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SEISMIC STRENGTHENING AND ENERGY RETROFIT WITH POST-TENSIONED TIMBER STRUCTURES AND BUILDING ENVELOPE COMPONENTS

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Abstract
Radical decarbonisation in the construction sector is an urgent need to mitigate climate change. Therefore, new environmentally sound technologies in timber have to be developed and applied for seismic strengthening of buildings in seismic active regions in order to allow them for a second life cycle. In combination with energy retrofit, such seismic intervention backs the EU renovation wave and empowers a clean energy system, because buildings operational heat energy demand will be lowered close to nearly Zero Energy Building (nZEB) level with an improved building envelope. The intervention adapts concepts and principles originally developed for precast concrete construction, post-tensioned (PT) timber frame systems have been developed and tested since 2005 at the University of Canterbury. The technology takes advantage of unbonded post-tensioned steel tendons passing through internal cavities in timber beams or walls to create a moment resisting connection. The seismic demand is satisfied through controlled rocking between structural elements and tendon elongation, which ensures recentering capabilities. Post-tensioned timber frames as two-dimensional or three-dimensional structure are an emerging concept in timber engineering with great potential for the creation of high-performance and cost-efficient joints. The suitability as a retrofit concept is evaluated on two case studies that are part of the ProGETonE H2020 research program, which aims to provide an innovative, and integrated retrofit concept. Both measures serve to prolong the use of the building and avoid its demolition, a reuse case almost at is best, providing ultimate circularity index results. Therefore, only almost, because such a deep renovation intervention consumes new resources to build and also requires the replacement of specific components as windows or even the adaptation of floor plans to today's needs. Decarbonisation effects are revealed by calculation of Life Cycle Assessment (LCA) indicators for timber-based external retrofit envelope components that are assembled onto existing buildings for stiffer structures and for insulation purposes. The design and technology concept revealed allowing for the combination of strong structural behavior, necessary building physics performance to achieve for nZEB energy demand; with new Cross-Laminated Timber (CLT) components exposed also connection details and construction processes are discussed.

1. INTRODUCTION

1.1. BACKGROUND
Radical decarbonisation in the construction sector is an urgent need to mitigate climate change. Existing buildings with significantly improved energy efficiency are an essential component of a decarbonization strategy for several reasons. In many places, deconstruction without replacement is inconceivable because urban housing markets are experiencing strong demand and the existing housing segment is very often home to socially weaker population groups in particular. As will be shown later in this article, replacement construction generates higher emissions and requires additional resources in the form of energy, raw materials, and production and construction waste. Reducing the thermal energy demand (heating and cooling) through renovation measures is much more climate-friendly and necessary, because properly implemented it leads to a strong reduction of permanent emissions from the operation. The one-time effect of avoiding additional resource consumption through deconstruction, partial recycling and partial waste disposal is also an immediate and important contribution to reducing emissions.

Therefore, new environmentally sound technologies from renewable materials have to be developed and applied for seismic strengthening of buildings in seismic active regions in order to allow them for a second life cycle. In combination with energy retrofit, such strengthening intervention backs the EU renovation wave [1] and empowers a clean energy system, because buildings operational heat energy demand will be lowered close to nearly Zero Energy Building (nZEB) level with an improved building envelope.

The intervention adapts concepts and principles originally developed for precast concrete construction. Post-tensioned (PT) mass timber systems have been developed and tested since 2005 at the University of Canterbury [2]. The technology takes advantage of unbonded post-tensioned steel tendons passing through internal cavities in glue-laminated timber beams or cross-laminated timber walls to create a moment resisting connection. The seismic demand is satisfied through controlled rocking between structural elements and tendon elongation, which ensures recentering capabilities. The suitability as a retrofit concept is evaluated on two case studies that are part of the Pro-GET-onE H2020 research program, which aims to provide an innovative, and integrated retrofit concept [3, 4].

1.2. SEISMIC RENOVATION

Increase durability, safety, and extend the technical life span of existing structures is a major driver in decarbonizing the construction sector. The longer life span contributes to maintained use and therefore it is a reuse of materials at the same location even without demolition and redistribution of resources. Traditional methods of reinforcing existing structure needs a lot of work inside buildings by applying for example Fibre Reinforced Polymer (FRP) jackets to strengthen the existing structure. Such works collide with the use of the building and as a result the occupants have to be dismissed, which is especially difficult if they are not only tenants. That is why the external application of measures is more promising than the conventional approach. The exoskeleton stiffens the building from outside and forms a strong structure outside of the existing in order to stabilize it and to take horizontal forces, reduces the movement / displacement of the buildings vertical structural elements and allows the existing structure to lean in the exoskeleton. The exoskeleton has a spatial geometry and inside the frame additional area is emerging which can be used for an extra room, sun-space or just a balcony. Sometimes it can even allow for extensions on the rooftop by its structural possibilities. These exoskeletons right now are mainly built out of steel structures in a two-dimensional or a three-dimensional framework. The 2D-exoskeleton takes mainly loads in same longitudinal direction as the external walls, while the 3D-exoskeleton deals preferably with the loads perpendicular to the external walls. A main goal of the steel structure is to minimize or avoid the use of bracings from crossed beams in the longitudinal direction because such a structural element often collides with window openings, while the other direction perpendicular to external wall can bring multiple bracings.

1.3. ENERGY RENOVATION

An energetic refurbishment of buildings not only includes the heating, cooling and ventilation systems and the delivery to the rooms, but rather involves a holistic and deep renovation including the building envelope. Only by effectively reducing heat loss through the exterior envelope can heating demand be brought close to an nZEB standard. This means that opaque exterior walls, windows, floors and roofs must have better insulating properties, which is also of great advantage for good summer thermal insulation, and thermal bridges must be substantially reduced. Such measures are possible by replacing of window components with higher performance components. The opaque surfaces are improved by the external application of insulation layers to increase the thermal resistance. The idea is now to combine the two measures of seismic reinforcement on the one hand with the insulation of the external walls on the other. The insulating parts of the façade are to become an integral part of the structure for absorbing forces from earthquakes.

1.4. INTEGRATED EXOSKELETON FACADE SYSTEMS

The development of an integrated envelope building system consisting of two types of seismically effective exoskeletons (2-dimensional and 3-dimensional) together with prefabricated infill elements as façade modules, comprising cladding, substructure, additional insulation or buildings service components. All components of the system should be flexibly adaptable to the construction types of existing buildings, their grid, overall geometry and mainly the seismic strengthening capability fulfilled by the exoskeleton. Three-dimensional steel exoskeletons for seismic structural stiffening of existing precast RC-concrete structures have already been proven [3, 4]. Other externally applied strengthening solution made of Cross-Laminated Timber (CLT) jackets, reveals itself as a not invasive intervention that is rigidly connected to the RC frames. Under seismic loads, CLT shear walls with properly designed connection systems are able to provide adequate lateral capacity for multi-storey buildings. Despite the lightness of the material, which allows having low values of mass, a higher level of lateral in-plane strength and stiffness can be reached [5]. These qualities make it a product that is easily applicable for extensions [6, 7] or renovation of existing buildings [8-12]. The technology takes advantage of unbonded post-tensioned steel tendons passing through internal cavities in timber beams or walls to create a moment resisting connection see Figure 1. The seismic demand is satisfied through controlled rocking between structural elements and tendon elongation, which ensures recentering capabilities [13].

The prefabrication strategy took principles from off-site manufacturing based on the knowledge from prefabricated timber construction. The prefabrication makes assembly at the construction site effective and allows implementing efficiently lean construction principles. In particular, CLT panels are produced to a high degree of prefabrication, which allows efficient and safe on-site installation, and they have been applied globally in many low-rise and mid-rise buildings typically using platform construction technology [14]. Integration of building services with several technical subsystems for RES, ventilation and for Information and Communication Technology (ICT), are part of new building envelope. The geometrical and organizational correct combination of active (e.g. heat pumps; ventilation units) and passive (e.g. ducts; switchboxes) sub-components integrated into the 'super-component' are challenging in terms of construction design [15].

1.5. RESEARCH OBJECTIVES

Radical decarbonisation and resource efficiency in the construction sector – that means for an existing building reuse of the existing structure to a maximum extent, almost no redistribution of materials, no sorting of debris and no treatment of the waste and even no disposal of waste. Additional all new construction products and components like the new exoskeleton required to maintain technical service life are made out of a high share of renewable and secondary resources and reduce carbon footprint by use of renewable material, store the biogenic carbon over a long period, and for components are prefabricated, with a minimum amount of waste during construction process.

The general hypothesis is that PT-Timber CLT exoskeletons have a very good potential for the creation of high-performance and cost-efficient stiffening measures as well as low-carbon components (for seismic strengthening exoskeletons).

Research question (1): Can calculation of GWP of PT-Timber-CLT structure show a reduction of GWP compared to steel or aluminum exoskeleton variants.

Research question (2): Does maintaining existing structure and renovating it for seismic safety (and energy efficiency) lead to a reduction of GWP emissions (instead of tearing buildings down).

2. METHODS AND MATERIALS

2.1. MATERIALS

Two fundamental different types of exoskeleton are introduced and examined in detail, see Figure 1. The first one is two-dimensional and applied in parallel with existing weak lateral stiffening in order to reinforce the building. Such concept can be adopted if the lateral walls have large opening for window, doors or other weakening properties. The 2D-exoskeleton is, to the moment, for small-scale application and for pure facade renovation. The second variant is the 3D-exoskeleton, which runs parallel as well as it extends the existing structure perpendicular to the existing façade and achieves extra space. The 3D-exoskeleton is dedicated to multi-storey apartment buildings. Together with the strengthening, it supplies additional façade components that allow to extent the living space with increase of net floor area of the existing flat. In both exoskeleton variants, technical components could be inserted within the structure to enable an integrated and multi-functional construction system for improved energy performance of the renovated building.

PT-system parts who are taken as input values for the LCA calculation are columns (vertical walls for 3D variant), beams (horizontal slabs for 3D variant), steel tendons, steel plates, hinges, brackets of the exoskeleton structure. Other components like facade elements made of elementized, large-format timber frames, additional insulation layers and façade claddings are excluded because they are equal for all different exoskeleton variants and materials.

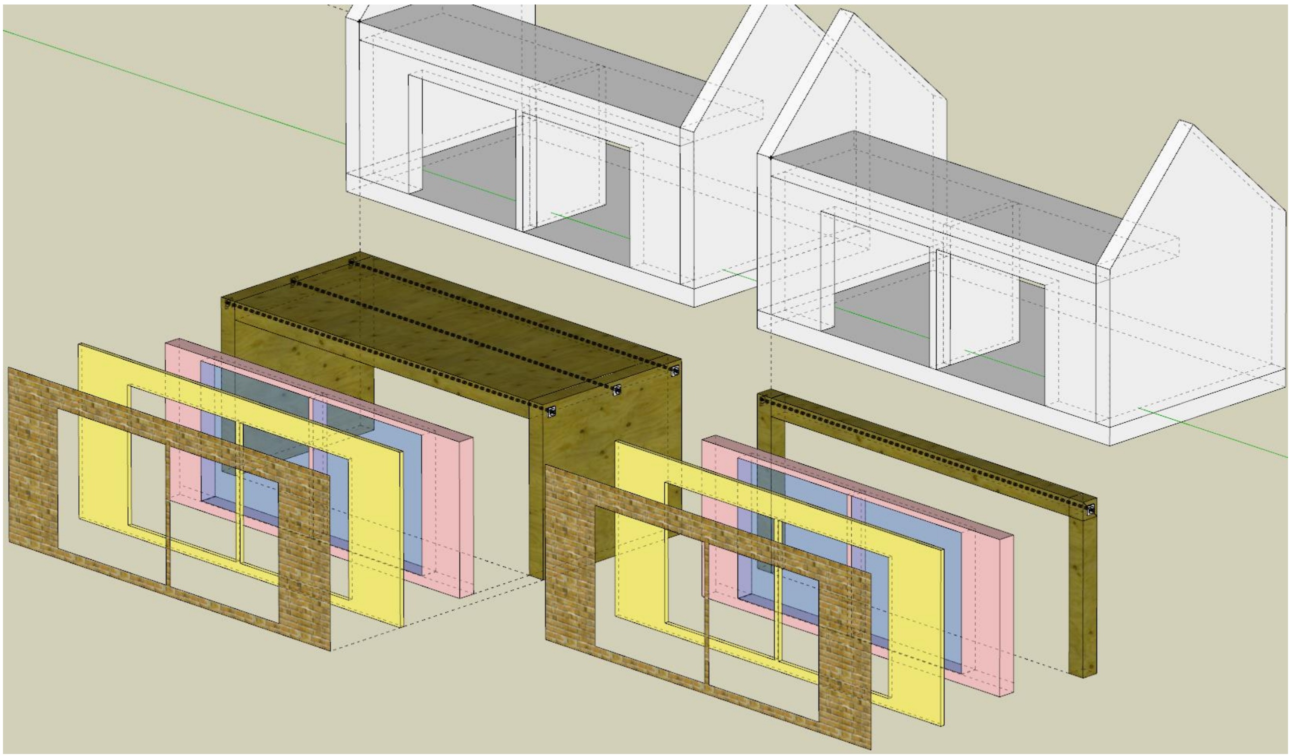


Figure 1. Overview 3D-PT-Frame (left) and 2D- PT-Frame both façade element infill, insulation layer and façade cladding [own model].

The environmental data sets used are from the publicly available database ÖKOBAUDAT version 2020-II from 12.11.2020, based on generic background data from the GaBi database and other, specific datasets from producer Environmental Product Declarations (EPD). All data on the ÖKOBAUDAT database are conform to the EN standard 15804:2012+A2:2019 [16, 17]. For calculation purposes, no material flows of fasteners, joints, connections and other supply material with less than five percent of the total material flow of the exoskeleton structure were considered.

Assumptions from bottom to top of the façade system:

a) Both solutions (steel / PT-timber) have to have the same foundation works (upper level foundation is equal because both use prefab timber element as facades -> 300 mm above ground).

b) In principle, both structures are similar in geometry and spatial arrangement and both follow the primary structure of the existing building. Two different materials for structures from foundation level upwards, similar steel fixation towards the existing structure.

c) Two different, but similar insulation and façade cladding solutions using prefabricated timber framed elements as a basis component. The latter can integrate better with PT-timber exo, avoiding gaps, steps in layers, due to heat bridges)

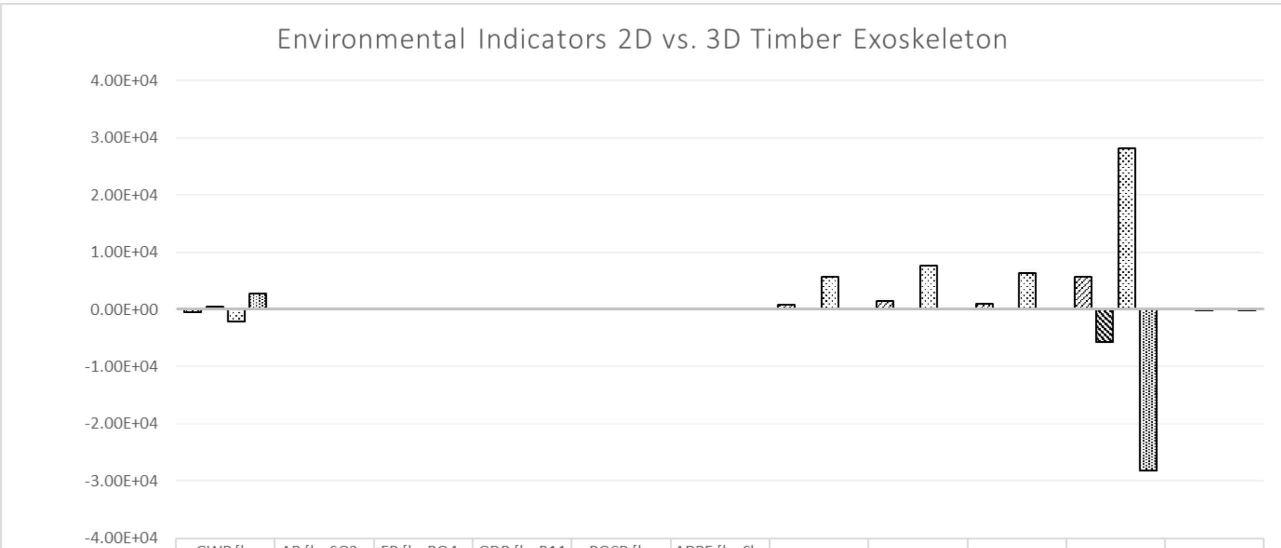
2.2. METHODS:

The environmental performance as a retrofit concept is evaluated on two case studies that are part of the Pro-GET-onE H2020 research program [18], which aims to provide an innovative and integrated retrofit concept. Both measures serve to prolong the use of the building and avoid its demolition. This is a reuse case on building level, providing circularity index results, which are not part of this article. ISO 14040:2009 and ISO 14044:2006 standards define the structure to perform a life cycle assessment and divide the process in the following framework: 1. Goal and Scope Definition; 2. Life Cycle Inventory Analysis; 3. Life Cycle Impact Assessment; 4. Interpretation. The goal and scope phase of a LCA-calculation defines important decisions on how to proceed with the functional unit, impact categories, dataset quality and system borders [19, 20]. Here we go for the exoskeleton of one spatial unit in different materials over a time of 50 a. The optimization of the goal and scope definition in consideration of the interpretation can only be met with various iteration processes, which reveal the interdependencies and relations [20]. In a regular LCA calculation for buildings and building components, based on EN 15978:2012 and EN 15804:2012+A2:2019, the life cycle of a building is divided in three modules A (Product and Construction stage), B (Use stage) and C (End of Life stage). Here the focus stays on the material production and material end-of-life, therefore module B is excluded. Input indicators were distinguished especially for primary energy in addition to renewable/non-renewable, between energy use and material use of primary energy. This is why an integral approach, transparency and iteration are part of the main principles of life cycle assessment [22].

Performance of an LCA for the steel, aluminum and PT-Timber exoskeleton components, based on a quantity survey and the environmental indicators for the materials used. The modules A, C and the sum of A+C are determined over a life cycle of 50 years. The LCA data of façade components, only with minor difference in construction techniques, foundation with no difference are excluded. Based on the previous results, the overall environmental impacts of the three different exoskeleton variants are further compared.

3. RESULTS OF LCA CALCULATION

The results of the calculation of the LCA of the PT-Timber structures are first described in more detail, see Figure 2. Due to the high proportion of wood in the PT-Timber structures, it is immediately apparent that module A contains the storage of biogenic carbon as a credit, which is then written off again in module C. When comparing the two variants of the 2D with the 3D exoskeleton, one recognizes the higher material requirement and thus the increased environmental impact across all indicators.



	GWP [kg CO2 -äq.]	AP [kg SO2 -äq.]	EP [kg PO4 -äq.]	ODP [kg R11 -äq.]	POCP [kg Ethen-äq.]	ADPE [kg Sb-Äq.]	ADPF [MJ]	PERE [MJ]	PENRE [MJ]	PERM [MJ]	PENRM [MJ]
2D A-Production	-4.52E+02	3.44E-01	7.14E-02	6.57E-10	5.94E-02	3.49E-05	8.79E+02	1.47E+03	1.00E+03	5.63E+03	3.42E+00
2D C-Disposal	5.36E+02	5.83E-03	1.04E-03	1.17E-11	-1.70E-04	1.57E-06	3.44E+01	1.70E+01	4.35E+01	-5.63E+03	-3.42E+00
3D A-Production	-2.14E+03	1.96E+00	3.84E-01	3.29E-09	3.40E-01	1.99E-04	5.63E+03	7.73E+03	6.38E+03	2.82E+04	1.71E+01
3D C-Disposal	2.68E+03	3.01E-02	5.44E-03	5.85E-11	-1.03E-03	7.87E-06	1.78E+02	8.53E+01	2.23E+02	-2.82E+04	-1.71E+01

Figure 2. Input and output indicators throughout 50 a lifecycle of 2D versus 3D variant of timber exoskeleton.

Similarly, all input and output results are summed across all life cycle phases and presented as totals of the respective indicator in Table 1. However, the high offset quantity of biogenic carbon, which remains in the structure during the entire service life of 50 a and does not generate any greenhouse gas effect, should be explicitly pointed out here as well.

Table 1. Environmental indicators of Timber in Total over 50 a.

Indicator	**GWP**	**AP**	**EP**	**ODP**	**POCP**	**ADPE**	**ADPF**	**PERE**	**PENRE**	**PERM**	**PENRM**
	[kg CO2-eq.]	[kg SO2-eq.]	[kg PO4-eq.]	[kg R11-eq.]	[kg Ethen-eq.]	[kg Sb-eq.]	[MJ]	[MJ]	[MJ]	[MJ]	[MJ]
2D SUM A+C	8.42E+01	3.49E-01	7.24E-02	6.68E-10	5.92E-02	3.64E-05	9.13E+02	1.48E+03	1.05E+03	0.00E+00	0.00E+00
3D SUM A+C	5.44E+02	1.99E+00	3.89E-01	3.34E-09	3.39E-01	2.07E-04	5.81E+03	7.81E+03	6.60E+03	0.00E+00	0.00E+00

Finally, Figure 3 compares the exoskeletons in the different materials steel, aluminum and wood and examines the 2D and 3D variants of each exoskeleton. No surprises are found in the two different sizes of the variants. The 3D variants cause more environmental impacts for all three materials. Let's have a closer look at the important indicator of GWP for all three materials. The steel variant has about half the GWP emissions that the aluminum variant shows up. The wood variant has the lowest GWP emissions over the entire life cycle of 50 years. Furthermore, the same positive biogenic carbon offset properties apply as already presented in the results of the PT-Timber variant.

	GWP [kg CO2 -äq.]	AP [kg SO2 -äq.]	EP [kg PO4 -äq.]	ODP [kg R11 -äq.]	POCP [kg Ethen-äq.]	ADPE [kg Sb-Äq.]	ADPF [MJ]
St-2D SUM A+C	8.10E+02	1.59E+00	1.80E-01	1.37E-11	2.85E-01	1.64E-04	8.17E+03
St-3D SUM A+C	2.13E+03	4.17E+00	4.71E-01	3.61E-11	7.49E-01	4.30E-04	2.15E+04
Al-2D SUM A+C	2.19E+03	6.68E+00	4.91E-01	3.90E-11	4.09E-01	2.59E-04	2.40E+04
Al-3D SUM A+C	5.69E+03	1.73E+01	1.28E+00	1.01E-10	1.06E+00	6.73E-04	6.23E+04
Ti-2D SUM A+C	8.42E+01	3.49E-01	7.24E-02	6.68E-10	5.92E-02	3.64E-05	9.13E+02
Ti-3D SUM A+C	5.44E+02	1.99E+00	3.89E-01	3.34E-09	3.39E-01	2.07E-04	5.81E+03

Figure 3. Environmental indicators of Steel (St) vs. Aluminum (Al) vs. Timber (Ti) exoskeleton each in 2D and 3D Variant.

4. DISCUSSION OF RENEWABLE RESOURCE LOW IMPACT

The relative comparison between the aluminum and the steel variant was already shown in a previous publication by Guardigli [23]. The exoskeleton made of aluminum has by far the highest environmental impact even if it has a high level of recycled content, but this level is high for steel as well. The recycling rate of metals and their recovery scenario of high value material recycling do not take anything away from either material and bring equal benefits to both for the EoL. Furthermore, it can be seen that the new variants made from PT-Timber Exoskeleton makes the metal variants both look significantly worse again. The best technology variant for a very low greenhouse gas output is the one made from renewable biogenic resources. It is also clear that these obviously also require energy for the manufacturing processes, but in much smaller quantities than the metal products. In addition, that such a result is rational can be seen very well from the PERE input shown in see Table 1 for both 2D and 3D variant. The range between 1.48E+03 and 7.81E+03 [MJ] of renewable primary energy (PERE), is already used in the production process, which is generated from sawmill waste and production residues by burning biomass. The non-renewable primary energy (PENRE) inputs are between a magnitude of

8.96E+03 and 7.67E+04 [MJ] per pure steel or aluminum exoskeleton, that is causing the direct effect on steep GWP emissions for both metal-based solutions.

5. CONCLUSIONS

The general hypothesis that PT-Timber-CLT exoskeletons have a very good potential for the creation of high-performance and cost-efficient stiffening structure as well as low-carbon components (for seismic strengthening exoskeletons) has been successfully proven by the application of LCA calculations over the lifecycle of the construction materials.

The first research question can be answered positively for the PT-Timber-CLT structure. Timber's low GWP emissions over the life cycle show high reduction of greenhouse gas emissions compared to steel or aluminum exoskeleton variants. It is about half the amount of greenhouse gas emissions produced by conventional building materials such as steel and aluminum. Doing such retrofit projects proposed within the Pro-GET-onE project the path of decarbonisation of the building stock and a powerful support of the renovation wave can be made possible by higher use of timber in upcoming projects. Biogenic carbon offset is in the magnitude of 4.76E+02 and 2.38E+03 [kg CO2] or in better graspable units between roughly 480 to 2.400 [kg CO2] per exoskeleton frame as the accounted functional unit.

Preserving the structural fabric of existing buildings is another unavoidable goal. This is because preservation avoids large quantities of greenhouse gases that would otherwise be produced for and during new construction. This is already shown in the assessment of new construction scenario versus conservation and renovation of substance in Guardigli et al. and they claim a 55 % impact of a renovation compared to demolition and new construction [23]. Together with a very high energy saving for the future operation by transforming the building towards the nZEB standard, an important decarbonization cornerstone is delivered. However, this preservation and renovation strategy can still be optimized by producing essential parts of the exoskeleton from renewable resources.

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