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Modelling the Slovenian Wood Industry's Response to the Greenhouse Gas Paris Agreement and the EU "Fit for 55" Green Transition Plan

Erwin M. Schau [1,*], Igor Gavrić [2], Iztok Šušteršič [3,4], Eva Prelovšek Niemelä [1], Balázs Dávid [1,3], Jaka Gašper Pečnik [1,3], David B. DeVallance [5] and Črtomir Tavzes [1,3,6]

1 InnoRenew CoE, Livade 6a, SI-6310 Izola-Isola, Slovenia
2 Element5 Limited Partnership, 67 Mowat Ave #114, Toronto, ON M6K 3E3, Canada; igor.gavric@elementfive.co
3 Faculty of Mathematics, Natural Sciences and Information Technologies, University of Primorska, Titov Trg 4, SI-6000 Koper, Slovenia
4 Modular Timber d.o.o., Avčinova ulica 9, SI-1000 Ljubljana, Slovenia
5 College of Science and Technology, Commonwealth University of Pennsylvania, 401 North Fairview Street, Lock Haven, PA 17745, USA; ddevallanc@commonwealthu.edu
6 Institute for the Protection of Cultural Heritage of Slovenia, Poljanska Cesta 40, SI-1000 Ljubljana, Slovenia
* Correspondence: erwin.schau@innorenew.eu

Abstract: Almost 200 nations, including the European Union, have signed the Paris Agreement that aims to limit the temperature rise to 1.5 °C above pre-industrial levels by reducing greenhouse gas (GHG) emissions. To meet this target, a significant decrease in GHG emissions by 2030 and net zero by 2050 is necessary. To determine the role of wood products in achieving a 55% reduction in GHG emissions by 2030 compared with 1990 levels, we investigated Slovenia's potential, which has close to 60% forested areas. Therefore, the country could use wood-based products to achieve the agreed-upon climate goals. Nevertheless, uncertainties remain regarding the extent to which increased tree harvesting, local manufacturing, and the utilization of wood products can aid in substituting fossil-derived materials and reducing GHG emissions. A new model was constructed to increase the understanding of the wood products' (throughout the forest-based industrial ecosystem, incl. construction) potential contribution to reaching the stated emissions targets. Using this linear programming (LP) mathematical optimisation model and carbon footprint calculations based on life cycle assessment methods, a wood flow distribution, the financial investment needed to process these quantities, and the GHG emissions produced and/or saved were calculated. The findings stipulated that Slovenia has the potential to achieve 55 % less GHG emissions by 2030 by expanding logging to at least 3 million m^3 and converting the timber to a larger amount of long service-life wooden items made (and utilised) within the country. Such products accumulate carbon for a long time and decrease the need for materials that cause higher GHG emissions. Concomitantly, a better appreciation of the substitution effects in official carbon accounting would be needed. Moreover, to materialize the potential decrease in emissions would require Slovenia's construction sector to replace fossil- and mineral-based materials with lignocellulosic products, and to increase the capacity to utilize lower-quality wood in high added value applications, which would require significant investment. This paper offers a comprehensive analysis of diverse optimisation outcomes obtained from the investigation into climate action through the use of wood products in Slovenia.

Keywords: wood; greenhouse gas mitigation; Slovenia; "Fit for 55"; carbon storage; substitution

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1. Introduction

To achieve the goals set out in the Paris Agreement, countries must significantly reduce their greenhouse gas (GHG) emissions. The target for the year 2030 is a reduction of 55% compared with 1990 levels, and ultimately, net-zero emissions by 2050 [1]. Slovenia, like other signatories to the Paris Agreement, is committed to achieving these targets. However, the country has faced a significant challenge in recent years as GHG emissions have increased from 14.2 million metric tonnes (t) carbon dioxide equivalent (CO_2e) in 1990 to 17 million t CO_2e in 2019 (total excluding memo items) [2]. This trend is concerning and suggests that Slovenia is not on track to meet the Paris Agreement targets.

To reach its goals, Slovenia will need to reduce its GHG emissions by 10.6 million t CO_2e per year by 2030. This target is ambitious, and achieving it will require a combination of policies, regulations, and incentives to encourage sustainable practices and reduce emissions across various sectors of the economy.

One area where Slovenia has a unique advantage is its abundance of forests. Forests are known for their ability to absorb carbon dioxide (CO_2) from the atmosphere and store it in the form of biomass. The use of wood products, such as timber and furniture, can also contribute to reducing emissions by substituting for more energy-intensive materials such as steel and concrete [3,4]. By expanding the use of wood products while preserving existing, well-established sustainable forest management practices, Slovenia can make a significant contribution to meeting its emissions reduction targets.

Namely, the Slovenian forests cover 58% of the total land area, providing more than one million hectares (ha) of economic-value forests [5]. Between 2016 and 2020, an annual average of 5.3 million cubic meters (m^3) of timber was produced. Concurrently, the average production of wood-based products was 4.8 million m^3, with industrial wood accounting for 75% of this total. Softwood species constituted 78% of the timber utilized in the manufacturing of industrial wood products. Within this category, sawlogs and veneer represented the largest use at 75%. Hardwood was predominantly used for heating purposes, comprising 56% of their total usage. The average consumption of roundwood over this period was 3 million m^3 per annum, with approximately 2 million m^3 being allocated to the production of industrial wood [6].

Given the present rates of harvesting and usage, a research topic of interest for Slovenian policymakers is how the national output and utilization of timber products, and the augmented felling of trees, could aid in substituting fossil-derived materials and mitigating GHG emissions. At present, the logs felled in Slovenia are primarily employed for firewood or exported (primarily in forms other than sawn wood logs), owing to the limited processing capacity in Slovenia that impedes their conversion into high-value timber products such as building materials, engineered timber products, composites, and the like. With the current scenario characterized by low-value utilization and exports, the Wood Industry Directorate under the Slovenian Ministry of Economic Development and Technology (MEDT) has established the ensuing objectives [7]: Firstly, the aim is to process 3 million m^3 of roundwood in Slovenia annually, an increase from the current processing level of 1.8 million m^3. Secondly, the objectives seek to elevate the turnover of the wood industry to a minimum of EUR 2.5 billion per year, a significant surge from the present EUR 1.2 billion. Thirdly, there is an impetus to raise the added value within the wood sector to a level comparable to the average of other Slovenian processing industries. Lastly, the objectives strive to augment the number of employees within the wood industry to a range between 18,000 and 20,000.

The goal of this study is to explore different optimisation possibilities for the potential economic and greenhouse gas reduction effects on the use of 3 million m^3 of timber in Slovenia over each of the seven years 2023–2030. For a better understanding of the importance of wood products' role in reducing GHG emissions, the main objective of this study is to present a model demonstrating how the forest-based value chain, including construction, could help reach the Paris Agreement goals. In this study, we examine the related environmental impacts, focusing on climate change indicators in the LCA analysis, the economic impacts associated with it, and opportunities for the optimisation of these impacts.

There have been previous studies on optimal wood use and its environmental and economic effects. This paper builds on previous research presented in [8] and, in an expanded analysis, offers new results together with diverse different optimisation outcomes obtained from this investigation into climate action through the use of wood products in Slovenia.

The integration of carbon storage balance in forests was studied by [9,10] who found that using the wood for energy production may result in lower carbon mitigation effects from the stored wooden products. However, younger trees absorb much more CO_2 for their growth than mature trees [11]. In Slovenia, where sustainable forest management (with natural regrowth after felling, no clear cuts, and therefore no need for artificial reforestation) has been in place for at least a century, this means that with every tree that is felled, there is space opened for the accelerated growth of juvenile trees. Therefore, it can be concluded that the GHG balance in Slovene forests is not drastically affected by the acquisition of timber for the purpose of durable wood product production.

In their 2007 report on climate change mitigation, the IPCC stated that the forest-based industry could contribute to the efforts by prolonging the carbon retention in processed wood-based products, substituting higher GHG emitting materials, and utilising lignocellulose for bio-energy. In the process, the carbon is sequestered from the atmosphere into timber, fibre, and energy that consequently serve to fulfil society's needs. Concomitant sustainable forest management maintains or increases forest carbon stocks and produces a continuous supply of the mentioned forest products, thusly generating the optimal, durable mitigation ([12], p. 543). In Leskinen et al. [3], the authors investigated the substitution effects of wood-based products in climate change mitigation with a global scope focused on the European Union. They found that using wood-based products as substitutes for greenhouse gas-intensive materials and fossil fuels can have climate benefits. While the positive role of forests in climate change mitigation is generally understood, the contribution of wood products to mitigation is less known and understood. However, summarizing 51 studies, they found that, overall, a substitution effect of 1.2 kg of C per kilogram of C in wood products could be suggested, based on the 433 separate substitution factors [3]. Geng [13] quantified the substitution benefits of wood furniture for China and found that wood materials can reduce greenhouse gas emissions by 2.67 kg CO_2e per kg. However, in China, the demand for timber is much higher than the forest growth [13], which is in contrast to the situation in Slovenia. Soimakallio et al. [14] assessed the extended life cycle of carbon emissions whilst considering the substitution impacts for various wood utilization scenarios over 100 years from 2010 onward for Finland and found that there is a significant trade-off between avoiding emissions through fossil fuel substitution and the reduction in forest carbon sink due to wood harvesting. However, the article is focused on rather short-lived pulp and paper products and wood for incineration. This is in contrast to our study, which includes a range of long-lived (construction) products of wood.

Hurmekoski et al. [15] reviewed the potential impact of large-scale material substitution at the market level of a region or sector and found that this remains challenging. The authors concluded that the results are of limited practical use, as the quantified results are context specific as they rely on specific assumptions such as which wood products substitute a specific other material.

Increased wood utilisation in Lithuania and its impacts on various areas, including sequestered carbon in wood products, was studied by Jasinevičius et al. [16]. Domestic wood flows were analysed using different wood-use scenarios. While positive impacts on socioeconomic factors were confirmed, the benefits on environmental impacts (carbon in forest and in the products) can only be realized with an increase in the utilization of wood for long-life wood products. Different scenarios of forest management were modelled for the German state of North Rhine-Westphalia [17]. The study showed that using wood has more desired long-term impact then other scenarios without its use. The relevance of wood upscaling options from an environmental perspective was studied in a case in Switzerland [18]. Dynamic material flow analysis, combined with an LCA study, was carried out to optimize the environmental performance of using wood products. The study suggested that environmental impacts could be further improved through wood cascading.

Baul et al. [19] investigated the climate change mitigation potential in boreal forests and the substitution of fossil resources in three boreal regions of Finland. They found that maintaining a higher stock of C in the forest was important, but also that the results were highly sensitive to the displacement factors used.

A study by Jang and Youn [20] evaluated the utilization of South Korean wood resources and cascading in terms of carbon sequestration impacts. The study compared the Tier 2 (electricity and heat emissions) and Tier 3 (other emissions not under the direct control of the company) carbon accounting and storage for the period from 1970 to 2080, assuming the current pattern of wood resource use for the next sixty years. The results showed that the current use of South Korean wood resources is inefficient in terms of mitigating climate change. Their results suggest that the carbon storage of harvested wood products may be overestimated when using the Tier 2 method in the case of net wood importing countries such as South Korea. The study therefore has a very different perspective than ours, as Slovenia is a net wood exporting country, and we use a life cycle assessment from the perspectives of Tier 1 to Tier 3 (all included as totals).

The mathematical optimisation of wood resource flows has also been studied in the past for various use cases. Wood value chains in Northern Iran were analysed using a multi-period and multi-product mixed-integer non-linear programming (MINLP) model for the comprehensive optimisation of harvesting sites, machinery, and transfer flows [21]. An overview of papers optimizing the cascade utilization of wood is given by [22]. Based on their findings, they also propose a multi-objective mixed-integer linear programming (MILP) model combined with LCA for five products in a case study of Lower Saxony, Germany. Slovenian forests' carbon stock was analysed with the CBM-CFS3 modelling framework, studying different harvesting scenarios and their impact on carbon dynamics [23]. It was concluded that Slovenian forests could still serve as a carbon sink with up to 9 million m^3 harvested per year. According to [24], the Slovenian forest supply chain of raw materials is underutilized, and more effective supply chains for high added value products should be considered, including more optimal use of high-quality raw materials.

2. Materials and Methods

Optimisation performance study of economic-related impacts and environmental impacts, focusing on the carbon footprint of the existing wood-value chain in Slovenia was performed. The study initiated with an extrapolation of the currently established wood production models to achieve the 3 million m^3 annual wood production volume target. For a better understanding and further optimisation process, each representative type of wood product group was defined. Next, the expected revenue for each product group was calculated.

The model for the distribution of wood processing quantities was designed to calculate an estimate of the highest possible turnover and/or GHG emission savings that could be achieved from the allocation and annual processing of 3 million m^3 of round wood in the Republic of Slovenia.

This optimisation model distributes this quantity to the product flows for coniferous and deciduous wood according to the ratio in the actual felling in the Republic of Slovenia in several possible ways (optimisations):

- (**Optimisation 1**) to generate the highest possible potential sales revenue;
- (**Optimisation 2**) to select products with the lowest carbon footprint;
- (**Optimisation 3**) to select products that contain as much biogenic carbon as possible;
- (**Optimisation 4**) to select products with the lowest carbon footprint, considering the stock of biogenic carbon;
- (**Optimisation 5**) to select products that have the smallest difference in carbon footprint with alternative non-wood products, taking into account the stock of biogenic carbon;
- (**Optimisation 6**) to select products that have the largest difference in carbon footprint with alternative non-wood products, taking into account the stock of biogenic carbon.

Furthermore, the model also considers limitations on maximum allowable amounts for each selected product stream and minimum allowable amounts for each product covered by the model. This is further explained in detail in Section 2.2.

After the completed optimisation process of quantities and material volumes of the determined product groups, an estimation of average GHG savings in terms of substitution factors and carbon footprints was calculated for all the products within the product groups. Finally, the expected revenue and projected total GHG savings were obtained with the optimisation model.

2.1. Product Groups

Twelve wood-based product groups were identified based on the initial input from MEDT and further suggestions from the research group's investigation on the engineered wood products most commonly used in construction, pulp and paper industry, bio-refining, and energy sectors. Next, non-wood-based products and wood-based alternatives with comparable performances based on the pre-determined criteria were compared with each other. For the construction products, the comparison criteria were selected based on the buildings' structural demands in Slovenia following Eurocode building code standards, as well as using engineering judgement. The non-wood-based counterparts were chosen based on what is most widely used in construction (e.g., concrete slabs) or what could be used in the construction where timber is the currently prevailing solution (e.g., aluminium profiles instead of wooden laths).

In the Sawn wood category (**Group 1**), we selected wooden battens with the function of a substructure for final layers, as well as an air gap forming layer in ventilated roofs or ventilated façades. They were compared with alternative elements made of other non-wood-based materials (steel, aluminium), which provide the same height of air gap (h = 5 cm), and at the same time have the smallest possible cross-section to perform this function. The comparison was performed for elements with length L = 1.0 m.

In the Sawn construction timber category (**Group 2**) and Cross-laminated timber (CLT) category (**Group 3**), two types of primary structural systems were compared: (i) wall elements and (ii) slab elements. The comparison was performed in terms of structural resistance performance for load cases under Eurocode standards for structural design, without including accidental impacts. The dimensions of structural elements were determined for regular buildings in terms of the floor plan and height up to three storeys in height. The considered floor height of wall elements was h = 3.0 m, the wall's segment length b = 3.0 m, and the slab span in both directions L = 6.0 m. The considered characteristic loads according to the Eurocode standards were self-weight of the structure, permanent (dead) load g,k = 2.0 kN/m^2, and imposed (live) load q,k = 2.0 kN/m^2. In the category of wall elements, we chose a timber frame system with double-sided OSB panels sheathing and a solid wall made of cross-laminated timber panels among the wood-based structural systems. We compared them with a solid reinforced concrete wall and a masonry wall with reinforced concrete ties. In the category of floor elements, we chose two wood-based systems: (i) a system made of structural timber beams with oriented strand boards (OSB) sheathing on the upper side of the beams; (ii) a cross-laminated timber floor panel. We compared them with a reinforced concrete floor panel. The comparison was performed on a segment area A = 1.0 m^2, considering the average values of the materials quantities of the entire analysed structural element.

In the Formwork boards category (**Group 4**), we compared typical plywood formwork panels with non-wood-based formwork panels made of materials such as steel, aluminium, and hollow plastic with a comparable load-bearing capacity. The comparison was performed exclusively for formwork panels without additional system components such as supports, beams, spacers, clamps, etc. The comparison was performed for the formwork panel area A = 1.0 m^2.

The Laminated wood stock category (**Group 5**) is used in Slovenia almost exclusively for the production of windows. Therefore, we decided to compare the carbon footprint of wood and non-wood comparable semi-products of this Group at the level of the final product. Therefore, the results are meaningfully included in **Group 7**.

The criteria for the selection of products in the Wood composite boards category (**Group 6**) was performed for the case of the sheathing of timber frame walls, which are acceptable as load-bearing elements to ensure adequate horizontal load-bearing capacity and rigidity of timber frame wall system according to the Eurocode standards. The selected wood-based products were OSB, plywood boards, laminated veneer lumber (LVL) boards, and medium-density fibreboards (MDF). We compared them with non-wood-based products that meet the criteria, such as gypsum fibreboards and cement particle boards. The same plate thickness (t = 12.5 mm) was chosen for all product types. The comparison was performed for the board surface area A = 1.0 m^2.

In the Window frames profiles category (**Group 7**), we compared windows that have comparable energy efficiency properties such as thermal conductivity and other physical properties. The main criterion for all compared products was thermal transmittance limit U = 1.5 W/m^2K. The comparison was performed for windows with a completely wooden frame, a combined wood-aluminium frame, aluminium frame, and a polyvinyl chloride (PVC) frame.

Within the Glue-laminated timber category (**Group 8**), we compared two types of structural elements, namely beams and columns according to the same selection principle as in the analysis of Groups 2 and 3. We considered the beams' span L = 6.0 m and the tributary load width b = 3.0 m. For the columns, we considered height h = 3.0 m and the tributary load area A = 5.0 m × 5.0 m = 25.0 m^2. In both structural element types (beams and columns), we compared corresponding glue-laminated timber elements with non-wood-based steel and reinforced concrete elements. The comparison was performed for segments of elements with length L = 1.0 m.

In the Pulp and paper product category (**Group 9**), a paper cup of liquid packaging board (wood-based material) was compared with a polystyrene hot beverage cup, for both 1 cup of maximum 250 mL hot beverage, food-grade materials.

In the Bio-refinery product category (**Group 10**), the emission data from the conversion of 1000 kg birch wood into phenol, propylene, oligomers, and raw carbohydrate pulp (for bioethanol) and their fossil-based counterpart were taken from a scientific publication by Liao et al. [25].

In the Thermal insulation category (**Group 11**), we compared products for thermal insulation of buildings such as wood wool, polystyrene foam, and stone wool. The selection criterion was thermal transmittance U = 0.28–0.34 W/m^2K.

In the last category, the Energy product category (**Group 12**), a small-scale residential-size wood heater (6 kW) and a large-scale industrial heat and power co-generation plant fuelled with wood chips (6667 kW) were assessed for the wood-based alternative. For the fossil-based energy production, four different alternatives were assessed: (i) a small-scale natural gas heat and power co-generation mini plant (2 kW); (ii) a district or industrial heat and power co-generation lignite plant; (iii) a small-scale light fuel oil boiler (10 kW); and (iv) a lignite briquette stove (5–15 kW). The common function for the energy product group was to deliver 1 GJ heat.

Table 1 shows an example of a product group with several wood-based products and two substitution materials for use in the sheathing of timber frame walls. In this example for product Group 6, the description is the same (thickness t is equal to 12.5 mm) for all products in this group. Other product groups with individual products are thoroughly described in Appendix A.

Table 1. Example of selected products in Group 6—Wood composite boards with the surface area A = 1.0 m^2, the product descriptions (thickness t equal for all in this product group), and calculated quantities. (* functionally equivalent non-wood-based products).

Product	Description	Volume [m^3]	Mass [kg]
OSB board	t = 12.5 mm	0.0125	8.13
Plywood board (softwood)			6.25
LVL board			6.38
MDF board			8.75
* Gypsum fibreboard			15.00
* Cement particle board			17.50

For each of the product groups, expected revenues (market prices of materials, intermediate products, and products) were collected directly from wood products companies and re-sellers (personal communication) and online sources, as needed.

2.2. Structure of the Mathematical Model

This section presents a linear programming (LP) mathematical model that was formulated to represent the flow of resources between the different product groups. The formulation is not specific to a single scenario but was designed to be generally applicable to any number of product groups and parameters. This model receives the various product groups, their characteristics (what resources can be allocated to the group, what the ratios are of the residuals after processing the input, what volume is needed for a unit product, what the revenue is for a unit product), and outputs the optimal distribution of resources between the product groups. The input data and parameters required for the formulation are summarized in Table 2, together with the decision variables of the model.

Table 2. The most important parameters and variables of the mathematical model.

Input Data	
X	set of conifer products
Y	set of non-conifer products
a_{wood}	total amount of available roundwood resources to be allocated, (m^3)
E	set of resource types, e.g., $E = \left\{ roundwood, chip, \frac{\frac{sawdust}{shaving}}{sanding}, bark \right\}$
$P(i)$	set of usable resources for group i, $P(i) \subseteq E$
$r^e_{\{co,i\}}$, $r^e_{\{nc,j\}}$	ratio of residual resource e left over in conifer/non-conifer product stream i/j based on allocated roundwood resource (m^3)
v_i, w_j	conversion ratio between allocated resource (m^3) and product unit in conifer group i/non-conifer group j
c_i, d_j	revenue for each unit of product in conifer stream i/non-conifer stream j, EUR
$min^j_{n,i}, max^j_{n,i}$	The minimum and maximum volume of resource j that can be allocated to product group i for conifer/non-conifer streams n
Decision variables	
x^e_i, y^e_i	total amount of resource type e to allocate in conifer/non-conifer product stream i (e.g., x^l_i is total amount of roundwood, x^c_i is total amount of chips), m^3
Derived values	
x_i, y_i	otal resource allocated to stream i, m^3

A general formulation of the LP model is given below:

$$maximize \sum_{i} c_i v_i x_i + \sum_{j} d_j w_j y_j \tag{1}$$

subject to

$$\sum_{i}^{|X|} x_i^l + \sum_{j}^{|Y|} y_j^l \leq a_{wood} \tag{2}$$

$$\sum_{i}^{|X|} x_i^l \geq a_{min,co} \tag{3}$$

$$\sum_{j}^{|Y|} y_j^l \geq a_{min,nc} \tag{4}$$

$$\sum_{i}^{|X|} x_i^j \leq \sum_{i}^{|X|} r_{co,k}^j x_k^l \;\; \forall j \in E^R \tag{5}$$

$$\sum_{i}^{|Y|} y_i^j \leq \sum_{i}^{|Y|} r_{nc,k}^j y_k^l \;\; \forall j \in E^R \tag{6}$$

$$x_i = \sum_{j \in P(i)} x_i^j, \; \forall i \in X \tag{7}$$

$$y_i = \sum_{j \in P(i)} y_i^j, \; \forall j \in Y \tag{8}$$

$$min_{co,i}^j \leq x_i^j \leq max_{co,i}^j, \; \forall i \in X, \forall j \in E \tag{9}$$

$$min_{nc,i}^j \leq y_i^j \leq max_{nc,i}^j, \; \forall i \in Y, \forall j \in E \tag{10}$$

The model considers a set X of conifer product groups, a set Y of non-conifer product groups, and a total amount of a_{wood} available roundwood resource to allocate. The decision variables of the model are given in the form of x_i^e and y_i^e, which represent the total amount (m^3) of resource type e allocated in conifer and non-conifer product group i, respectively. The amounts of total allocated resources are denoted by x_i (for conifer groups i) and y_j (for non-conifer groups j), respectively, and are calculated as the sum of the allocated roundwood (x_i^l, y_i^l), chips (x_i^h, y_i^h), sawdust/shavings/sanding (x_i^s, y_i^s) and bark (x_i^b, y_i^b), which are the decision variables of the model. This is presented in constraints (7) and (8). The objective function (1) aims to maximize revenue over these streams by determining the total amount of resources allocated to each product group. While roundwood is available as the input of the system, the other resource types are generated as residual materials of different product streams. Vectors **v** and **w** provide the conversion ratios of the allocated resources to units of products for each stream, and **c** and **d** give the revenue per unit for each product group. Constraint (2) ensures that the allocation of roundwood does not exceed the available amount, while (3) and (4) determine minimum amounts to be allocated for conifers and non-conifers, respectively. Constraints (5) and (6) control the use of residual resources (chips, sawdust/shavings/sanding, and bark) for conifers and non-conifers, ensuring that the allocated amount of a residual does not exceed the total available amount generated by the streams. The ratio of residuals that is generated by a product stream is given by vectors $\mathbf{r_{co,k}^j}$ and $\mathbf{r_{nc,k}^j}$ ($j \in \{h, s, b\}$ stands for a given residual). All variables of the model are non-negative, and lower and upper limits can be enforced on them (minimum or maximum number of resources to use/units to produce/etc.). These limits are expressed by constraints (9) and (10). If a product group does not allow the allocation of a certain resource, then its corresponding maximum limits should be set to 0.

If other aspects are also considered during optimisation, the model can be extended with the introduction of additional objectives:

$$minimize \sum_i t_i^{co} v_i x_i + \sum_j t_j^{nc} w_j y_j \tag{11}$$

$$minimize \sum_i f_i^{co} v_i x_i + \sum_j f_j^{nc} w_j y_j \tag{12}$$

$$minimize \sum_i \left(t_i^{co} + f_i^{co}\right) v_i x_i + \sum_j \left(t_j^{nc} + f_j^{nc}\right) w_j y_j \tag{13}$$

$$maximize \sum_i \left(p_i^{co} - t_i^{co} + f_i^{co}\right) v_i x_i + \sum_j \left(p_j^{nc} - t_j^{nc} + f_j^{nc}\right) w_j y_j \tag{14}$$

Vectors $\mathbf{t^{co}}$ and $\mathbf{t^{nc}}$ stand for biogenic stock/unit of the different products, while $\mathbf{f^{co}}$ and $\mathbf{f^{nc}}$ give the carbon emissions to produce a single unit. The sum of these values for a product provides its carbon footprint. Vectors $\mathbf{p^{co}}$ and $\mathbf{p^{nc}}$ give the carbon footprint non-wooden alternatives for the same product type. Objective (11) aims to provide the best biogenic stock (stock values are represented as negative numbers, thus the minimization), while (12) ensures the lowest possible carbon emissions during the production processes. Their combination (13) results in products with the lowest carbon footprint. Optimizing for (14) provides a solution where the produced wooden products have the biggest total difference in carbon footprint (and thus the biggest savings) compared with their non-wooden alternatives.

Any of these functions can be used for single-objective optimisation instead of the original revenue maximization objective of the original model. However, multi-objective optimisation can also be performed, resulting in a solution that considers more than one objective. In the scope of this project, this was performed by the hierarchical optimisation of the above objectives. In this case, a series of single-objective optimisation problems are solved, but the optimal objective value of a solution is introduced as a new constraint to the remaining problems (providing an upper/lower threshold for the given value). For example, if the goal is to maximize revenue and minimize carbon emissions at the same time, the first optimisation problem to be solved is maximizing the revenue, resulting in solution $\boldsymbol{Z}$ as the optimum. In this case, a second optimisation problem also has to be solved that minimizes carbon emission with the inclusion of the additional constraint:

$$\sum_i c_i v_i x_i + \sum_j d_j w_j y_j \geq Z$$

Alternatively, minimizing emissions can be performed as the first solution, resulting in optimal value $\boldsymbol{E}$. Then the second optimisation problem for maximizing revenue should be performed with the following additional constraint:

$$\sum_i f_i^{co} v_i x_i + \sum_j f_j^{nc} w_j y_j \leq E$$

Performing hierarchical optimisation in both of the above-described ways will usually result in two different solutions for the same problem, with no obvious best choice between the two. This hierarchical method works similarly in the case of three or more objectives as well.

2.3. Plants and Factories

Increased production of wood and wood-based products requires new plants and factories in Slovenia. Based on existing plants or investment plans/feasibility studies from all over the world, Table 3 provides typical capacities for different wood processing infrastructures.

Table 3. Wood processing factories/plant types and processing capacity.

	Factory/Plant Type	Processing Input Capacity per Year	Investment Cost [Euro]	Source
1	Sawmill plant	300,000 m^3	51 million	[26]
2	Sawmill plant	50,000 m^3	9 million	[26]
3	Cross-laminated timber (CLT) production plant	87,000 m^3	72 million	[27]
4	CLT production plant	31,000 m^3	15 million	[28]
5	Glue-laminated timber plant	27,000 m^3	6 million	[29]
6	Veneer and plywood production plant	230,000 m^3	56 million	[30]
7	Oriented Strand Board (OSB) board production plant	310,000 t	74 million	[30]
8	Pulp production plant	615,000 t	800 million	[31]
9	Particle board production plant	180,000 m^3	37 million	[30]
10	Energy production plant	108,000 m^3 *	3.5 million	[32]
11	Energy production plant	43,000 m^3 *	1.7 million	[32]
12	Wood wool production plant	50,000 t	59 million	[33]
13	Biorefinery plant	220,000 t	550 million	[34]
14	Fiberboard production plant	177,000 m^3	46 million	[30]

* Combustion capacity.

2.4. Optimisation Scenarios and Carbon Footprint

Using the general mathematical model developed in Section 2.2, several optimisation scenarios were developed for the distribution of available resources. These scenarios all considered different objective functions for optimisation.

Standardized life cycle assessment techniques (following ISO 14040/44) [35,36] were employed to determine the carbon footprint of wood-derived products and their non-wooden counterparts across a range of product categories. The Ecoinvent v3 [37] database was utilized to obtain life cycle inventory data. A cradle-to-gate analysis was conducted, beginning with the acquisition of necessary equipment and fuel for forestry and timber harvesting, followed by the construction and maintenance of forest roads, and concluding with the processing of the raw material, including debarking and sawing, to produce the final product. In the case of building materials, the analysis adheres to the A1-A3 scope as defined in EN 15804+A2:2019 [38].

The method opted for the impact assessment was the Environmental Footprint as advised by the European Union [39]. It considers characterisation factors for climate change based on the IPCC 2013 report. For the characterisation factors (CFs) of biogenic CO_2 uptake and emissions, these were set equal to "−1" (CO_2 uptake) and "+1" (CO_2 release), similar to EN 15804:A2:2019 [38]. The GHG savings that could be achieved were determined by quantifying the difference in the carbon footprint between selected wood-based and non-wooden products within each product group. As the model calculates both "CO_2 savings considering the stock of biogenic carbon: comparison of the smallest difference" and "CO_2 savings considering the stock of biogenic carbon: comparison of the largest difference", the difference between the wooden product with the highest and the non-wooden product with the lowest carbon footprint for the former, and the difference between the wooden product with the lowest and the non-wooden product with the highest carbon footprint for the latter, were determined (see Section 2.2, Objectives 11, 12, 13, and 14). These quantities were then multiplied by the ratio of the volume of wood assigned to each product group by the model and the volume of wood contained in the said wooden products (substitution effect). Furthermore, the potential for carbon storage was calculated for each product group based on the volume of wood allocated to it (sequestration effect). The cumulative potential GHG savings were obtained by summing the substitution and sequestration effects across all the product groups.

2.5. Data and Assumptions

The main assumption made was that there is a market for all the quantities of the products that the model calculated, at the prices that were gathered for these products at the time of the study. In the calculation of potential sales revenue, the model contributed results for products in primary wood processing (category C16 in the decimal classification of industrial activities) and energy production. The production of furniture (C31) and wood construction (obtained from the Association of Slovene wooden prefabricated housing producers) was included in the analysis. Conversion factors for roundwood biomass were acquired from UNECE/FAO [40], while Ecoinvent [37] was utilized to assess the carbon footprint of wood products and their non-biobased counterparts, except for biorefinery products [25]. Potential revenue calculations were based on prices from November 2020, which are subject to temporal fluctuations. It is worth noting that prices have undergone a significant increase in 2021 and 2022 [41], which may impact the validity of the results.

3. Results

The results from the six different optimisations are shown in Figures 1–6. The quantity of wood is depicted on the first vertical axis with bars, and the potential greenhouse gas (GHG) savings are on the second vertical axis for substitution only (triangles) and including stock use (cross). In Appendix B, the contents of all figures, with additional information on revenue and the needed investment for each of the six optimisations, are given in Tables 1 and 2.

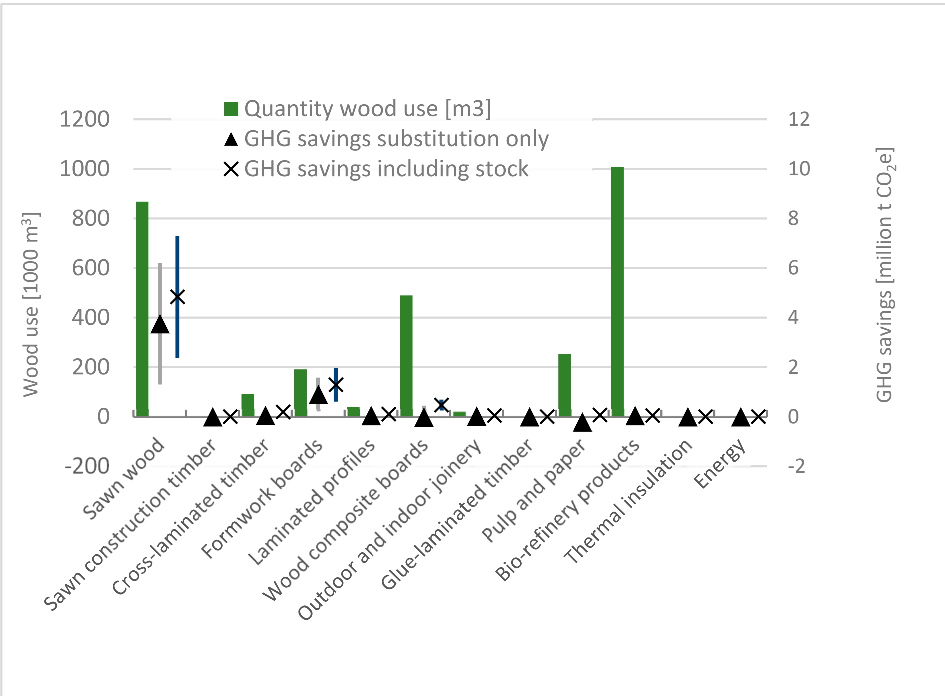

Figure 1. Results of 3 million m^3 of wood distribution in the product groups when optimised for expected sales revenue (**Optimisation 1**). Quantity of wood at the 1st vertical axis and potential greenhouse gas (GHG) savings (on the second vertical axis) for substitution only, and including stock.

In Optimisation 1 for revenue, depicted in Figure 1, the biorefinery gets the most wood (1 million m^3), followed by sawn wood (867 thousand m^3) and wood composite boards (490 thousand m^3). The potential GHG savings are highest for the sawn wood, with 3.76 and 4.84 million tonnes of CO_2e for respective substitution only and including stock effects. Both categories of biorefinery and sawn wood were also identified in [3], in terms of highest quantities, as they appear as the most important forest products in the EU.

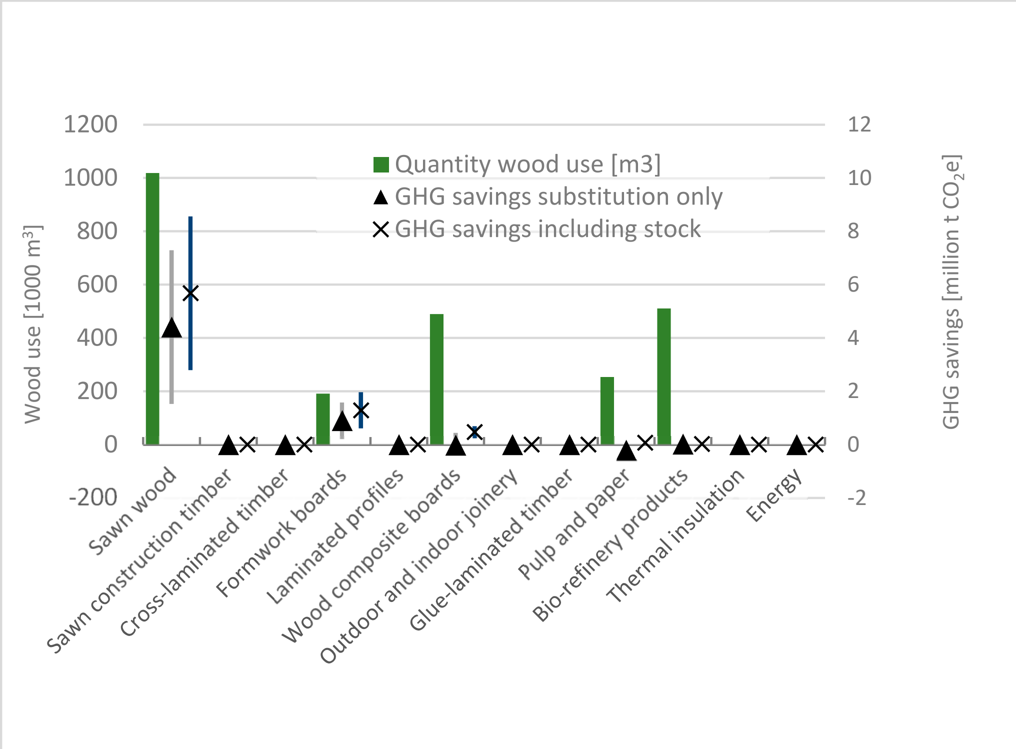

Figure 2. Results of 3 million m^3 of wood distribution in the product groups when optimised for minimal carbon footprint I (**Optimisation 2**). Quantity of wood at the 1st vertical axis and potential greenhouse gas (GHG) savings (on the second vertical axis) for substitution only and including stock use in.

In optimisation 2 for minimum carbon footprint without taking into account the biogenic carbon stock (carbon footprint I) depicted in Figure 2, the sawn wood gets the most wood (1018 thousand m^3), followed by biorefinery (510 thousand m^3), and wood composite boards (490 thousand m^3). The potential GHG savings are highest for the sawn wood, with 4.41 and 5.68 million tonnes of CO_2e for respective substitution only and including stock effects.

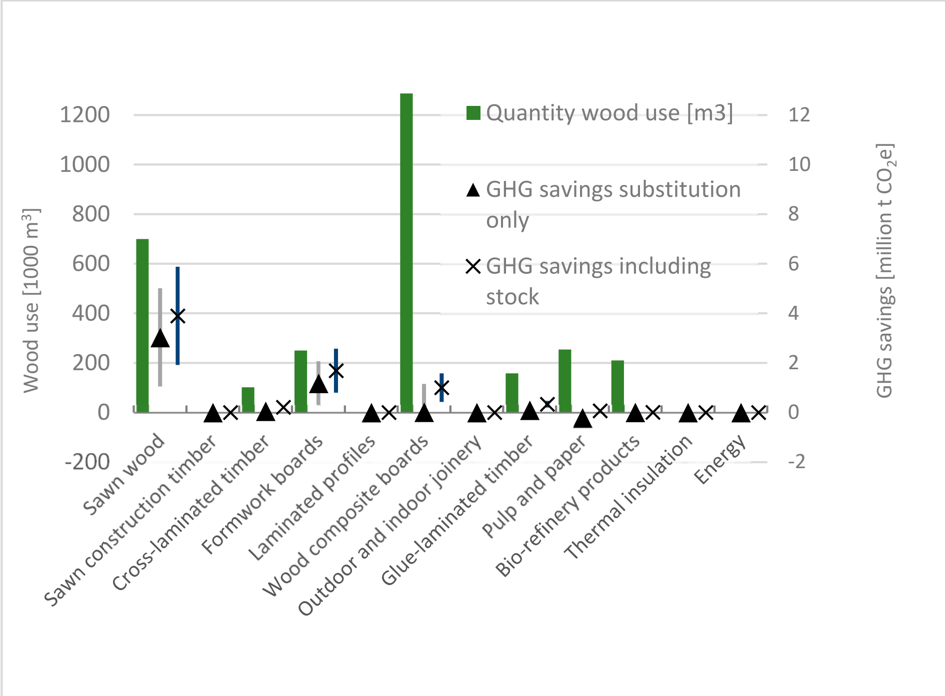

Figure 3. Results of 3 million m^3 of wood distribution in the product groups when optimised for maximum biogenic carbon stock (**Optimisation 3**) Quantity of wood at the 1st vertical axis and potential greenhouse gas (GHG) savings (on the second vertical axis) for substitution only and including stock.

In Optimisation 3 for the highest biogenic stock, depicted in Figure 3, the wood composite boards get the most wood (1287 thousand m^3), followed by sawn wood (700 thousand m^3). The potential GHG savings are highest for the sawn wood, with 3.03 and 3.90 million tonnes CO_2e for respective substitution only and including stock effects.

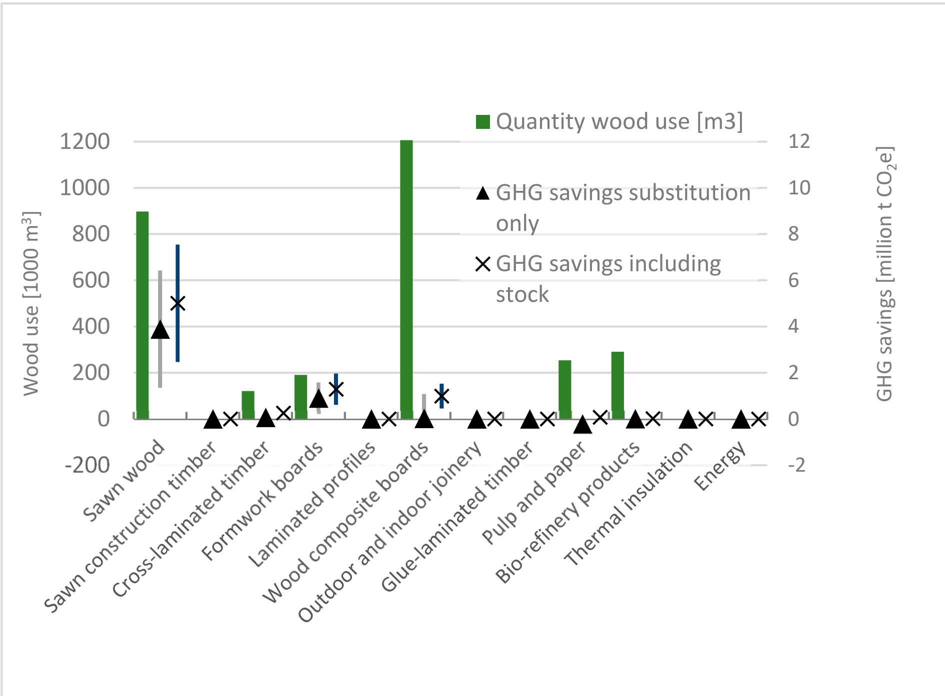

Figure 4. Results of 3 million m^3 of wood distribution in the product groups when optimised for minimal carbon footprint II (**Optimisation 4**) Quantity of wood at the 1st vertical axis and potential greenhouse gas (GHG) savings (on the second vertical axis) for substitution only and including stock.

In Optimisation 4 for the highest carbon footprint including stock effects (carbon footprint II), depicted in Figure 4, the wood composite boards get the most wood (1206 thousand m^3), followed by sawn wood (897 thousand m^3). The potential GHG savings are highest for the sawn wood, with 3.89 and 5.00 million tonnes CO_2e for respective substitution only and including stock effects.

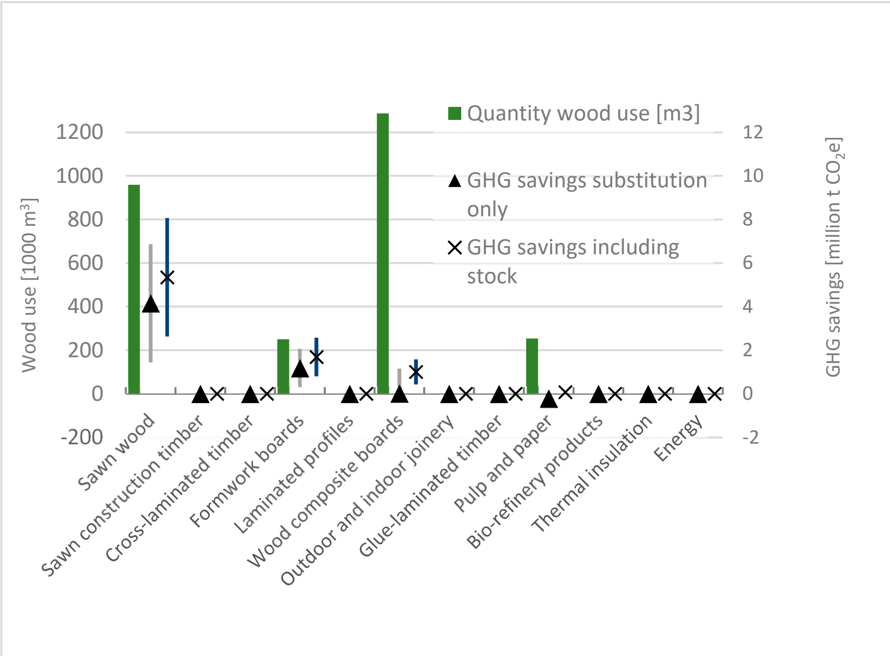

Figure 5. Results of 3 million m^3 of wood distribution in the product groups when optimised for the smallest difference in CO_2 savings of carbon footprint II, taking into account the stock of biogenic carbon (**Optimisation 5**). Quantity of wood at the 1st vertical axis and potential greenhouse gas (GHG) savings (on the second vertical axis) for substitution only and including stock.

In Optimisation 5 for CO_2 savings, taking into account the stock of biogenic carbon (comparison of the smallest difference in carbon footprint II), depicted in Figure 5, the wood composite boards get the most wood (1287 thousand m^3), followed by sawn wood (959 thousand m^3). The potential GHG savings are highest for the sawn wood, with 4.15 and 5.35 million tonnes CO_2e for respective substitution only and including stock effects.

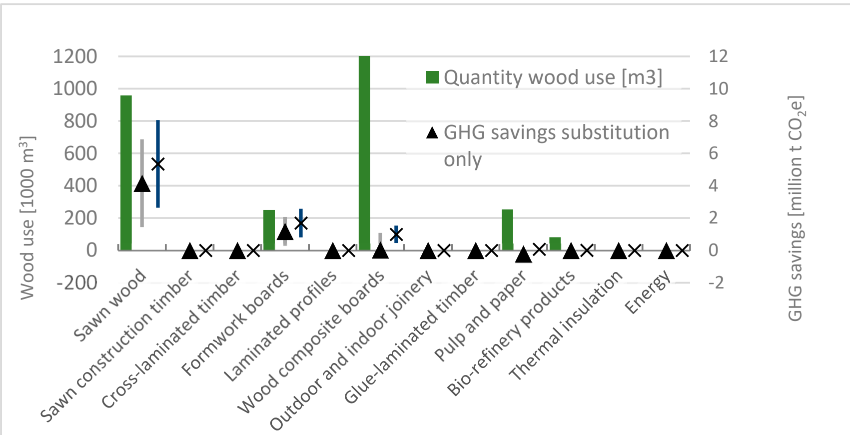

Figure 6. Results of 3 million m^3 of wood distribution in the product groups when optimised for the largest difference in CO_2 savings of carbon footprint II, taking into account the stock of biogenic carbon (**Optimisation 6**). Quantity of wood at the 1st vertical axis and potential greenhouse gas (GHG) savings (on the second vertical axis) for substitution only and including stock.

In optimisation 6 for CO_2 savings, taking into account the stock of biogenic carbon (comparison of the largest difference in carbon footprint II), depicted in Figure 6, the wood composite boards get the most wood (1206 thousand m^3), followed by the sawn wood (959 thousand m^3). The potential GHG savings are highest for the sawn wood, with 4.15 and 5.35 million tonnes CO_2e for respective substitution only and including stock effects.

The ultimate outcomes in terms of environmental impact, specifically the potential reduction in greenhouse gas (GHG) emissions resulting from both substitution and sequestration measures, demonstrate a relatively equal performance across all six optimisation scenarios examined (cf. Figure 7). This parity can be attributed to the imposition of a constraint on the quantity of wood put into the model. The results range between 2.57 million tonnes of CO_2e per year (after 2030) (in Opt3 selecting products that contain as much biogenic carbon as possible) of substitution only and up to 6.78 million tonnes of CO_2e including stock effects (Opt6 products that have the largest difference in carbon footprint II with alternative non-wood products). Optimisation for revenue (Opt1) does not notably change the environmental results.

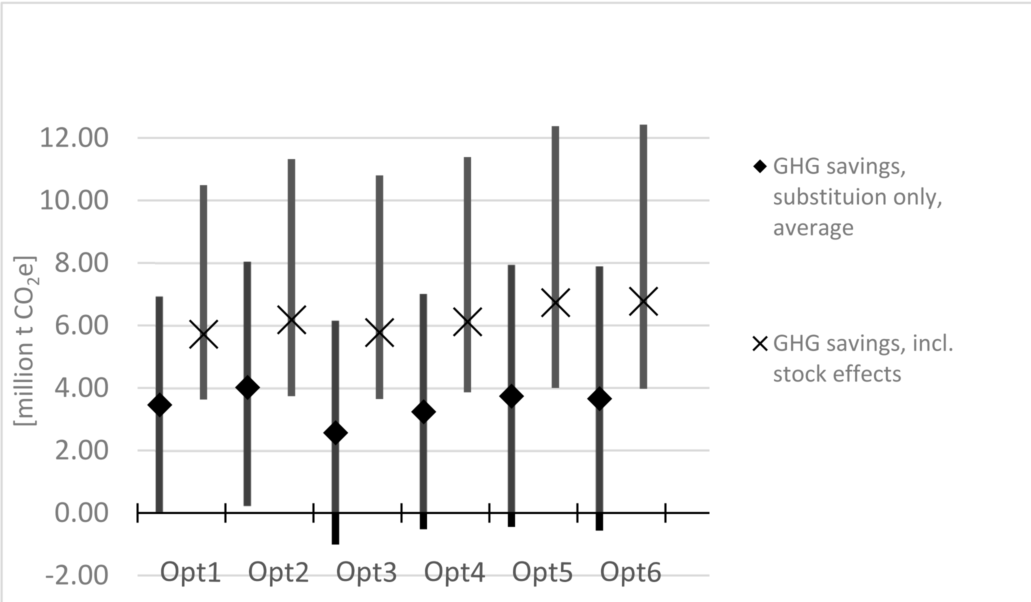

Figure 7. Quantity of CO_2e saved for substitution only (triangles) and including stock use (cross) on the vertical axis for the different optimisations (Opt) 1–6 on the horizontal axis. Bars indicate maximum and minimum potential CO_2e savings in each of the six optimisation scenarios.

The economic results (cf. Appendix B), calculated by the model for the six mentioned optimisations, indicated that all of them achieve the objectives of the MEDT, which is to achieve a minimum target of EUR 2.5 billion in revenue by the year 2030. This objective is based on the processing of approximately 3 million cubic meters of wood, which encompasses a wide range of industries such as the manufacturing of paper and paper products, furniture production, and wood construction. In the optimisation for revenue (Opt1), the primary production of wooden forest products (calculated by the model, representing mainly the category C16 in the decimal classification of industrial activities) reaches this goal almost alone with 2.48 million EUR in revenue per year. In the other five optimisation scenarios, the addition of the sub-sectors C17, C31, and wooden constructions (buildings) are needed to achieve the stated MEDT goal.

However, the model predicted quite a high investment needed to achieve the goals for each of the six optimisation scenarios. They ranged from 2,951,367,000 EUR when the optimisation criterion was the highest expected sales revenue (Optimisation 1) to 170,172,680 EUR when the optimisation criterion was CO_2 savings considering the stock of biogenic carbon in comparison with the largest difference (Opt6). The most glaring observation was that in none of the optimisations therewas a need to invest in new sawmilling capacity (that does not mean that no improvement in the technology of existing plants is needed). Unsurprisingly, on the other hand, the model also did not foresee any investment in energy-producing plants, as burning wood is not an activity that would generate either high added value or large potential GHG savings. The results clearly showed that, in the current structure, Slovenia mostly needs production capacities for the use of "lower quality" wood (e.g., biorefinery, particleboards, fibreboards, etc.) and the engineered timber construction products (e.g., CLT, OSB, glulam, etc.).

4. Discussion

Investing in the primary production of forest-based products, such as wood, can lead to increased economic revenue and has the potential to significantly reduce greenhouse gas emissions through substitution and sequestration effects. However, to meet the goals set by MEDT, it is necessary to increase both the amount of wood transformed into products and to develop the markets for the derived wood products.

The lack of production capacity for the high-added value use of "lower quality" wood and engineered timber construction products is particularly evident in Slovenia (e.g., the model showed the need for a biorefinery plant in five out of six optimisation scenarios—Table A3). To address this issue, it may be necessary to develop new technologies and production methods that allow for the efficient use of lower quality wood and other species than currently employed by the industry, as well as increased investment in the research and development of engineered timber products.

Primary production investment in forest-based products, such as the utilization of wood resources, is a promising approach to generate greater economic development while simultaneously having the potential to achieve substantial reductions in greenhouse gas (GHG) emissions through the implementation of substitution and sequestration strategies for forest-based products. Especially engineered wood products show the promise of a significant increase in carbon stock in such products, as corroborated with other studies [3,42]. Nonetheless, the findings of this study suggest that meeting the targets set by the MEDT would require both an increase in the volume of wood processed and a transformation in the structure of the forestry and wood industry. This is most apparent in the lack of production capacity for the high-added value use of "lower quality" wood and for the engineered timber construction products (the proposed new processing plants in Table A3). Moreover, the model presented does not assess the possibility of wood-based textiles replacing cotton and fossil-based textiles. Therefore, it is imperative that future models incorporate this type of analysis, as other studies suggest that the substitution of wood-based feedstock in these sectors could result in substantial reductions in greenhouse gas emissions [43]. The economic analysis presented herein has not taken into account the potential impacts of the European carbon markets, also known as the Emissions Trading System (ETS), which enables the trading of CO_2 emissions among various sectors. Currently, the non-ETS sectors are not permitted to trade saved CO_2 emissions, thus rendering this aspect outside the scope of this study. As of 2020, the cost of emitting one t of CO_2 was estimated to be around EUR 25, however, as of September 2021, the price has surged to approximately EUR 60/tonne. It is anticipated that this price will continue to escalate with the realization of the European Union's "Fit for 55" initiative [44] and the "Green Deal" [45]. At the time of writing, the price for 1 t CO_2 is around 100 Euro, with a clear upward trend. Therefore, the economic effects of the suggested restructuring could be even higher. As a result of these policy changes, greenhouse gas savings in sectors outside of the EU Emissions Trading System are anticipated to be monetized. This monetization would enhance the economic viability of investing in wood processing facilities. Furthermore, the computations conducted in the present investigation did not incorporate the external costs associated with climate change. These expenses were assessed for Germany in 2021 to be within the range of 201 to 690 Euro per t of CO_2 emitted [46]. Although the social costs of climate change have not, to our knowledge, been specifically quantified in Slovenia, such estimates could be significant for policymakers as they provide an insight into the societal costs linked to CO_2 emissions. Therefore, incorporating these costs into policy considerations could be essential in the development of effective and sustainable strategies for mitigating climate change impacts and derived forest and industrial policies; this strategy is also linked to how to use forest products.

This study is characterized as a bottom-up analysis, which begins by examining the product level, such as building materials. However, further research is needed to assess the market acceptance of these products in Slovenia and in export markets. Investigating these factors will be crucial in evaluating the feasibility of implementing the strategies outlined in this study and in determining the potential economic and environmental impacts of such initiatives. Nevertheless, it was clearly shown that substantial investment is needed in the country's woodworking sector (the proposed new processing plants in Table A3), and that such investment would generate a significant increase in expected sales revenue (Table A2). However, calculating the expected return on investment was out of the scope of this study.

In this study, the carbon footprint methodology used is referred to as cradle-to-gate Life Cycle Assessment (LCA). This approach assesses the amount of greenhouse gas emissions related to a product's entire life cycle, starting from the extraction of raw materials (cradle) and ending at the point of manufacture (gate). This approach does not take into account the use and disposal stages of a product's life cycle, as these are typically too far into the future to be accurately predicted, particularly given that the end of life for most of the products examined in this study falls well beyond the year 2050. While cradle-to-gate LCA provides a comprehensive evaluation of greenhouse gas emissions associated with the production of a product, it is important to note that it does not capture the full environmental impact of the product's life cycle. The use and end-of-life stages are usually significant contributors to a product's environmental impact, and these should be considered in future studies as more information becomes available on these stages.

This study did not intend to investigate the energy requirements (as an indicator) for the production of wood and biobased materials. This is a limitation of this study related to the set scope. However, it is reasonable to assume that increased wood production would lead to an increase in energy usage within the sector. It is important to note, however, that unlike non-wooden materials, which rely heavily on non-renewable fossil fuels, the wood sector has access to a large source of renewable energy that is closely tied to the wood resource itself. By-products from the trees, such as bark and small branches, can be used as a source of renewable energy, and the energy for photosynthesis, which is the primary source of the wood's biomass, comes directly from the sun. Furthermore, advances in wood processing technology have led to increased manufacturing process efficiency, resulting in reduced energy consumption and emissions. On the other hand, it can be argued that the earth system is abundant in energy, such that energy use per se is not the problem, but the emissions and other external effects related to the energy use are. As such, we focus on the life cycle of greenhouse gas emissions rather than simply energy usage.

In addition to greenhouse gas emissions, other environmental impacts, such as water use, land use, biodiversity, and impact on health, should also be taken into account in future assessments. This would provide a more comprehensive understanding of the environmental impact of wood processing and connected industrial activities, but this was not within the scope of our investigation.

During this study, we used a static methodology to determine the substitution effects. Given this approach, we expect the substitution effects to also be reduced in the future. This reduction is expected because in this research we did not take into account that the other building type sectors and material industries would also need to comply with the Fit for 55% goal by 2030, as well as being net climate neutral by 2050. On the other hand, the wood industry's fossil carbon footprint is also expected to decrease during the same period. Therefore, we strongly suggest that substitution effects that are created using wood-based materials, components, and products, instead of more energy-intensive or even fossil-based materials, get a much more prominent role in official reporting schemes and are accounted for in the efforts to reach the set climate-related goals.

The biogenic carbon stored within the wood products evaluated in this study was determined based on carbon uptake values for tree growth. This calculation was in line with the Ecoinvent database used during this research. Using this methodology, we did not consider any forest carbon storage variation or soil impacts. These variables were not considered as the forestry practices in Slovenia where the wood products are produced have been historically managed sustainably [47]. Specifically, the Slovene tradition of sustainable management and current forestry techniques spans at least 250 years, and subsequent changes in forestry practices would have only introduced further improvements, as the science in this area progressed [48].

Transferring our results of CO_2 savings due to substitution, from 2.57 (Opt3) to 4.02 (Opt2) million t CO_2e, and calculating from C to CO_2 using 44/12 and 250 kg of C in each m^3 of wood, we have a substitution effect of 0.93 (Opt3)–1.46 (Opt2). This can be compared with the substitution effect of approximately 1.2 kg C in [3], ranging from 1–1.5 kg C (in other product categories such as chemicals) to 2.8 kg C in textiles (which we did not include) and 1.3 kg C for structural construction. We can conclude that our results are in line with those found in Leskinen et al. [3] on the product level. On the macro level [49], the results of this study suggest that Slovenia has the potential to achieve the 55% GHG emissions reduction target by 2030 by utilizing its existing tree inventory to in-crease the production of wood-based building products domestically.

5. Conclusions and Outlook

This paper presents a study with the objective to explore forest-based products, building materials, and construction practices to contribute to achieving the Paris Agreement targets in Slovenia, i.e., a 55% reduction in greenhouse gas emissions by the year 2030. In a mathematical optimisation model of Slovenian wood resources flows to 12 different product groups, we optimised the expected sales revenue, carbon stock, or carbon footprint and modelled the associated carbon footprint.

Regarding the different product groups, the optimisation model outcome revealed that sawn wood is the most important product group in terms of GHG savings, the biorefinery product group is most important in terms of economic revenue, while the wood composite boards product group is important for the wood quantity in some of the investigated optimisations.

Wood-based products can store carbon for long periods and can be used to replace other high greenhouse gas (GHG)-emitting materials. This creates an opportunity to prevent GHG emissions from entering the atmosphere. The results of this study suggest that Slovenia has the potential to achieve the 55% GHG emissions reduction target by 2030 by utilizing its existing tree inventory to increase the production of wood-based building products domestically.

However, to meet the goals set by the MEDT, it is necessary to increase the amount of wood (especially "lower quality" wood and fuel wood) transformed into products (especially engineered timber construction products). The lack of production capacity for such high-added value use of round wood is particularly evident in Slovenia. Therefore, increasing the utilization of domestically produced wood-based building products to realize this potential reduction in GHG emissions would necessitate industry restructuring and increased manufacturing capacity within Slovenia. Furthermore, this reduction in GHG emissions would include the replacement of fossil- and mineral-based materials consumption with wood and other natural, renewable materials-based products. The resulting investment into increased domestic wood products manufacturing, which is expected to increase Slovenia's wood transformation sector's expected revenue from sales, could increase to almost Euro 3 billion in the most favourable scenario, a significant growth from the present Euro 1.2 billion. As these are expected projections, further research is necessary to validate and test these projections.

A more significant role of substitution effects in official carbon accounting schemes, including financial incentives to reward such savings, could act as a driver for the necessary investment and is therefore strongly suggested by the authors. This would create favourable market conditions for products and services based on natural materials from renewable sources.

Author Contributions: Conceptualization, E.M.S., Č.T. and I.G.; methodology, Č.T., E.M.S., I.G., I.Š., E.P.N., B.D. and D.B.D.; software, E.M.S. and B.D.; formal analysis, E.M.S., B.D. and Č.T.; investigation, E.M.S., Č.T., B.D., I.G. and J.G.P.; resources, I.G., Č.T., J.G.P., D.B.D., I.Š. and E.P.N.; data curation E.M.S., I.G., Č.T., J.G.P. and D.B.D.; writing original draft preparation, E.M.S.; writing—review and editing, all authors; visualization, E.M.S.; supervision, E.M.S. and Č.T.; project administration, E.M.S.; funding acquisition, Č.T. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in Appendices A and B.

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Appendix A

Table A1. The product groups, product names, their descriptions, and calculated quantities. (* Non-wood-based products chosen for comparison study).

	Product Group	Product Name	Product Description	Volume [m^3]	Mass [kg]
1	Sawn wood	Wooden batten	b/h = 5/5 cm, L = 100 cm	0.0025	1.05
		* Aluminium “U” channel profile	b/h/t = 50/50/3 mm, L = 100 cm	0.00043	1.17
		* Steel “U” channel profile	b/h/t = 50/50/2 mm, L = 100 cm	0.00029	2.26
2	Sawn construction timber: (i) walls	Timber frame wall	Frame: b/h = 8/20 cm (C24), e = 62.5 cm	0.048	20.16
			Sheathing: 2 × OSB plate t = 12.5 mm	0.025	16.25
	Sawn construction timber: (ii) slabs	Timber frame slab	Joists: b/h = 10/24 cm (C24), e = 31 cm	0.0774	32.52
			Sheathing: OSB plate t = 22 mm	0.022	14.30

Table A1. *Cont.*

	Product Group	Product Name	Product Description	Volume [m^3]	Mass [kg]
3	Cross-laminated timber (CLT): (i) walls	CLT wall	t = 100 mm, 3-layered	0.100	48.00
		* Reinforced concrete wall	t = 200 mm (C25/30)	0.200	480.00
			2 × Q283 reinforcement mesh + 2 × Φ12 reinforcement bars on perimeter + Φ8/20 cm stirrups (S500)	0.0020	16.00
		* Masonry wall	hollow bricks t = 29 cm	0.29	188.50
			mortar between bricks (40 litres/m^2)	0.04	72.00
			vertical reinforced concrete ties at the wall corners (b/d = 20 × 29 cm; C25/30)	0.0387	92.80
			4 × Φ12 reinforcement bars; Φ8/20 cm stirrups (S500)	0.00054	4.25
	Cross-laminated timber (CLT): (ii) slabs	CLT slab	t = 200 mm, 5-layered	0.200	96.00
		* Reinforced concrete slab	t = 200 mm (C25/30)	0.200	480.00
			2 × Q283 reinforcement mesh + 2 × Φ12 reinforcement bars on perimeter + Φ8/20 cm stirrups (S500)	0.0020	16.00
4	Formwork boards	Plywood formwork panel	t = 18 mm	0.018	9.00
		* Hollow Plastic formwork panel (PP—Polypropylene)	t = 18 mm	0.018	9.72
		* Aluminium formwork panel	t = 4 mm	0.004	10.80
		* Steel formwork panel	t = 3 mm	0.003	23.55
5	Laminated wood stock	(semi-products for windows and doors frame)	-	-	-
6	Wood composite boards	OSB board	t = 12.5 mm	0.013	8.13
		Plywood board (softwood)			6.25
		LVL board			6.38
		MDF board			8.75
		* Gypsum fibreboard			15.00
		* Cement particle board			17.50
7	Window frames profiles	Wood window frame	thermal transmittance U = 1.5–1.6 W/m^2K (average frame for 1 m^2 of window opening)	0.23	80.2
		* Aluminium window frame		-	-
		* PVC (polyvinyl chloride) window frame		-	-
8	Glue-laminated timber: (i) beams	Glue laminated timber beam	b/h = 20/40 cm (GL24h)	0.08	33.60
		* Steel beam	HEB 200 (S235)	0.0078	61.31
		* Reinforced concrete beam	b/h = 20/40 cm (C25/30)	0.08	192.00
			3 × Φ18 + 2 × Φ12 reinforcement bars; Φ8/20 cm stirrups (S500)	0.0013	10.00
	Glue-laminated timber: (ii) columns	Glue laminated timber column	b/h = 20/20 cm (GL24h)	0.04	16.80
		* Steel column	SHS 200/200/8 (S235)	0.0061	48.23
		* Reinforced concrete column	b/h = 20/40 cm (C25/30)	0.04	96.00
			4 × Φ12 reinforcement bars; Φ8/20 cm stirrups (S500)	0.0006	4.40
9	Pulp and paper	Paper cup	1 cup of maximum 250 mL hot beverage, food grade materials	-	0.009
		* Polystyrene cup		-	0.003
10	Bio-refinery products	Bio-phenol	chemicals derived from 1000 kg of birch wood	-	42.00
		Bio-propylene			20.00
		Bio-oligomers (lignin based)			64.00
		Carbohydrate pulp (raw material for bioethanol production)			653.00
		* Phenol	an equivalent quantity of chemicals to those obtained from 1000 kg of birch wood		42.00
		* Propylene			20.00
		* Oligomers			64.00
		* Carbohydrate pulp			653.00

Table A1. *Cont.*

	Product Group	Product Name	Product Description	Volume [m^3]	Mass [kg]
11	Thermal insulation	Wood wool	thermal transmittance U = 0.28–0.34 W/m^{2}K	1.0	50
		* Polystyrene foam		1.0	30
		* Stone wool		1.0	80
12	Energy	Wood heater (6 kW)	deliver 1 GJ heat	0.181	-
		Wood chips plant (6667 kW)		0.069	-
		* Natural gas mini plant (2 kW)		-	-
		* Lignite plant (industrial scale)		-	-
		* Light fuel oil boiler (10 kW)		-	-
		* Lignite briquette stove (5–15 kW)		-	-

Appendix B

Table A2. Potential CO_2e savings and expected sales revenue, calculated in six different optimisations by the Wood Processing Allocation Model for the scenario "MEDT Objectives to 2030", without restrictions on new wood processing plants.

Output	Optimisation Parameter					
	Expected Sales Revenue	Carbon Footprint of Wood Products Production	Biogenic Carbon Stock	The Carbon Footprint of the Production of Wood Products Considering the Stock of Biogenic Carbon	Co_2 savings Considering the Stock of Biogenic Carbon: Comparison of the Smallest Difference	Co_2 Savings Considering the Stock of Biogenic Carbon: Comparison of the Largest Difference
Carbon footprint of wood processing into selected products [t CO_2 e]	1,130,897	**1,082,295**	1,603,134	1,439,447	1,495,721	1,557,729
*** CO_2 savings [t CO_2e]: comparison of the smallest difference**	1,161,626	**1,307,185**	591,658	915,933	1,048,931	993,646
*** CO_2 savings [t CO_2e]: average**	4,591,656	5,099,882	4,170,518	4,679,594	**5,237,797**	5,219,098
*** CO_2 savings [t CO_2e]: comparison of the largest difference**	8,021,686	8,892,579	7,749,378	8,443,253	9,426,663	**9,444,550**
Biogenic carbon stock	−2,463,551	−2,428,515	**−3,052,017**	−2,940,476	−2,948,486	−2,976,275
**** Carbon footprint of wood processing into selected products [t CO_2e]**	−1,332,654	−1,346,220	−1,448,881	**−1,501,028**	−1,452,765	−1,418,545
**** CO_2 savings [t CO_2e]: comparison of the smallest difference**	3,625,177	3,735,700	3,643,674	3,856,410	**3,997,417**	3,969,922
**** CO_2 savings [t CO_2e]: average**	5,722,553	6,182,178	5,773,653	6,119,041	6,733,518	**6,776,828**
**** CO_2 savings [t CO_2e]: comparison of the largest difference**	10,485,236	11,321,094	10,801,394	11,383,729	12,375,149	**12,420,826**
Expected sales revenue (EUR/year)						
Model	**2,479,062,333**	1,646,829,530	1,518,191,438	1,564,852,849	1,485,594,902	1,394,124,375
C17 Paper and paper-products	846,585,131	846,585,131	846,585,131	846,585,131	846,585,131	846,585,131
C31 Furniture production	360,836,161	360,836,161	360,836,161	360,836,161	360,836,161	360,836,161
Wood construction	167,735,110	167,735,110	167,735,110	167,735,110	167,735,110	167,735,110
TOTAL: the whole sector	**3,854,218,735**	3,021,985,932	2,893,347,840	2,940,009,251	2,860,751,304	2,769,280,777
Estimation of the required investments amount to achieve optimisation	**2,951,367,000**	1,229,760,000	812,971,680	692,356,020	683,172,680	170,172,680

* Only the substitution effect considered. ** Considering the stock of biogenic carbon.

In the calculation of potential sales revenue, the model contributed results for products in primary wood processing (category C16 in the decimal classification of industrial activities) and energy production. To obtain a complete picture for expected revenues of the whole forest-based industry, statistical data were added for categories Paper and paper-products (C17), Furniture production (C31), and Wood construction (obtained from the Association of Slovene wooden prefabricated housing producers).

Table A3. Results of calculations of the Wood Processing Allocation Model for the scenario "MEDT Objectives to 2030": type and number of plants in which it would be necessary to invest, and projected value of investments, according to the type of model optimisation.

Plant/Factory Type	Optimisation Parameter					
	Expected Sales Revenue	Carbon Footprint of Wood Products Production	Biogenic Carbon Stock	The Carbon Footprint of the Production of Wood Products Considering the Stock of Biogenic Carbon	Co_2 savings Considering the Stock of Biogenic Carbon: Comparison of the Smallest Difference	Co_2 Savings Considering the Stock of Biogenic Carbon: Comparison of the Largest Difference
Sawmill plant, processing capacity 300,000 m^3/year	-	-	-	-	-	-
Sawmill plant, processing capacity 50,000 m^3/year	-	-	-	-	-	-
Cross-laminated timber (CLT) plant, processing capacity 87,000 m^3/year	1	-	1	1	-	-
Cross-laminated timber (CLT) plant, processing capacity 31,000 m^3/year	-	-	-	1	-	-
Glue-laminated timber plant, processing capacity 27,000 m^3/year	-	-	4	-	-	-
Veneer and plywood production plant, processing capacity 230,000 m^3/year	1	1	1	1	1	1
OSB board production plant, processing capacity 310,000 t/year	1	1	1	-	1	1
Pulp production plant, processing capacity 615,000 t/year	-	-	-	-	-	-
Particle board production plant, processing capacity 180,000 m^3/year	-	-	1	-	-	1
Energy production plant, combustion capacity 108,000 m^3/year	-	-	-	-	-	-
Energy production plant, combustion capacity 43,000 m^3/year	-	-	-	-	2	2
Wood wool production plant, processing capacity 50,000 t/year	-	-	-	-	-	-
Biorefinery plant, processing capacity 220,000 t/year	5	2	1	1	1	-
Fiberboard production plant, processing capacity 177,000 m^3/year	-	-	2	3	2	2
Estimation of the required investments amount to achieve optimisation [Eur]	**2,951,367,000**	**1,229,760,000**	**812,971,680**	**692,356,020**	**683,172,680**	**170,172,680**

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