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Ecological comparison of hygrothermally safe floor constructions based on renewable raw materials for multi-storey buildings

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ABSTRACT

The major goal of the European Green Deal states that Europe will be climate neutral by 2050. Hence, massive changes have to happen in the construction industry. One way to reduce the environmental impact caused by the building sector is the use of building materials consisting of renewable raw materials. In order to enable a wider application of bio-based building products, the hygrothermal safety of all building components has to be guaranteed. In this paper, three floor constructions based on renewable raw materials, each representing a type of construction and foundation, were examined for their hygrothermal safety. In addition, these were compared with a conventional floor structure in terms of their environmental characteristics. The ecological evaluation was carried out by the analysis of the global warming potential, Oekoindex OI3, disposal indicator and on the basis of corresponding environmental product declarations (EPDs). The software WUFI 2D was used for the hygrothermal evaluation. The results prove the constructions' hygrothermal safety in the simulated climate. The ecological calculation shows the possible reduction of the global warming potential of the floor constructions of up to 82% per m^2, depending on the choice of construction type and materials. Applying the other three methods mentioned above, the analysis results in a reduction potential of the environmental load of approx. 53–55% per m^2. Depending on the chosen assessment method the results differ. This states clearly how sensitive the selection of suitable indicators is. Fact is, that the data situation around the ecological indicators of building products is a key issue which has a major effect on the results of the evaluations. All results of the ecological assessment presented in this study were strongly influenced by the foundation type. Consequently, the material efficiency and type of foundation used have a significant effect on the ecology and the environmental performance of the simulated floor constructions.

1. Introduction

The construction sector causes remarkably high environmental burdens. According to current calculations, the sector is responsible for 35% of global primary energy demand and 38% of global emissions [1]. The main goal of the European Green Deal states that Europe should reach climate neutrality by 2050. Therefore, it is necessary that great changes take place in the construction industry in the near future. The changes concern the ecological impact of buildings, that can be reduced at various levels. In general, a distinction is made between environmental impacts that occur during the use of a building and those embodied in materials. In recent decades,

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ecological calculation focused on the environmental impacts that arose during the use of buildings. This share relates to the demand of cooling and heating as well as the type of electricity and varies greatly from building to building. The more efficient the operation of a building, the lower its impact on the environment and vice-versa. The environmental impacts of buildings can be significantly influenced by the choice of building materials. The mining and manufacturing of materials and chemicals has been found to contribute to a total of 90% of total CO_2 emissions [2]. The consideration of the environmental impact embodied in constructions is therefore becoming increasingly relevant [3–5]. However, the share of the environmental impact of the materials used varies greatly depending on the type of a building and the energy used. In highly efficient buildings, the embodied energy accounts for between 74% and 100% of the total energy needed [6]. For high-rise buildings, embodied CO_2 is responsible for 27–58% of total emissions, depending on the composition of the energy mix used [7]. In summary, even in highly energy-efficient buildings, a large proportion of the environmental impact can be saved when using materials with a low percentage of embodied energy and embodied CO_2.

The use of building materials made from renewable raw materials is one way to reduce the energy demand as well as the environmental load. In addition, the use of natural building materials not only reduces the environmental impact, but also has a positive effect on human health [8]. However, depending on the requirements, the substitution of conventional building materials with those made from renewable raw materials is not possible for every building component layer. For these layers, especially in the splash water area, recyclable and recycled building materials play an equally important role in ecological building constructions.

It is true that many countries have a long tradition of constructing buildings with regional building materials made from renewable raw materials, as this was originally the easiest and cheapest way of construction. In recent decades, however, some of this knowledge has been lost and many building standards have changed over the years. Thus, building with traditional bio-based building materials has to be recombined with today’s standards.

Bio-based materials can be used for the static components as well as for non-load-bearing components or interior finishing. While timber is becoming increasingly popular as a construction material, in Europe insulation is predominantly made of glass and rock wool (approx. 58%) and polymer-based insulation materials (approx. 41%) [9]. Only an extremely small proportion (less than 1%) consists of renewable raw materials [9]. Accordingly, the use of bio-based materials can be greatly increased especially in the areas of insulation and interior finishing.

When bio-based materials are used, the designs must be at least as good as conventional designs in terms of robustness and durability. Along load-bearing requirements, hygrothermal safety in constructions is one of the most important factors in order to construct long-lasting, sustainable and healthy buildings. Most renewable building materials are hygroscopic and can therefore absorb water molecules from the environment [10]. They are sensitive to the growth of mould, which on the one hand can cause the material to degrade, and on the other hand can bring unhealthy effects on the indoor climate of its inhabitants, if not built in correctly [11]. However, if installed correctly, they can lead to high hygrothermal comfort due to the water storage capacity. In order to be able to exclude damage and health risks, hygrothermal safety is particularly relevant in the use of these building materials. Many studies therefore focus on researching the hygric properties of natural building materials [12–14].

A large number of hygrothermally safe ecological exterior wall constructions already exist for the construction of multi-storey buildings. These are mainly constructions based on cross laminated timber or frame construction, which are combined with ecological insulation such as cellulose, straw or wood fibre. Ventilated or non-ventilated variants are listed, for example, on dataholz.eu [15]. However, ecological variants for floor constructions are not listed on this page. In recent years, ecological comparisons of constructions have been carried out mainly for exterior walls [16–20], for non-load-bearing interior walls [21–23] and suspended ceilings [24]. Floor constructions in contact with the ground have hardly been evaluated ecologically, although they often lead to high environmental impacts. Reasons for the high impacts are the frequently applied floor slabs made of reinforced concrete and the polymer-based insulation layer, which are located in the area in contact with the ground and splash water area. However, ecological variants of floor constructions are as important as other building components.

The method for determining whether components are ecological is called life cycle assessment. This calculation includes various indicators and the possibility to define different frameworks. For a long time the consideration of the consumption and use of non-renewable resources dominated the discussion as the only indicator for the ecological assessment of buildings [25]. Studies on the other side refer to the necessity of considering the greenhouse gas potential in order to achieve the climate goals [26]. These two indicators are therefore often chosen as the decisive measure for assessing environmental performance. According to EN 15804, more than 20 indicators per building material have to be considered [27]. The assessment differs not only in the choice of indicators, but also in the definition of the system boundaries. The environmental impacts of the life cycle of entire buildings, individual constructions or even only of building products can be calculated and compared.

The examined floor structures were developed within the natuREbuilt project [28]. The consortium consists of a collaboration of several experts in the field of ecological building construction. Ecological solutions for floor constructions already exist for single-family houses, but they cannot be adopted to multi-storey buildings without modifications [29]. The focus of this study investigates floor constructions which are suitable for buildings with 2–3 storeys or more, depending on the requirements. Due to the very different standards in the implementation of the details in different countries, this paper only assesses the basic constructions. It does not address the exact connection details to exterior walls or the size and dimensions of the foundations.

Based on the floor constructions developed in the natuREbuilt project, two goals were defined for the assessment:

- first, to validate the functionality of the constructions by performing hygrothermal simulations;
- second, to compare the ecological impact of the studied constructions with that of a conventional construction by calculating life cycle assessments with different method settings;

The hygrothermal simulation was carried out with the software WUFI 2D. In order to obtain a comprehensive analysis of the environmental impact of the constructions, various methods of ecological assessment were used and compared in this study.

2. Materials and methods

Depending on the foundation and insulation type, one floor construction per type was analysed:

- **F1a and F1b**: Ventilated floor construction with ground screw foundations
- **F2a and F2b**: Floor construction with external insulation and slab foundation
- **F3**: Floor construction with internal insulation and strip foundation

The three types cover a wide range of floor constructions that can be adapted in their exact design, depending on the application.

2.1. Selection and description of the analysed floor constructions

2.1.1. Ventilated floor construction with ground screw foundations (F1a and F1b)

Fig. 1 shows a ventilated floor construction, which can be realised with steel screw foundations. The layers of the construction are presented in Table 1. The design of a ventilated timber floor construction is used in Scandinavia and North America since the middle of the 19th century and still counts as a building standard [30]. Even in Austria, buildings with 1–3 storeys are built this way. The ventilation is used to avert condensate, outside air humidity, condensation water, diffusion humidity from the interior rooms and installation humidity by air circulation. The construction usually is supported on screw foundations made of steel or on point or strip foundations made of reinforced concrete.

Due to the elevated design, the construction is outside the splash water area, which has a positive effect on moisture protection. A disadvantage of the elevated structure is the difficulty of a barrier-free access due to the elevated position of the flooring. The ventilated area should be closed with a grating or delimited by a surrounding reinforced concrete base with a ventilation opening. The building material adjacent to the air layer can be finished with larch formwork or, alternatively, with a cement-bonded wood-based panel; these are referred to here as variant F1a and F1b. In the hygrothermal evaluation, the alternative with the larch formwork (F1b) was examined in greater depth.

Evaporation from the soil is a relevant source of moisture that must be minimised with a diffusion-inhibiting layer [31]. In the German standard DIN 68 800–2, a full-surface diffusion-inhibiting layer with an sd - value ≥ 100 m directly above the soil is recommended [32].

2.1.2. Floor construction with external insulation and slab foundation (F2a and F2b)

Fig. 2 shows two versions with insulation underneath the reinforced concrete slab. In one version perlite are blown in the installation level, in the other sheep's wool is placed between the timber framework. The material layers of the two constructions are shown in Table 2 and Table 3. The foundation is designed as a floor slab, the versions differ in the use of standard concrete with an

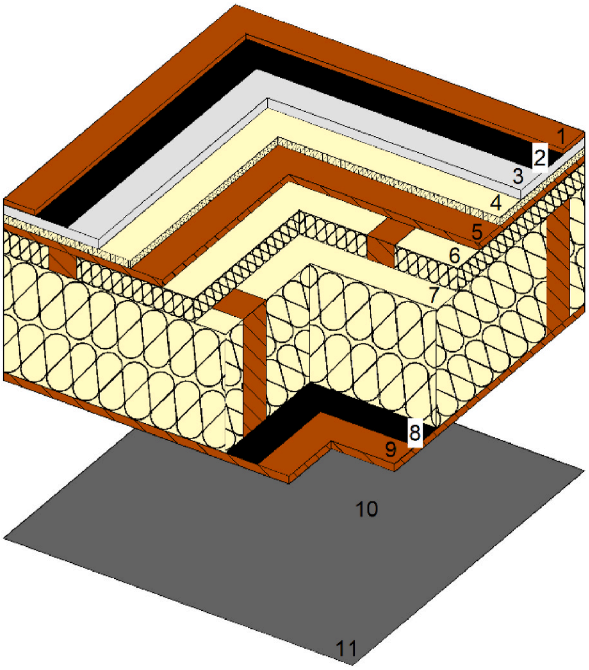

Fig. 1. Construction F1a and F1b [30].

Table 1
Material layers F1a [33].

	Material	Layer thickness (cm)	Area share (%/m^2)
1	Parquet flooring	1.30	100
2	Parquet adhesive	0.10	100
3	Gypsum fibreboard (dry screed)	2.50	100
4	Wood fibre board (footfall sound insulation)	2.00	100
5	OSB panel	1.80	100
6	Cellulose (blow-in insulation)	6.00	88
	Timber	6.00	12
7	Cellulose (blow-in insulation)	30.00	85
	Timber	30.00	15
9	Cement-bound particle board (F1a)	2.00	100
	Larch shuttering (F1b)		
8	Permeable air barrier	0.06	100
10	Air	40.00	99.50
	Ground screw foundation		0.50
11	Polypropylene fleece	0.20	100
		Σ 85.96	

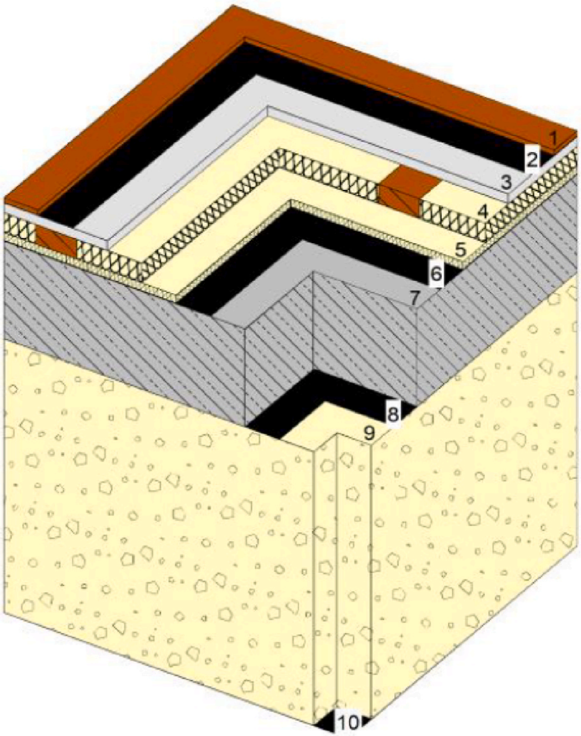

Fig. 2. Construction F2a, F2b [33].

EPDM foil as well as with waterproof concrete. In the hygrothermal calculation, the version with standard concrete and EPDM foil (F2b) was examined more closely.

The insulation layer of glass foam granulate lies below the floor slab. Glass foam granulate is a fill made of recycled, expanded glass that can be used as a load-bearing, heat-insulating and draining layer under a floor slab [32]. Theoretically, the recycled material can be reused in another project, provided it has not been contaminated. Due to the recyclability and the production of the material from a secondary raw material, it is defined in the industry as an ecological alternative for thermal insulation under a reinforced concrete floor slab. A layer thickness of up to 90 cm is possible, whereby the material must be poured and compacted in several layers from 30 cm thickness upwards [32].

2.1.3. Floor construction with interior insulation and strip foundation (F3)

Fig. 3 shows the construction F3, Table 4 presents the material layers of the construction. Here, the insulation is placed above the waterproofing layer. Lean concrete between strip foundations is chosen as the substructure. The internal insulation above the

Table 2
Material layers F2a.

	Material	Layer thickness (cm)	Area share (%/m^2)
1	Parquet flooring	1.30	100
2	Parquet adhesive	0.10	100
3	Gypsum fibreboard (dry screed)	2.50	100
4	Sheep wool insulation	5.00	18
	Timber	5.00	82
5	Wood fibre board (footfall sound insulation)	2.00	100
6	Polyethylene foil	0.25	100
7	Water-resistant concrete with 1% reinforcing steel	25.00	100
8	Polypropylene fleece	0.20	100
9	Granulated glass foam	70.00	100
10	Polypropylene fleece	0.20	100
		Σ 106.55	

Table 3
Material layers F2b.

	Material	Layer thickness (cm)	Area share (%/m^2)
1	Parquet flooring	1.30	100
2	Parquet adhesive	0.10	100
3	Gypsum fibreboard (dry screed)	2.50	100
4	Wood fibre board (footfall sound insulation)	2.00	100
5	Perlite fill	5.00	100
6	EPDM[a] sealing	0.25	100
7	Standard concrete with 1% reinforcement steel	25.00	100
8	Polypropylene fleece	0.20	100
9	Granulated glass foam	70.00	100
10	Polypropylene fleece	0.20	100
		Σ 106.55	

[a] *Ethylene-propylene-diene rubber sealing.*

foundation level creates a hygrothermally more complex situation. Due to convective flow behind the insulation or gaps in the insulation system, interior insulation can cause mould growth if not carried out properly [34]. Accurate calculation as well as proper execution are therefore particularly relevant for this design.

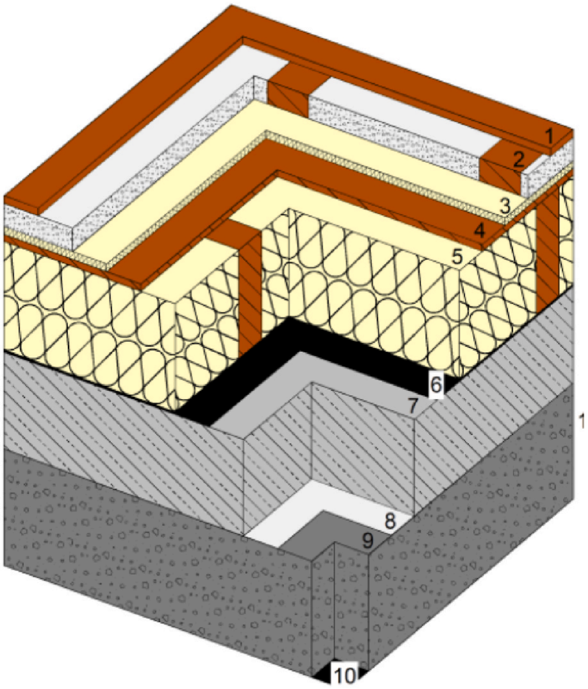

Fig. 3. Construction F3 [33].

Table 4
Material layers F3.

	Material	Layer thickness (cm)	Area share (%/m^2)
1	Wooden flooring	2.00	100
2	Perlite fill	6.00	82
	Timber	6.00	18
3	Wood fibre board (footfall sound insulation)	2.00	100
4	OSB board	1.80	100
5	Cellulose (blow-in insulation)	28.00	85
	Timber	28.00	15
6	Bituminous sealing	0.60	100
7	Lean concrete	25.00	45
	Standard concrete with 1% reinforcement steel (strip foundations)	25.00	55
8	Construction paper	0.03	100
9	Gravel	30.00	100
10	Polypropylene fleece	0.20	100
		Σ 95.63	

2.1.4. *Conventional floor construction (F4)*

A construction from the Passive House Building Components Catalogue was chosen as a comparison floor [35], which is shown in Fig. 4. The material layers are listed in Table 5. The construction represents a conventional design with a floor slab and polymer-based insulation.

2.2. *Hygrothermal evaluation*

In the field of building physics, hygrothermal simulations are widely used to predict the hygrothermal behaviour of building materials, components and whole buildings. The aim of the simulations performed with WUFI was to be able to make a prediction about the functional efficiency and the robustness of the structures. However, the results only provide values of the moisture behaviour. In order to make a statement about the hygrothermal safety of the components, the calculation results must be interpreted.

In order to comply with the passive house standard, a U-value of less than 0.15 was set as the limit value for the thermal insulation of the floor constructions investigated. The hygrothermal analysis was carried out using the WUFI 2D software with an observation period of 15 years. As a boundary, 1.25 m of soil was added to the construction. A sinusoidal curve with a mean value of 95% and an amplitude of 5% was assumed for the relative humidity. The maximum value of 100% occurs in the month of August. A sinusoidal curve was also created for the temperature value, with an average of 8.75 °C and an amplitude of 6.25 K. With this model, based on [36] the soil in central Germany (Königsberg) was simulated at a depth of 1.25 m. As initial conditions of all materials 80% relative humidity and a temperature of 20 °C were chosen. An air exchange source of 10 [1/h] was assumed for the ventilation of construction

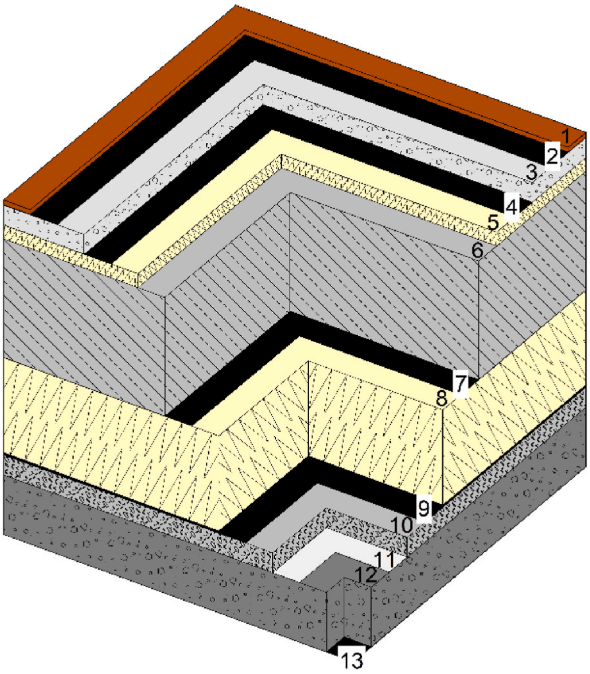

Fig. 4. Construction F4.

Table 5
Material layers F4.

	Material	Layer thickness (cm)	Area share (%/m^2)
1	Parquet flooring	1.20	100
2	Parquet adhesive	0.10	100
3	Cement screed	5.00	100
4	Polyethylene foil	0.01	100
5	Glasswool	3.50	100
6	Water-resistant concrete with 1% reinforcement steel	30.00	100
7	Polyethylene foil	0.04	100
8	Extruded polystyrene (XPS-G)	24.00	100
9	Hot bitumen	0.60	100
10	Lean concrete	5.00	100
11	Construction paper	0.03	100
12	Gravel	15.00	100
13	Polypropylene fleece	0.20	100
		Σ 84.48	

F1b. The characteristic values of the individual materials are given in Table 6.

The total water content of the entire construction was calculated above the sealing layer, in the construction F2b above the ventilated area. The calculation of the total water content was used for the qualitative assessment of the construction. The assessment via isopleths shows the risk of mould growth on the inner surface.

2.3. *Ecological evaluation*

An Environmental Product Declaration (EPD) provides environmental information over the life cycle of a product to enable comparisons between products of the same function. At the EU level, the EN 15804 [27] and ISO 14024 [37] standards regulate the procedure of preparation and the content of an EPD. Based on the EPDs of different building products, constructions can be compared ecologically with the use of various indicators.

In Austria, the Oekoindex OI3 is a widely used method for calculating the environmental impact of constructions and buildings [38]. It can be calculated, for example, with the eco2soft software [39] and includes the three parameters of global warming potential, non-renewable primary energy and acidification potential. The disposal indicator [40] is also an indicator used in Austria and considers the end of the product life cycle, therefore it is a reasonable supplement to the Oekoindex OI3.

In order to represent the entire life cycle of a product, phases A to D are defined for the calculation of a life cycle assessment. Phase A stands for production, B for the use phase and C for disposal. Phase D can include different values that occur outside the defined system [27].

In this study, phase B was excluded because the focus was on the impact of the materials only. As there is usually sufficient data on the manufacturing process of a product, scenarios are often given in phase C and D, which bring some uncertainties to the ecological assessment [41]. Sometimes in data sets, the value 0 is given instead of scenarios, as it is unclear what happens to the product at the end of its life cycle.

The lifetime of the building products used was assumed to be 50 years; only one life cycle was compared. The unit of measurement used was m^2, as square metres of floor area is the most common unit of comparison in life cycle analyses [42]. In order to maintain

Table 6
Hygrothermal data of the materials used in WUFI 2D.

Material	Raw density [kg/m^3]	Porosity [m^3/m^3]	specific heat capacity [J/kgK]	thermal conductivity [W/mK]	Water vapour diffusion resistance [−]
Bituminous sealing	1100	0.001	1260	0.23	10000
EPDM sealing	1500	0.001	1500	0.2	99000
Soil	1500	0.01	2000	1.5	50
Wood fibre board (footfall sound insulation)	140	0.91	1400	0.039	3
Gravel	1500	0.3	1000	0.7	1
Air (44 cm)	1.3	0.999	1000	2.44	0.0106
Lean concrete	2200	0.18	850	1.6	92
Standard concrete	2322	0.15	850	1.7	192
OSB panel	630	0.6	1400	0.13	650
Parquet	650	0.47	1400	0.13	200
Perlite fill	173	0.84	1400	0.0494	3.09
Timber	400	0.73	1400	0.09	200
Polyproylene fleece	130	0.001	1500	3	25
Granulated glass foam	120	0.25	850	0.045	1
Gypsum fibreboard (dry screed)	1153	0.52	1200	0.32	16
Permeable air barrier	219	0.001	2300	2.3	80
Cellulose (blow-in insulation)	50	0.95	2110	0.037	1.8

comparability, cellulose was chosen as ecological blow-in insulation in all three constructions.

2.3.1. Global warming potential (GWP)

A large number of gases such as nitrous oxide, methane and CO_2, which are the main drivers of climate change, are included in the calculation of the global warming potential. Thus, GWP is of central importance and is used as a leading indicator in many studies [43].

Furthermore, it can be assumed that the indicator will become even more important in the coming years, should a CO_2 tax or a similar approach to taxing greenhouse gases be established by legislators.

For the assessment of the global warming potential over the entire life cycle, corresponding EPDs or generic data were obtained from the German database ökobaudat [44].

2.3.2. Oekoindex OI3

The Oekoindex OI3 provides an ecological assessment based on the 3 indicators of global warming potential, acidification potential and primary energy content [45]. The equation for calculating the Oekoindex OI3 is shown in Eq. (1):

$$\Delta \mathrm{OI3} = \frac{1}{3} * \left[\frac{0.1}{MJ} * (PENRT) + \frac{0.5}{kgCO_2equ.} * (GWP) + \frac{400}{kgSO_2equ.} * (AP) \right] \tag{1}$$

Δ OI3: Oekoindex OI3 [-]

PENRT: Primary energy non-renewable, total [MJ/m^2].

GWP: Global warming potential [kg CO_2 equ./m^2].

AP: Acidification potential [kg SO_2 equ./m^2].

The Austrian database baubook via eco2soft [39] was used as a database for the assessment by means of Oekoindex OI3 and disposal indicator.

2.3.3. Disposal indicator

The disposal indicator is a semi-quantitative assessment method that indicates the current disposal route and the recycling potential of a building material. The evaluation is done in points and is dimensionless. The five-point scale represents the best disposal and recovery with 1. The higher the value, the more complicated the deconstruction and the more environmentally damaging the building material. Since only one life cycle was considered in this work, the calculation corresponds to the EI_{KON}(End of Life) [40,46].

The EI_{KON} was calculated according to Ref. [40] as shown in Eq. (2):

Table 7
Indicators.

Indicator	Abbreviation	unit	evaluation
Global warming potential - total	GWP	kg CO_2 eq.	–
Depletion potential of the stratospheric ozone layer	ODP	kg R11/CFC11 eq.	–
Formation potential of tropospheric ozone	POCP	kg Ethen eq./kg NMVOC eq.	–
Acidification potential	AP	kg SO_2 eq.	–
Eutrophication potential	EP	kg PO_4 eq.	–
Abiotic depletion potential for non-fossil resources	ADPE	kg Sb äq.	–
Abiotic depletion potential for fossil resources	ADPF	MJ	–
Use of renewable primary energy excluding renewable primary energy resources used as raw materials	PERE	MJ	not considered
Use of renewable primary energy resources used as raw materials	PERM	MJ	not considered
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	PERT	MJ	–
Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials	PENRE	MJ	not considered
Use of non-renewable primary energy resources used as raw materials	PENRM	MJ	not considered
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	PENRT	MJ	–
Use of secondary material	SM	kg	+
Use of renewable secondary fuels	RSF	MJ	+
Use of non-renewable secondary fuels	NRSF	MJ	+
Net use of fresh water	FW	m^3	–
Hazardous waste disposed	HWD	kg	–
Non-hazardous waste disposed	NHWD	kg	–
Radioactive waste disposed	RWD	kg	–
Components for re-use	CRU	kg	+
Materials for recycling	MFR	kg	+
Materials for energy recovery	MER	kg	+
Exported electrical energy	EEE	MJ	+
Exported thermal energy	EET	MJ	+

$$EI_{KON}(End\ of\ life) = \sum_{n}^{i} V_i * 1 * Entsorg(IST)_i * Verwert(POT)_i \qquad (2)$$

V_i Volume of component layer i per m^2 [m^3/m^2].

Entsorg $(IST)_i$ Disposal classification of a component layer in the construction (classes 1 to 5).

Verwert $(POT)_i$ Reduction or increase factor in the sub-steps 0.25/0.5/0.75/1.00/1.25 according to the recovery potential of a component layer (1–5) based on the expected future disposal routes and taking into account the costs for disposal; a recycling potential of 1 means a “theoretical” reduction of the volumes generated to 25%, 5 an increase to 125%

2.3.4. LCA based on EPDs

Corresponding EPDs or generic data from the ökobaudat database [44] were used as data sources. The indicators used refer to the available indicators in the corresponding EPDs. The standard [27] does not propose any standardisation of the values, but the dimensions of the individual indicators are very different. The level of a value has a positive or negative effect depending on the parameter, thus an assessment of the indicators was first made, shown in Table 7. The indicators with a high value describing a negative impact are marked with "-" in Table 7 and are in the assessment included. For the calculation of the primary energy content, only PERT and PENRT are considered, as they represent the sums of the other energy parameters. After this basic allocation, a number between 0 and 100 was assigned to each value according to eq. (3). The maximum value of 100 is given to the construction with the highest environmental impact. Subsequently, the assigned numbers are displayed in colours in a heat map. The plot shows the sum of life cycle phases A, C and D per indicator.

$$norm(I) = \frac{I}{\max(I)} \times x \qquad (3)$$

I Indicator in corresponding unit, e.g. GWP in [$kgCO_2/m^2$].

Max(I) maximum result

x 100

Norm(I) unitless normalised value in the range defined by x.

3. Results and discussion

In order to ensure a healthy indoor climate and living in buildings for people, the durability of constructions and their protection against mould growth are defined as the most important parameters. Therefore, the results of hygrothermal safety are listed in the first place, followed by the ecological evaluation.

3.1. Hygrothermal evaluation of the constructions

The total water content of the structures is presented below to provide a general assessment of functional efficiency. It indicates the proportion of water in the materials. If the water content increases overall in a structure, moisture accumulation is to be expected. The evaluation was made from the sealing layer upwards per metre of the construction. In this qualitative assessment of the moisture balance, shown in Fig. 5, it is evident that moisture is decreasing and reaches a steady state in all three floor constructions. The general decrease of the curve means that the initial moisture of the construction is able to dry out over the years. Since different combinations of various materials were used in all three designs, the absolute level of water content is not of great importance to the functionality of

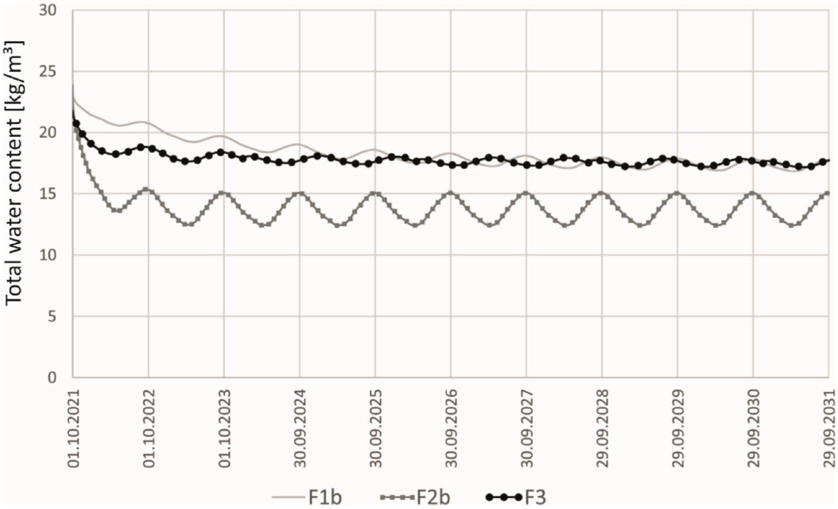

Fig. 5. Total water content above the sealing layer.

the design.

The following three figures show the water content of the specific materials made from renewable raw material for each construction. For each material layer, the total water content must not exceed a certain material-specific limit. The limit value for wood is 20 wt%, for wood-based materials 18 wt%, below which no damage to the substance is to be expected [47].

Fig. 6 shows the water content in wt% of these material layers in construction F1b. The wood in the insulation level has a maximum value of 18.37 wt%, but has permanently less than 18 wt% moisture in the steady state. The other materials show a decrease in moisture and reach a steady state after 5 years. Cellulose, the wood fibre board and the parquet have very similar moisture contents. Cellulose dries out the least, but also drops slightly in its curve. Cellulose represents a hydrophilic bio-based insulation material, which is also able to store moisture. According to this calculation, the stored moisture can dry out every year. It can be assumed that no damage is to be expected in the examined layers.

In Fig. 7 the water content of the bio-based material layers of construction F2b are shown. The construction F2b consists of a significant proportion of granulated glass foam. The materials made of renewable raw materials are limited to the parquet and the sound insulation made of wood fibre. Both building materials have less than 10 wt% moisture in the steady state and are therefore safe from moisture damage. The annual fluctuation of sealed parquet floors is on average 4% [48]. The annual fluctuation in this construction is less than 3%, accordingly, no damage is expected due to the fluctuations.

Fig. 8 presents the building materials from renewable raw materials from construction F3. The sound insulation and the parquet show less than 10 wt% in the steady state. Wood and cellulose insulation have less than 14 wt.-% in the third simulated year, the OSB also reaches less than 14 wt%. Compared to the above-mentioned limits of 20 wt% for wood and 18 wt% for wood products, all materials made from renewable raw materials are in the hygrothermally safe range and are not affected by wood-destroying fungi. The parquet shows the same fluctuations as in the construction F1b. For the other materials, the fluctuations are even smaller.

The hygrothermal condition on the interior surface (parquet) does not pose a risk for mould growth as shown in Fig. 9. After the setting time, the relative humidity is permanently below 70% and thus in all three constructions below the limit values according to the standard [49].

For exterior walls and roofs, much research has been done to develop numerical models and validate them with experimental data. Recent studies show that there is a lack of thorough validation of hygrothermal simulations of basements [50]. Since complex moisture situations are to be expected in these areas in particular, simulations are important to ensure that no damage is to be expected when using materials made of renewable resources.

Furthermore, bio-based materials are able to store moisture, leading to a better indoor climate [51]. The effect of moisture buffering can also reduce heating energy consumption in winter and cooling demand in summer [52]. Higher rates of use of such materials allow these properties to be better taken advantage of. It is discussed, that the currently used models in simulations are not sufficient to represent the hygric conditions of bio-based porous materials [53]. Thus, further development of hygrothermal simulations of bio-based building materials and especially applied on floor constructions is a great necessity.

3.2. Ecological assessment

The long version of the interpretation of the evaluation results can be read in Ref. [33]. The data sets used for the indicators can also

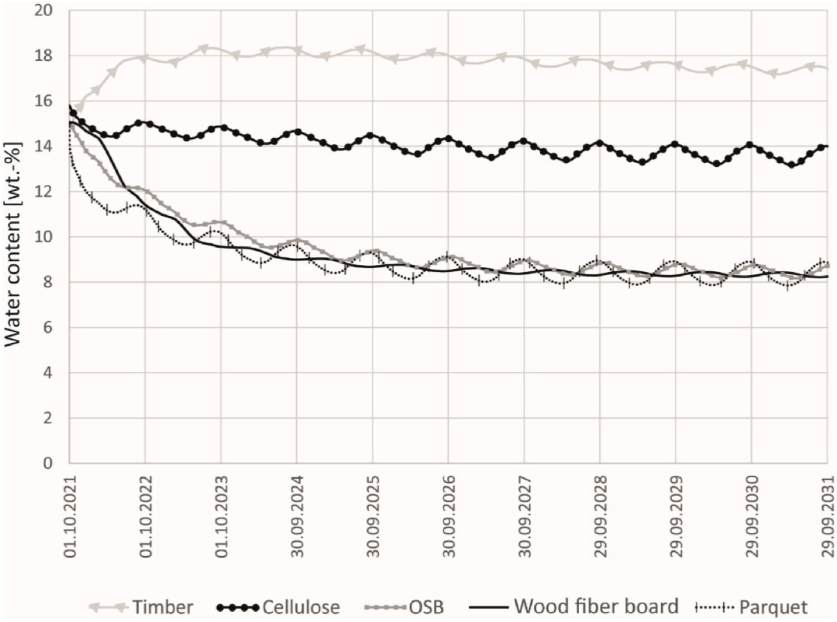

Fig. 6. Water content of the material layers made of bio-based raw materials in F1b.

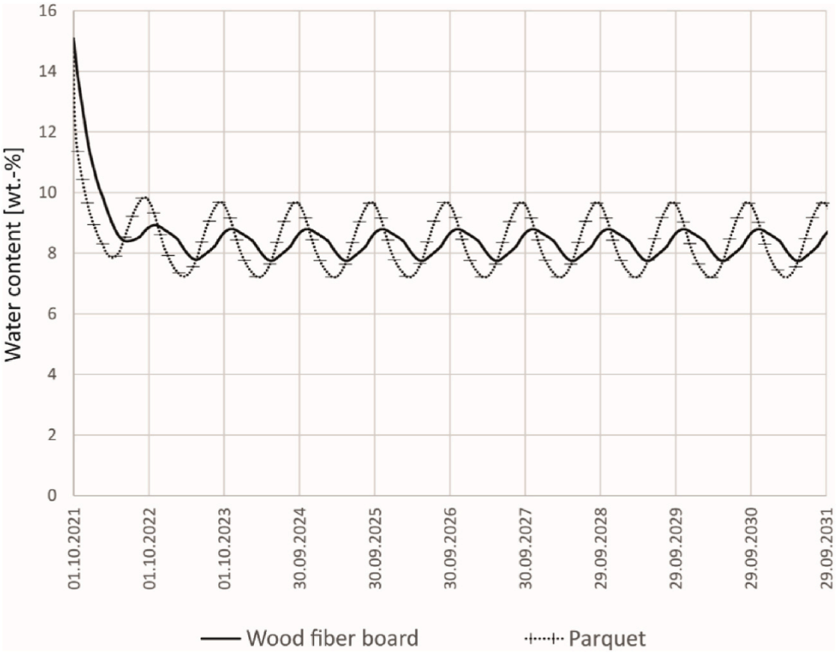

Fig. 7. Water content of the material layers made of bio-based raw materials in F2b.

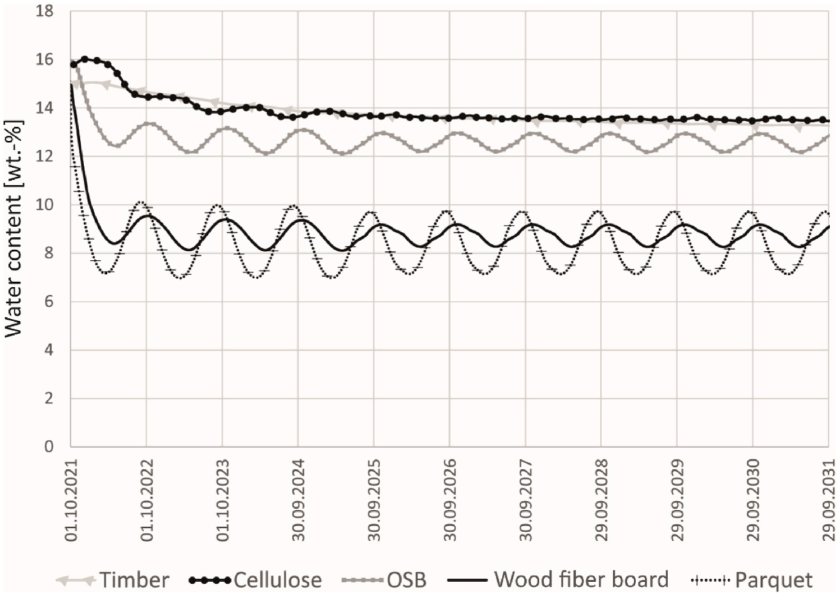

Fig. 8. Water content of the material layers made of bio-based raw materials in F3.

be found in Ref. [33].

3.2.1. Global warming potential

Fig. 10 shows the comparative greenhouse gas potential, divided into the individual phases A, C and D on the left side. On the right side, the negative values are subtracted from the positive ones and the sum of the CO_2 balance is displayed.

The greatest differences are evident in phase A, which represents the manufacturing phase. The two variants of F1 show the difference when replacing a single building product. There is a difference of around 52 $kgCO_2$ eq./m^2.

The construction F1b has the lowest greenhouse gas potential with 33.2 $kgCO_2$ eq./m^2. In contrast to the comparative floor F4 with 183.1 $kgCO_2$eq./m^2, about 82% CO_2 per m^2 can be saved. By using F3 with 49.06 $kgCO_2$eq./m^2, approx. 73% per m^2 can be saved. The use of F1b construction with ground screw foundations is particularly useful when dealing with horizontally extending buildings up to

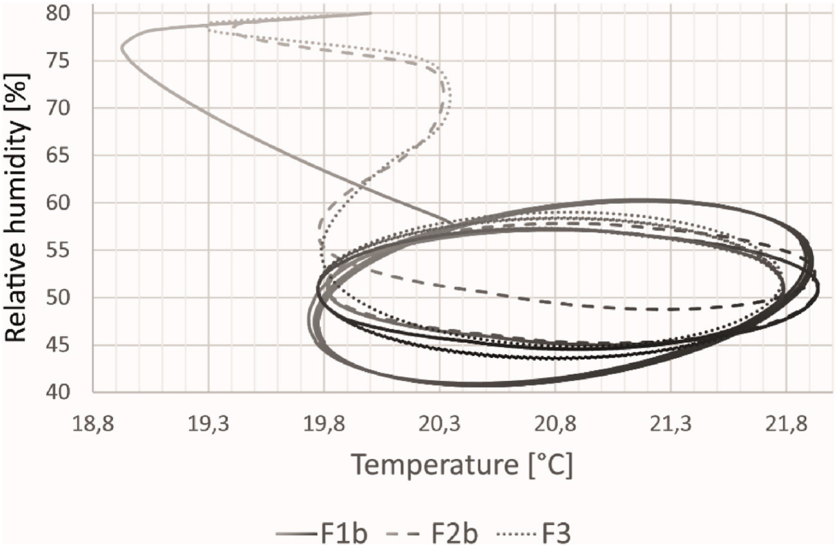

Fig. 9. Risk of mould growth of F1b, F2b and F3.

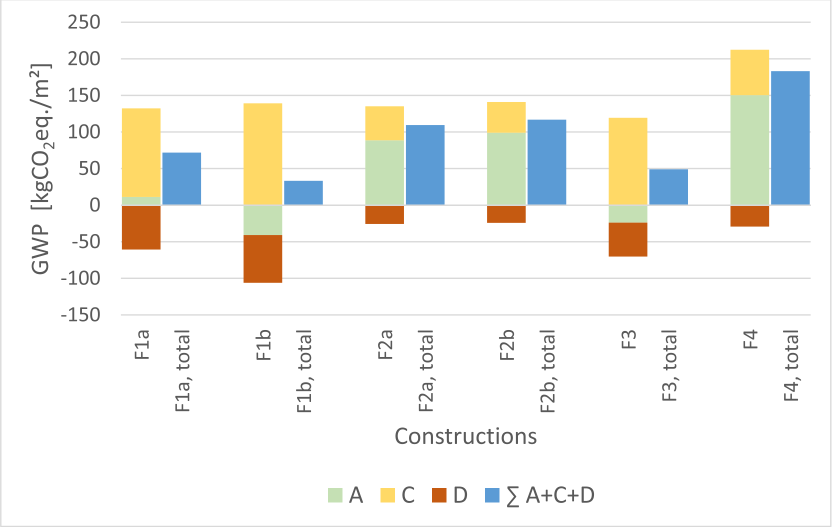

Fig. 10. Global warming potential of the analysed constructions.

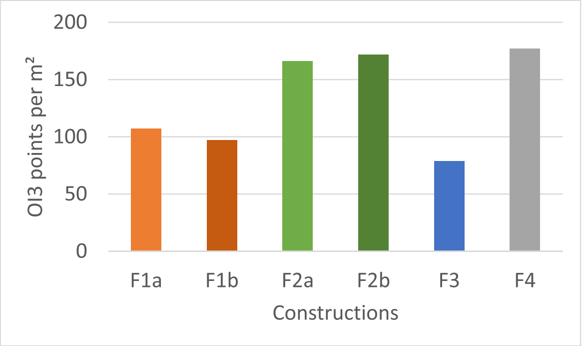

Fig. 11. Assessment with Oekoindex OI3.

3 stories. In this case, the large ecological savings potential would be especially decisive.

Buildings with wooden structures usually have a lower GWP than buildings based mainly on structures made of reinforced concrete or steel [54]. Accordingly, the result is plausible that the construction, which consists most of renewable raw materials, has the lowest GWP. To reduce the GWP even further, it is possible to assume a longer life span. The CO_2 sink would then be even more effective compared to conventional materials. Another option would be to use fast growing bio-based materials [55].

3.2.2. Assessment with Oekoindex OI3

Fig. 11 shows the Oekoindex OI3 of the constructions. When examining the variants, relatively large differences can be noted between F1 and F3 as well as F2 and F4, whose range of values is lower than more than 60 OI3 points. This is mainly due to the different design of the foundation and insulation.

The results of F1 show the central importance of the material selection. The two variants differ only in one layer. The use of a larch formwork instead of a cement-bonded wood chipboard achieves an improvement of 10 OI3 points per m^2. However, the cement-bonded wood chipboard has significantly higher scores than the larch formwork in all environmental indicators (PENRT, GWP, AP). Furthermore, the result was considerably influenced by the foundation. The screw foundations are included in the evaluation with 54 OI3 points and are thus responsible for more than 50% of the overall result.

F2a and F2b differ in the insulation in the installation level and the sealing used. Accordingly, the two constructions receive similar ratings, with the greatest difference caused by the sealing layer. Thus, it is shown that single layers with a large environmental impact sometimes also have a large impact per m^2.

In F2a, a waterproof concrete with PE foil on top is selected, while F2b represents a standard concrete slab with EPDM foil. The combination of waterproof concrete and PE foil has a slightly lower rating than the variant in F2b. Insulation and foundation together account for about 70% of the final result. Granulated glass foam as insulation receives a comparatively high rating of 62 points, and comes close to the rating of the conventional floor F4. It can therefore be concluded, that granulated glass foam has a high negative impact on the environment. On the other hand, it consists of recycled material and can be reused after the life cycle of a building without any loss of quality. This possibility makes the building material recyclable despite high embodied energy, which is a relevant aspect of ecological building products. Further, glass foam granulate has lower embodied energy and GWP than glass foam boards as well as other moisture insensitive insulation materials [56].

The construction F3 obtains the lowest rating. Using strip footings instead of a slab foundation can save approximately 24 points per m^2, depending on the size of the strip foundation. However, the bituminous sealing achieves about twice as many points compared to a waterproofing made of EPDM. As with the other constructions, the foundation accounts for about 50% of the total points.

The Oekoindex OI3 includes the indicators GWP, PENRT and AP. In relation to these three indicators in another study the foundation was responsible for 57.8%, 29.9% and 30.4% respectively of the total impact of an average residential building made of masonry [57]. It can therefore be assumed that foundations are responsible for the majority of emissions not only in calculations per m^2, but also in assessments of entire buildings.

3.2.3. Disposal indicator

The results of the disposal indicator, as shown in Fig. 12, do not show the same tendency as the Oekoindex OI3. The fourth structure F2b, which previously received the worst rating, has the lowest and thus best disposal score. The simple structure without multi-part layers ensures good separability. The construction F2a, which is very similar to the construction F2b, receives 0.06 points more, which can be associated with the sheep's wool insulation material. This receives a higher disposal rating and a worse recycling potential than the perlite filling in F2b. The cellulose insulation accounts for about 70% of the points. The material combination is decisive for the high value of the F3 construction. The three layers of cellulose, gravel and lean concrete account for 85% of the score.

An effective strategy for the disposal of demolition waste from dismantled buildings can greatly reduce CO_2 emissions [58]. Furthermore, the construction industry is responsible for a significant part of the solid waste. Designing for limited waste is therefore the most essential and first step towards an effective waste management [59]. An ecological evaluation of construction components should include both the production as well as the end of the life cycle.

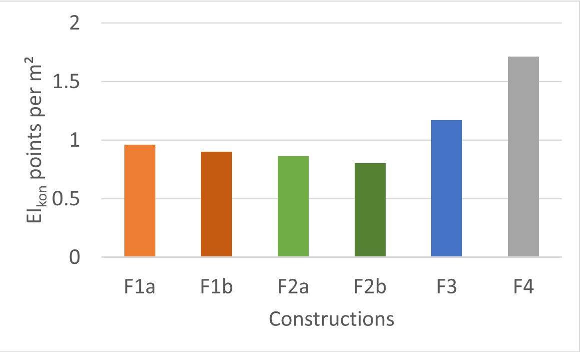

Fig. 12. Disposal indicator.

3.2.4. *LCA based on EPDs*

The heat map shown in Fig. 13 is based on the indicators that are available in the respective EPDs. The indicators whose values describe negative environmental impacts are shown on the left-hand side. On the right side are indicators whose values are not directly related to a negative environmental impact. For example, they describe secondary fuels (NRSF) or substances that can be reused for recycling (MFR). The construction with the highest negative impact receives a value of 100, the remaining constructions receive a value between 0 and 100 according to eq. (3) in chapter 2.3.4. If the respective points are added together, the two constructions F1b and F3 have almost identical scores, followed by F1a and F2b.

F1a scores relatively low in all indicators compared to F3, but has a higher PERT - value, which describes the total renewable primary energy. F1b also differs greatly to F1a in this assessment, although only one material layer was changed.

The results of F2 are in some areas significantly higher than those of F1. This is mainly due to the use of the building material reinforced concrete, which increases the values of some indicators such as AP or EP. Two variations stand out for the two variants of construction F2: The stratospheric ozone depletion potential and the use of freshwater resources are significantly higher for the production of F2a than for F2b. This circumstance is largely due to the data set sheep wool used. Furthermore, the non-hazardous waste (NHWD) is remarkable. This can be directly attributed to the use of the granulated glass foam, which accounts for 82% of the value. In the EPD used for granulated glass foam, two different scenarios for phases C and D are given. Concerning C, the reclaimed material is recycled in the first scenario. In D, the degraded material is landfilled in the first scenario, whereas in the second scenario, the material is recycled without further processing steps in phase C, which is included as a credit in phase D. Within the framework of the calculation, one of the two paths must be chosen. In this case, the first and thus ecologically worse scenario was chosen for phase C. For phase D, the second scenario was chosen to reflect the recycling of the material in the calculation. This is an example of how different results can be achieved even with the same data set.

The result of F3 receives the lowest ecological impact. The increased POCP value refers to the bituminous sealing used. Therefore, if the construction is to be further ecologically optimised, one could start with an alternative for the sealing layer. The high value of the NHWD indicator, which describes the non-hazardous waste, is caused by the use of the gravel.

Unlike the Oekoindex OI3, all the indicators used in Fig. 13 are weighted equally. This method represents a novelty and can be performed without software. The only things that are needed are suitable EPDs or generic ecological data of the materials used.

The fact that the results of the methods differ among themselves depends on the methods, indicators and data sets. For example, the energy source used has a major influence, which varies greatly from country to country. Timber has an embodied energy value between 0.3 and 61.3 MJ/kg [60], which depends besides the type of construction (solid wood or frame construction) also on the type and origin of the timber. This circumstance and other uncertainties, have been discussed in other studies [61,62], which highlights the need of sensitivity analyses. For the most accurate method to calculate realistic values every EPD would have to be available of every building material used in a building.

4. Conclusion

In order to enable a wider application of bio-based building products in the building construction sector, the hygrothermal safety of all building components is absolutely necessary. In this paper, three possible ecological constructions were shown for their hygrothermal safety under the simulated climate conditions. Hygrothermal investigations are often performed for walls or roofs. For bio-based floor constructions in contact with the ground, the hygrothermal calculation performed in this study is a novelty. To take advantage of all the benefits of bio-based materials, such as heating and cooling energy reduction as well as moisture storage capacity, further research on accurate simulation of these building materials is recommended.

The comparison of the environmental evaluation reveals, that there is a great potential to reduce the ecological impact of floor constructions per m^2 through the choice of materials. The comparison of the global warming potential of the different constructions shows that the choice of materials and construction, as well as the choice of foundations, can save up to 82% of greenhouse gases per m^2 compared to a similar conventional floor design. The evaluation with the Oekoindex OI3 shows that F3 can achieve an ecological improvement of 55% compared to the conventional floor design. The disposal indicator results in an improvement of 53% by applying F2a. In the comparison of the indicators based on their EPDs, F1a and F3 have the lowest summed environmental impacts and received overall values of 56% lower than F4. All results are strongly influenced by the foundation type. In this study, they are responsible for up to 50% of the environmental impact per m^2. Thus, material-efficiency and the type of foundation have a major influence on the ecology and environmental impact of ground constructions. Therefore, this study can serve as a basis for further research regarding the

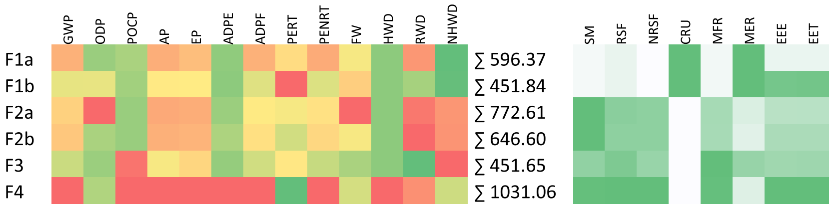

Fig. 13. Heat Map
Abbreviations GWP, ODP,etc. see Table 7.

ecologization of foundations. Reusable, prefabricated strip foundations would be an alternative to slab foundations in this regard. Screw foundations for multi-storey buildings are an ecological alternative whose limits and potential should be researched in detail. The usage of heavy equipment is not considered in this study. However, equipment and transportation for the construction of the foundation are responsible for a significant share of emissions [63]. For further research these factors should also be considered.

The application of various assessment methods leads to different results. This issue was also addressed in Ref. [64], previous studies also attribute this problem to the different calculation methods of the individual indicators [65]. The indications of scenarios show how products differ in the evaluation. The selection of the appropriate indicators is therefore crucial and should be specified according to protection objectives. Since separability and, furthermore, grade purity and cleanliness are becoming increasingly relevant, an indicator for assessing recyclability should always be taken into consideration. All ecological evaluations were performed with Austrian and German databases. The method using EPDs represents a novelty and is relatively easy to use without the need of a specific software tool.

The data situation around the ecological indicators of building products is a central problem that strongly influences the results. The origin of the material used makes a big difference, hence data sets cannot simply be adopted from another country. Also, the standardisation and presentation of the results is not uniformly regulated and thus left to the interpretation of the ecological assessment. A comparison of several constructions of one type is necessary in order to find the most ecological variant among them. This possibility loses significance the fewer constructions are included in the analysis. Variant studies are therefore important in order to find the most ecological variant of a building design.

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Author statement

Henriette Fischer: Conceptualization, Methodology, Validation, Writing – Original Draft, Writing – Review & Editing, Visualization.

Florian Frühwald: Writing – Review & Editing, Visualization, Data Curation.

Azra Korjenic: Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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