impossible to isolate metal or plastic from the whole building element, such waste has been directed to a landfill or an incineration plant. Such cases have been very rare and, as the results presented in Table 9 show, in most cases metal, plastic and glass waste has been recycled. In the case of wood and wood-based materials, incineration has been assumed with energy recovery, and the negative indicator results for such waste result only from the environmental benefit related to such recovery. The wood incineration process itself leads to a number of negative environmental interferences, including also the emission of greenhouse gasses, which has been taken into consideration in the analyses. In the case of house B2, after adding indicator results for *the final disposal* for wood waste including cellulose, the result of −0.3 Pt has been obtained, which constitutes the greatest benefit generated by this group of waste within the scope of all analysed houses (A1 = −0.1 Pt, A2 = −0.1 Pt, B1 = −0.2 Pt, B2 = −0.3 Pt). It should, however, be added that the environmental benefit resulting from the disposal of metal and plastic waste has been in any case higher than in the case of wood materials, which results from the higher environmental benefit of recycling them and higher energy recovery indicators for plastics in the case of incinerating them.

The results provided in Table 9 also show the amount of the negative impact on the environment related to the disposal of used impregnates and paints. The indicator result for this waste category for the masonry buildings equals 0.01 Pt, whereas in the case of the wooden houses it is twice as high (0.02 Pt). This waste category includes not only paints used for maintaining wood elements, but also paints for painting walls and facades of the masonry buildings. The obtained indicator results (Table 9) include, therefore, the negative impact resulting from the incineration of impregnates and paints related to the used windows, doors, facades, floor, but also related to the storage of paints present in the wall waste on the landfill. Due to the fact that the amount of paint used for painting internal walls has been similar in the case of all buildings, it must be acknowledged that the difference between buildings within the scope of environmental impact of the disposal of this waste group results only from the increased requirement for impregnates and paints of the wooden buildings.

3. Conclusions

In the conducted analyses the wood and wood-based materials, as the only ones from among the analysed building materials, have shown an environmental benefit both from the “cradle-to-gate” (stage 1) and “gate-to-grave/reincarnation” (stage 7) perspective. In the first case, it has been directly connected with the effect of photosynthesis and absorbing carbon dioxide, positive for the global warming, which takes place in the “cradle”, i.e. during tree growth in the forest. Because not only products made of wood, but also wood-based products (OSB, MDF/HDF, plywood) are based on wood material, the positive ecological effect of the “cradle” has been also noted in their case. The negative final ecoindicator result for this material group means that the environmental benefit within the scope of *global warming* has exceeded the negative environmental impact visible in the case of the remaining impact categories. Cellulose, used as the insulation material of external walls and the ceiling of house B2, has been an exception here, because in its case the negative impact of energy consumption and using chemical compounds in the production has exceeded the positive ecological effect related to the use of wood material. But even in the case of building B2, after adding the indicator result for cellulose and obtaining a small positive (unfavourable) environmental impact because of that, wood materials still belong to the ones having the smallest environmental impact from among all the materials used in the analysed buildings. In reference to wood materials treated as waste, there is no source of environmental benefit in the resource itself, but it results from the incineration scenario assumed in the analysis, wherein the recovery of electrical energy and heat energy has been assumed. Because it is a scenario adopted also for many other waste materials, therefore, among the results for stage 7, wood and wood-based materials are not the only materials eventually showing a favourable environmental impact (negative indicator result). However, it might be characteristic that if we look at the results for all life cycle stages while overlooking the use which has been dominated by energy-related questions, wood houses B1 and B2 turn out the most favourably, which must be related to the material structure of these buildings. As the obtained results have shown, the assessment of building materials should be made in a broader perspective and should not be limited only to the scope of “cradle to gate”. Materials such as foam glass, cellulose and electrical cables, constitute valid proofs of that, and which, if perceived solely from the perspective of stage 1 – *production of building materials*, turn out unfavourably in the assessment, but upon taking into account their susceptibility to recycling or possibility of recovering energy via incineration, they are classified as waste generating an environmental benefit.

Yet, the benefits of using wood in the building industry do not come down only to its neutral carbon balance and the possibility of recovering energy by the way of incineration. In the analyses that have been carried out, the benefits have become visible in other stages of buildings’ life cycles too, and they have been related to the following areas: transport (lower weight of shipping both generated by building materials delivered to the building site and by demolition waste moved to the disposal site), building site (shorter construction time related to the prefabrication of selected modules and a different building technology, lower water and electric energy consumption, lower amount of building waste) and demolition (lower electric energy consumption). The only weaker link of using wood has turned out to be the necessity of undertaking more frequent activities related to conservation and renovation (painting, impregnation) during the use of the building, and almost two times higher use of impregnates and paints connected with that (which has its environmental consequences both from the point of view of production of such materials and disposal of waste generated from them).

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