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Analysis of Primary Value Chains in Slovenian Forest and Wood Bioeconomy

Analiza primarnih lanaca vrijednosti u slovenskome šumskom i drvnom biogospodarstvu

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ABSTRACT • *Green value chains are becoming increasingly important due to the current European and global strategic orientation. Wood and wood-related value chains are one of them. There are many challenges to overcome in the Slovenian forest-wood bioeconomy in order to strengthen it and make it more efficient. One of the biggest challenges is the increasing share of deciduous trees in Slovenian forests. This raises the question of how to build or strengthen forest-wood value chains with hardwood of different qualities as a basic raw material. The most important thing for the entire forest-wood bioeconomy is to have effective and functioning primary value chains in order to have a strong basis for multiplying the impact and value in the entire forest-wood value chain. The aim of this study was to analyze the primary value chains in the Slovenian forest-wood bioeconomy, with a focus on the processing of hardwood. The main research question was whether the primary value chains are equivalent for the efficient functioning of the forest wood chain, whose main raw material is hardwood. Based on an in-depth qualitative multi-criteria decision-making analysis, we can conclude that all analyzed primary value chains are very important for creating the conditions for the maximum utilization of the potential of hardwood raw materials of different quality. From the point of view of providing basic and advanced materials for further value chains in the wood sector (and related industries), these are mainly the chains P1 Sawlogs, P2 Veneer logs and P3 Wood for pulp and composites, and for other industries also the most advanced materials from the chain P4 Other industrial wood, which still require a lot of investment in research and development to reach the level of their wider (industrial) implementation. In terms of ensuring circular economy and sustainability, connecting chains C6 Residues and C7 Reclaimed wood are particularly important.*

KEYWORDS: *value chains; forest-wood chain; primary production; bioeconomy; hardwood*

SAŽETAK • *Zeleni vrijednosni lanci postaju sve važniji zbog trenutačne europske i globalne strateške orijentacije. Drvo i lanci vrijednosti vezani za drvo jedni su od njih. U slovenskome šumsko-drvnom biogospodarstvu mnogo je izazova koje treba prevladati kako bismo ga ojačali i učinili učinkovitijim. Jedan od najvećih izazova jest*

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sve veći udio listopadnog drveća u slovenskim šumama. Postavlja se pitanje kako izgraditi ili ojačati vrijednosne lance šuma – drvo listačama različite kvalitete kao osnovnom sirovinom. Za cjelokupno šumsko-drvno biogospodarstvo najvažnije je imati učinkovite i funkcionalne primarne vrijednosne lance kako bismo imali čvrstu osnovu za multipliciranje utjecaja i vrijednosti u cijelom lancu vrijednosti šuma – drvo. Cilj ove studije bio je analizirati primarne lance vrijednosti u slovenskome šumsko-drvnom biogospodarstvu, s fokusom na preradi listača. Glavno istraživačko pitanje bilo je jesu li primarni vrijednosni lanci ekvivalentni za učinkovito funkcioniranje lanca šuma – drvo, čija su glavna sirovina listače. Na temelju dubinske kvalitativne analize višekriterijskog odlučivanja možemo zaključiti da su svi analizirani primarni lanci vrijednosti vrlo važni za stvaranje uvjeta za maksimalno iskorištenje potencijala sirovinâ listača različite kvalitete. Sa stajališta opskrbe osnovnim i naprednim materijalima daljnjih lanaca vrijednosti u drvnom sektoru (i u srodnim industrijama), to su uglavnom lanci P1 – pilanski trupci, P2 – furnirski trupci i P3 – drvo za celulozu i kompozite, a za ostale su industrije također najnapredniji materijali iz lanca P4 – ostalo industrijsko drvo, za koje je još potrebno mnogo ulaganja u istraživanje i razvoj da bi dosegnuli razinu svoje šire (industrijske) primjene. U smislu osiguranja kružnoga gospodarstva i održivosti posebice su važni povezani lanci C6 – ostatci i C7 – regenerirano drvo.

KLJUČNE RIJEČI: *lanci vrijednosti; lanac šuma – drvo; primarna proizvodnja; biogospodarstvo; listače*

1 INTRODUCTION
1. UVOD

Green value chains are becoming very important due to the current European and global strategic orientations. One of the most important strategic documents supporting the transition to a green society is the "Green Deal" from 2019 (Evropski zeleni dogovor: Postati prva podnebno nevtralna celina, no date; Evropska komisija, 2019). This is a unique opportunity to strengthen green value chains, the forest-wood value chain being one of the most important. (European Organization of the Sawmill Industry (EOS), n.d.). In EU policies, there is a special emphasis on the use of wood for construction purposes, although wood currently accounts for only 3 % of all materials used. (The international wood industry in one information service, 2020).

On this basis, there are many opportunities for the development of the entire Slovenian forest-wood value chain. However, the forest-wood value chain has faced several challenges in recent decades. Increasing competition, especially in the supply of raw materials, including those based on wood and/or wood biomass, and the past loss of production infrastructure, especially in the production of veneer, wood composites and pulp, entails a high degree of dependence on international markets and uncertainty about the possible breakdown of supply chains. The functioning and ability of competitive production of primary forest-wood value chains ensures stability for more advanced wood value chains (e.g. wood construction, furniture, vehicles and ships, etc.) and other value chains (e.g. construction, chemical and textile industries, etc.). On the other hand, these chains face a variety of challenges. One of the long-term challenges of the domestic forest-wood value chain is the expected change in the structure of the domestic supply chain of forest-wood assortments, in which the share of hardwood trees will increase due to climate change, as well as the share of lower-quality assortments.

According to the Slovenian Forest Administration (ZGS), the hardwood stock in Slovenian forests is increasing and accounted for 55.7 % of the total wood stock in 2021 (in 2000 it was 51.7 %). The most frequently represented tree species in Slovenian forests is European beech (*Fagus sylvatica*) with a share of 33 % (Breznikar and Poljanec, 2023; Ščap and Triplat, 2023), which continues to increase (the share of Norway spruce (*Picea abies*) is 30 % and declining). In 2021, the volume of harvested trees in Slovenia amounted to 4.075 million m^3 (Statistični urad RS, 2023) with a 47 % share of hardwood. According to the study on the material flows of hardwood logs and sawn wood in Slovenia (Ščap and Triplat, 2023), the estimated total volume of processed hardwood sawlogs in Slovenian sawmills in 2021 was 27,000 m^3, the veneer mills processed 34,000 m^3 of hardwood logs, of which about 90 % were imported. In the reference year, 223,000 m^3 of low-grade industrial hardwood was processed by companies in the wood-based panels, mechanical pulp and chemical industries. For energy purposes, 0.997 million m^3 of total hardwood production was used in Slovenia (year 2021). Projections of hardwood potential show that in 2025 there will be similar quantities of wood on the market as in the reference year (Ščap and Triplat, 2023).

Climate change will cause a redistribution of existing forest types and a change in their tree species composition, which will also have consequences for the entire forest-wood chain (Arnič *et al.*, 2023; Breznikar and Poljanec, 2023; Gričar *et al.*, 2023). Model predictions about tree composition in the future are rather vague, but despite everything, experts agree that the ratio between conifers and deciduous trees is changing quite strongly in favor of the latter (Breznikar and Poljanec, 2023). The decline in the share of spruce in the wood stock of forests has already been observed in the last decade and is primarily the result of pronounced fluctuations in growing conditions, natural damage and bark beetle infestation. According to current forecasts on the development of climate indicators, forest production and wood properties, the following tree species have the greatest potential in Slovenia in the future: European beech (*Fagus sylvatica*), Sycamore maple (*Acer pseudoplatanus*), silver fir (*Abies alba*), European oak (*Quercus robur*, *Quercus petraea*), black locust (*Robinia pseudoaccacia*), black poplar (*Populus nigra*), black pine (*Pinus nigra*), Scots pine (*Pinus sylvetris*), Douglas fir (*Pseudotsuga menziesii*) and sweet chestnut (*Castanea sativa*) (Gričar *et al.*, 2023). In the long term, climate change is also expected to result in a higher proportion of low-grade wood, as thermophilic forest communities, which are generally less economically interesting (Breznikar and Poljanec, 2023). However, this represents a (currently still) untapped potential and is an opportunity for the development of new (innovative) ways of using such raw materials (Kropivšek and Čufar, 2015; Gornik Bučar *et al.*, 2017; Zule *et al.*, 2017).

According to the United Nations Economic Commission for Europe (UNECE) (UNECE, 2023), the consumption of hardwood in Europe is increasing, which could represent an opportunity for the activation of new and different uses of hardwood in Slovenian bioeconomy. The term bioeconomy is used to describe the broad spectrum of forest and wood products in the utilization of renewable natural resources. Bioeconomy can be defined as an economy in which the basic building blocks for materials, chemicals and energy are derived from renewable biological resources (McCormic and Niina, 2013). Another definition states that "bioeconomy is the production of renewable biological resources and the conversion of these resources and waste streams into value-added products such as food, feed, bio-based products and bioenergy" (Stegmann *et al*., 2020). In our case, we understand the bioeconomy as the integration of the sustainable production of renewable biological resources and the transformation of these resources and waste streams into value-added products. It should form an integrated, sustainable and robust bioeconomy system that connects different bioeconomy sectors, including forestry and wood processing (Juvančič *et al*., 2023).

One of the most important reasons for the inefficient utilization of hardwood is a poorly functioning forest-wood chain, which is interrupted at certain points and so the great potential of (mainly) high-quality raw materials is lost. That results in a higher consumption of other, non-environmentally friendly materials.

The insufficiently efficient functioning of the forest-wood chain, in which the main raw material is hardwood, is also confirmed by the data on the structure of hardwood production by purpose, as fuelwood traditionally dominates with more than 50 % (Ščap and Triplat, 2023; Arnič *et al.*, 2023; Kropivšek *et al.*, 2023). Research results (Marenče *et al.*, 2017; Marenče *et al.*, 2020) show that more than 60 % of the wood mass of beech trees is often not or only partially used for energy, as a large part of the wood volume often remains in the forest.

Arnič (2023) states in the latest detailed analysis, in which five scenarios for the restructuring of the forest-wood chain in Slovenia were created, that the available quantities of roundwood in Slovenia are between 1.6 and 2.4 times the current processing capacities, whereby the currently available processing capacities of veneer and saw logs from hardwood are even 3.8 to 5.4 times lower than the projected availability of roundwood. Ščap and Triplat (2023) also state that in the Slovenian market in 2021 only 30 % of the estimated available amount of low-grade hardwood was processed in the particleboard, mechanical pulp, and chemical pulp industries. We can conclude that a large part of the hardwood of different quality in Slovenia remains unused or underutilized, which also indicates inefficient functioning of the forest-wood chain.

This is also reflected in the poor performance of the individual connections in the chain, low profits and inadequate implementation of the concepts of sustainability and circular economy. The solution lies in the search for innovative products, which can be achieved through the development and introduction of modern technologies and digitalization, but above all through the development of new, even more complex value chains.

All of this requires certain investments, the introduction of a modern organization and an increase in employee skills in all forest-wood chains. By introducing digitalization (anautomation) of processes in these chains, greater efficiency and flexibility of these chains can be achieved on the one hand, and on the other a lower carbon footprint and a more people-friendly operation of the entire forest and wood chain (including social sciences and humanities (SSH) as an essential element of the activities needed to address each of the social challenges in order to increase their impact) (Directorate-General for Research and Innovation, 2020). With this aim in mind, value chains in the Slovenian forest and wood bioeconomy were analyzed, paying attention both to existing chains and to the concept of new value chains; value chains are interlinked and interdependent and do not end with the forest and wood industry, but also extend to other sectors and can have major multiplier effects on the economy (Straže *et al.*, 2023). There are differences between the individual chains, both in terms of the (current) level of development and the potential for further development. This is influenced by many factors. In previous research, a SWOT analysis (Benzaghta *et al.*, 2021) was used to strategically analyze the value chains in the Slovenian forest and wood bioeconomy, which makes it possible to formulate a strategy to build on strengths, eliminate weaknesses, exploit opportunities and avoid threats (Kropivšek *et al.*, 2023). The optimal functioning of value chains requires investments in (certain) technologies (e.g. structural timber, veneer production, wood-based composites, etc.), increasing the competencies of employees and introducing digital transformation throughout the organization. By taking advantage of the benefits in the value chains, we can very effectively exploit opportunities or reduce risks. Among the most important measures are certainly those that strengthen the functioning of the individual chains, creating effective connections between them (and outwards to other sectors). These results support key measures for the development of the wood processing industry in Slovenia (MGRT, 2022).

The aim of this study was to analyze the primary value chains in the Slovenian forest-wood bioeconomy, with a focus on the processing of hardwood. The primary value chains were analyzed and evaluated with regard to the technological, environmental, market and innovation potential as well as the social aspect. The main research question was whether the primary value chains are equivalent for the efficient operation of the forest wood chain, whose main raw material is hardwood.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

For decision-makers at the national level, it is extremely important to analyze and evaluate the individual chains in more detail from a national and economic perspective. The starting point for the assessment of value chains is the concept of value chains, which enables a systemic approach to their assessment (Wang, 2015), as well as the concept of marginal quality of the input raw material (marginal log), which determines the intended use of the wood according to its quality (Ringe and Hoover, 1987). In this way, available logs can be used to manufacture products with the highest possible added value. In previous research, SWOT analysis of value chains in the Slovenian forest and wood bioeconomy were used (Kropivšek *et al.*, 2023). One of the main limitations of the SWOT method is its inability to rank criteria and prioritization strategies (Shakoor Shahabi *et al.*, 2018), which is why it is often extended/supplemented by other methods (Kurttila *et al.*, 2000; Abdel-Basset *et al.*, 2018; Taghavifard *et al.*, 2018). A more detailed assessment requires an in-depth analysis that helps to identify the most strategic value chains and predict (propose) the actions needed to improve them. A deeper and more detailed analysis usually requires the consideration of a different (usually larger) number of criteria, not all of which are equally important. It is therefore a typical case of multi-criteria decision making (MCDM), where alternatives are evaluated against multiple, possibly conflicting, criteria (Trdin and Bohanec, 2018).The MCDM problems can generally be solved using different methods, such as the Analytic Hierarchy Process (AHP) (Saaty, 2008; Saaty and Vargas, 2012), the French acronym for Elimination and Choice Expressing Reality (ELECTRE) (Roy, 1990), the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and so on. Each of the MCDM methods has its own advantages and disadvantages or is familiar or unfamiliar to different decision makers (Omer Saracoglu, 2016). MCDM methods are widely used in the assessment of various cases (Taherdoost and Madanchian, 2023), including for agri-food supply chain performance evaluation (Bhattacharya *et al.*, 2014; Uygun and Dede, 2016; Kumar *et al.*, 2022). The essential element of these methods is to break down the decision problem into smaller sub-problems, which are later treated individually (Bohanec and Rajkovic, 1995). The evaluation/ranking process is then a process that can differ between the methods, while behind the process there are different procedures. One of the MCDM methods is also DEX, which was used in this analysis.

2.1 Qualitative value chain evaluation with DEX method
2.1. Kvalitativno vrednovanje lanca vrijednosti DEX metodom

DEX is a qualitative multi-attribute decision modeling method that integrates multi-criteria decision modeling with rule-based expert systems (Bohanec *et al.*, 2013). The main advantage of this method is that it can also be used for attributes that cannot be quantified. The evaluation is (often) based on the comparison of different alternatives at the level of a specific attribute and not on a precise evaluation of the attribute.

Like all other MCDM methods, DEX aims to evaluate and analyze a set of decision alternatives $A=\{a_1, a_2, \ldots, a_m\}$ described with a set of variables $X=\{x_1, x_2, \ldots, x_n\}$, called attributes, which represent all observed or evaluated properties of the alternatives (Bohanec *et al.*, 2017). In DEX, each attribute $x_i \in X$ has an associated qualitative value scale $D(x_i)=D_i=\{v_{i1}, v_{i2}, \ldots, v_{iki}\}$, where each v_{ij} represents some ordinary word, such as "low", "high", "acceptable", "excellent". The hierarchical topology allows decomposition of the decision problem into simpler sub-problems. In DEX, the alternatives are described with qualitative values that are taken from the scales of the corresponding input attributes in the hierarchy. The evaluation of alternatives is performed in a bottom-up way, utilizing aggregation functions defined for each aggregated attribute in the form of decision rules (Trdin and Bohanec, 2018). The bottom-up aggregation of the values of alternatives is defined in the form of decision rules, which are specified by the decision maker and are usually represented in the form of decision tables. Each aggregated attribute in the model has an associated decision table that defines how the value of that attribute is determined (aggregated) from the values of its immediate descendants in the hierarchy. Within the decision tables for the purpose of aggregation, the decision maker has to define an aggregation function (f_y):

$$f_y: D_1 \times D_2 \times \cdots \times D_r \rightarrow D_y$$

In DEX, the aggregation function $y=f_y(x_1, x_2, \ldots, x_r)$ is defined with a set of decision rules of the form

$$if\ x_1=v_1\ and\ x_2=v_2\ and\ \ldots\ and\ x_r=v_r\ then\ y=v_y.$$

Here, $v_i \in D_i$ and $v_y \in D_y$.

In principle, any number of decision rules can be defined by the decision maker for each aggregate attribute. However, the decision maker is encouraged to define as many rules so that the decision space $D_1 \times D_2 \times \cdots \times D_r$ is covered as completely as possible (Bohanec *et al.*, 2017). The evaluation of alternatives is then as a straightforward bottom-up aggregation procedure. The method DEX is implemented as a computer program called DEXi that supports both the development of DEX models and their application for the evaluation and advanced analysis of decision alternatives (Bohanec *et al.*, 2013, 2017).

In our research, for the evaluation of value chains in the bioeconomy, first the value chains were listed as alternatives and a list of evaluation variables with measurement scale and description was created; then, utility functions were defined for each aggregate attribute in the form of decision rules; and finally, each value chain was evaluated bottom-up as an alternative in the decision-making process. The assessment was carried out by a group of three experts from different fields (economics, material science and technology, all related to wood), each of whom gave an individual assessment. The assessments were then compared by calculating the average value and standard deviation to identify the attributes within a single value chain with the greatest differences between the assessors. These attributes were then discussed in a joint meeting of evaluators to determine the final score. After calculating each individual value chain using the DEXi software, the final score was determined. Based on the final "what-if" analysis of the alternatives, where different scenarios were considered, the final discussion was held.

2.2 Value chains
2.2. Lanci vrijednosti

In the Slovenian forest and wood bioeconomy, five primary (P1...P5) and two connecting (C6...C7) value chains were identified based on the quality classes of hardwood as input material (Straže *et al.*, 2023): P1 *Sawlogs*, P2 *Veneer logs*, P3 *Wood for pulp and composites*, P4 *Other industrial roundwood* (for chemical processing – biorefinery), P5 *Fuelwood* (for energy use), C6 *Residues* and C7 *Reclaimed wood*. The chains are intertwined, and the (semi-)products and residues that arise within the chains can be the beginning of other chains or be included in one of the phases. The results of the primary value chains are outputs that are destined for further processing into higher value-added products, mainly in the wood industry, but also in other sectors (e.g. construction, chemical and food industries, paper production, etc.). The connecting chains (C6 *Residues* and C7 *Reclaimed wood*) ensure the circular economy, as they do not obtain their resources directly from nature. Instead, they are based on the residues from other chains and supply the primary chains with their outputs.

2.3 List of evaluation variables
2.3. Popis varijabli za evaluaciju

When evaluating chains, various criteria can and have to be considered (Hurm*ekoski et al.*, 2018): the technology readiness level (TRL), feasibility, quantitative potential, availability of resources, market interest, cost efficiency and sustainability. Based on the literature and the SWOT analysis of value chains in the Slovenian bioeconomy (Kropivšek *et al.*, 2023), a comprehensive tree of evaluation variables was created (Figure 1) with 19 different variables. According to the DEX method, the variables were divided into five groups to assess the technological, environmental, market and innovation potentials as well as the social aspects.

Each of the evaluation variables for this tree was then aligned with the measurement scale and a short description (Table 1).

Using measurement scales related to a specific attribute, utility functions were first defined for each aggregated attribute in the form of decision rules. In the next phase, each value chain was evaluated bottom-up as an alternative in the decision-making process.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The final evaluation of the value chain is summarized in Figure 2 and is fully in line with previous research (see: Kropivšek *et al.*, 2023), as it identifies chains P1 *Sawlogs* and P3 *Wood for pulp and composites* as excellent and very perspective chains, while others received lower final grades.

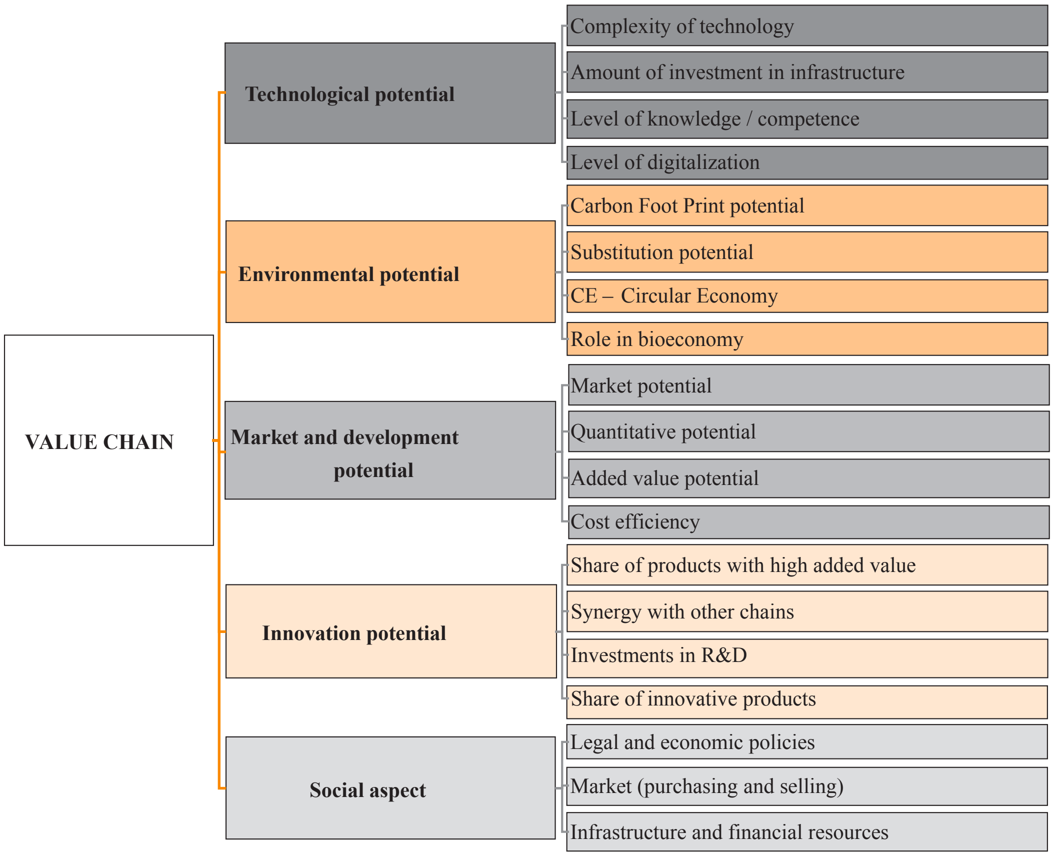

Figure 1 Tree of evaluation variables (attributes)
Slika 1. Stablo varijabli (značajki) za evaluaciju

The detailed results of the DEX analysis (Table 2) show a great environmental and development potential of the chain P1 *Sawlogs*, which currently operates in Slovenia mainly at a basic level and in some cases at a more technologically sophisticated level. Currently, the use of hardwood in timber construction is associated with some challenges (e.g. standardization of structural hardwood, use of different tree species for certain products, etc.), but the same (similar) challenges also exist abroad. Knowing these challenges and, above all, solving them as quickly as possible, can also give this chain a competitive advantage on an international level.

In the case of sufficient investment in technology, infrastructure and improving the skills of employees, the chain P2 *Veneer logs*, which is currently (almost completely) non-functioning in Slovenia, is recognized as a very perspective chain (Kropivšek *et al.*, 2023), which could produce innovative products with very high added value (Gornik Bučar *et al.*, 2017). If this chain fails, the marginal log quality criterion, which is the fundamental criterion in the design of value chains, will not be met, as the raw material for this chain is of the highest quality.

The operation of the chain P3 *Wood for pulp and composites*, which is very limited in the current situation, requires large investments in infrastructure and in the competence of employees, while the chain has an extremely great potential for the production of innovative products. These products supply other forest-wood and related chains (e.g. timber construction, furniture manufacturing, ship and vehicle manufacturing, etc.), have great potential to replace other materials (Gornik Bučar *et al.*, 2017) and show great synergy effects.

The chain P4 *Other industrial wood* is supplied with raw material that is suitable for chemical processing or biorefineries. It has great potential for innovative products and for the substitution of other materials, but requires high investment in technology, additional expertise and investment in research and development. We assume that with appropriate social aspects (which we currently do not consider to be supportive), reasonable cost efficiency could be achieved in a relatively short time, which would have a positive impact on the entire chain. The chain P5 *Fuelwood* is a chain where the raw material is of the poorest quality and the end products are intended for energy use (mainly as firewood and/or pellets). Even though wood is a natural material, and the energy use of wood is recognized as CO_2 neutral, it should be emphasized that the use of wood as raw material for energy purposes means the shortest possible cycle, so the chain is also the shortest,

Table 1 List of evaluation variables with measurement scale and description
Tablica 1. Popis varijabli za procjenu s ocjenama i opisom

Aggregate attributes *Zbirne značajke*		Measurement scale *Ocjene*	Description / *Opis*
	Input attributes (1st level) *Ulazne značajke (1. razina)*		
Value chain		Poor; Good; Very good; Excellent	Final evaluation of a value chain
Technological potential		1…limited; 2…medium; 3…great	What is the status of technological potential?
	Complexity of technology	1…low; 2…medium; 3…high	What complexity of (production) technology is required to operate the chain?
	Amount of investment in infrastructure	3… medium; 2... high; 1… very high	What is the level of investment in the technology at national level given the current situation?
	Level of knowledge / competence	3...same; 2...a little higher; 1... much higher	What level of knowledge is required to operate the chain given the current state of the industry/economy?
	Level of digitalization	1…low; 2…medium; 3…high	What is the potential/reasonable level of digitalization of the chain (smart chain, smart factory, etc.)?
Environmental potential		1…limited; 2…medium; 3…great	What is the status of environmental potential?
	Carbon Footprint potential	1…limited; 2…medium; 3…great	What is the potential for environmental protection?
	Substitution potential	1…limited; 2…medium; 3…great	What is the potential to replace other materials?
	CE – Circular Economy	1…small; 2…medium; 3…great	To what extent does the chain/product comply with modern EU and global guidelines (development of rural areas, settlements, cities, etc.)?
	Role in bioeconomy	1…small; 2…medium; 3…large	What significance does the chain have for the bioeconomy in the broader sense (incl. SSH)?
Market and development potential		1…limited; 2…medium; 3…great	What is the status of market and development potential?
	Market potential	1…limited; 2…medium; 3…great	Global and local potential of the chain/products in terms of market size, market attractiveness, opportunities for market expansion, competition, and trends.
	Quantitative potential	1…limited; 2…medium; 3…great	What is the potential given the availability of the raw material in suitable quality – marginal roundwood?
	Added value potential	1…limited; 2…medium; 3…great	How high is the value creation potential for the products depending on the raw material used?
	Cost efficiency	1…low; 2…medium; 3…high	What is the level of cost efficiency?
Innovation potential		1…limited; 2…medium; 3…great	What is the current situation regarding innovation potential?
	Share of products with high added value	1…low; 2…medium; 3…high	How high is the proportion of products with higher added value due to investments in the chain?
	Synergy with other chains	1…low; 2…medium; 3…high	What synergies or linkages are there with other chains, industries, products?
	Investments in R&D	3…low; 2…medium; 1…high	What investments in R&D can be expected in order to achieve the chain development potential?
	Share of innovative products	1…low; 2…medium; 3…high	How high is the proportion of innovative products in the next 5 years (current level: TRL 4 and higher)?
Social aspect		1…not supportive; 2…neither-nor; 3…supportive	What influence do external and social factors have on the chain?
	Legal and economic policies	1…not supportive; 2…neither-nor; 3…supportive	Industrial strategy; digital society development; current and future economic growth; legal opportunities
	Market (purchasing and selling)	1…not supportive; 2…neither-nor; 3…supportive	Purchasing power in the market; environmental awareness of the market and customers; competition for products with high added value
	Infrastructure and financial resources	1…not supportive; 2…neither-nor; 3…supportive	Infrastructure development, supportive environment; government incentives (e.g. Green Deal...); availability of finance and investments; state aid for investment in R&D

as CO_2 is released much faster than when it is embedded in wood products. The chain has no great technological and innovative potential (except in the case of advanced biofuel production) and the added value of the products (especially pellets) is very sensitive to social aspects. The chain P5 *Fuelwood* has a very limited

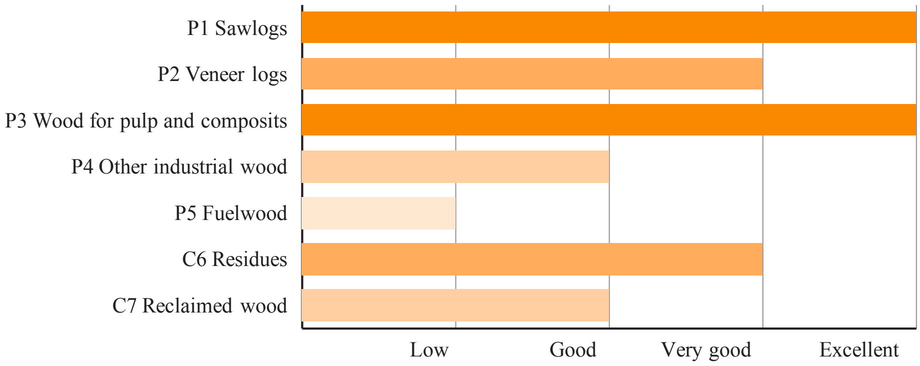

Figure 2 Final evaluation of alternatives (primary value chains)
Slika 2. Konačna ocjena alternativâ (primarni lanci vrijednosti)

potential for the introduction of the Industry 4.0 concept. There is currently a quantitative potential that can or will be fully exploited in the near future. From a sustainability perspective, chain P5 *Fuelwood* has no scope for expansion without interfering with the concept of marginal log quality. Furthermore, if the chains P4 *Other industrial wood* and P3 *Wood for pulp and composites* were to operate efficiently, the scope for the chain P5 *Fuelwood* would even be reduced in the future.

The connecting chains C6 *Residues* and C7 *Reclaimed wood* are not primary chains, but they are extremely important chains in the concept of the circular economy and sustainability. If the outputs of these chains are inputs for the chains P3 *Wood for pulp and composites* and P4 *Other industrial wood*, we also follow the concept of cascading use, so both chains are very promising and important for the forest-wood bioeconomy. However, if the outputs of the connecting chains are (mostly) inputs for chain P5 *Fuelwood*, the perspective and circularity of these chains is severely limited. The chains C6 *Residues* and C7 *Reclaimed wood* can otherwise be operated as fully separated chains, partially or fully connected, as they face (at least on a simple technological level) similar challenges (e.g. dispersion of input, collection and sorting logistics, etc.); on a more technologically demanding level, the chain C7 *Reclaimed wood* requires relatively large investments and new skills, while at the same time showing potential for innovation and substitution (Mehr *et al.*, 2018) and positive environmental impact. The operation of the chain C7 *Reclaimed wood* is also very sensitive to social aspects.

4 CONCLUSIONS
4. ZAKLJUČAK

It can be concluded that all primary value chains in the Slovenian forest and wood bioeconomy are very important for creating conditions for the maximum utilization of the potential of hardwood raw materials. From the point of view of providing basic and advanced materials for further value chains in the wood sector (and related industries), these are mainly the chains P1 *Sawlogs*, P2 *Veneer logs* and P3 *Wood for pulp and composites*, and for other industries also the most advanced materials from the chain P4 *Other industrial wood*, which still require a lot of investment in research and development to reach the level of their wider (industrial) implementation. In terms of ensuring circularity and sustainability, connecting chains C6 *Residues* and C7 *Reclaimed wood* are particularly important. To exploit their innovation and substitution potential, it is necessary to invest in development, research and employee knowledge.

However, due to the complexity of the forest-wood chain, we cannot choose the chain according to the "best option" principle, because for an optimal functioning of the entire forest-wood value chain, whose main raw material is hardwood, all primary chains are crucial (by analogy with (Falcone *et al.*, 2020), but they are not equivalent for the efficient functioning of the forest wood chain, which is the answer to our main research question.

For further research, we suggest extending the focus to the entire forest-wood chain, i.e. including the production of finished wood products (timber construction, furniture, vessels and other groups). When analyzing the chain, it would be useful to include all tree species, i.e. also conifers, which would provide a comprehensive picture of the functioning of the entire forest wood chain. In any case, it would be necessary to carry out an even more thorough analysis of the other chains linked to the wood chain and to investigate how they influence each other. We specifically refer to wood in construction, which is also recognized at the European level as a very perspective industry. Therefore, it is thoroughly researched, resulting in many ideas for improving the state of traditional wood chains (e.g. the European Basajaun project, which explores the possibilities of increasing the use of wood in construction (Cordis, 2023; Romih and Kropivšek, 2023). It is also necessary to network and collaborate with other forest

Table 2 Final evaluation of alternatives – detailed results
Tablica 2. Konačna ocjena alternativa – detaljni rezultati

Attributes *Značajke*	***P1*** Sawlogs *Pilanski trupci*	***P2*** Veneer logs *Furnirski trupci*	***P3*** Wood for pulp and composites *Drvo za celulozu i kompozite*	***P4*** Other industrial roundwood *Ostala industrijska oblovina*	***P5*** Fuelwood *Ogrjevno drvo*	***C6*** Residues *Ostatci*	***C7*** Reclaimed wood *Regener-irano drvo*
Value chain	**Excellent**	**Very Good**	**Excellent**	**Good**	**Poor**	**Very Good**	**Good**
Technological potential	**Medium**	**Medium**	**Medium**	**Medium**	**Limited**	**Great**	**Medium**
Complexity of technology	Medium	High	High	High	Low	Medium	Medium
Amount of investment in infrastructure	High	High	Very High	Very High	Medium	Medium	High
Level of knowledge / competence	Same	A little Higher	A little Higher	Much Higher	Much Higher	Same	A little Higher
Level of digitaliza-tion	Medium	High	High	High	Low	High	Medium
Environmental potential	**Great**	**Medium**	**Great**	**Great**	**Limited**	**Great**	**Great**
Carbon Footprint potential	Medium	Medium	Medium	Medium	**Limited**	**Great**	Medium
Substitution potential	**Great**	**Great**	**Great**	**Great**	Medium	Medium	Medium
CE – Circular Economy	**Great**	Medium	**Great**	Medium	**Small**	Medium	**Great**
Role in bioecono-my	Medium	Medium	Large	Large	**Small**	Large	Large
Market and development potential	**Great**	**Great**	**Great**	**Medium**	**Limited**	**Medium**	**Medium**
Market potential	**Great**	**Great**	**Great**	**Great**	Medium	Medium	Medium
Quantitative potential	**Great**	Medium	**Great**	**Great**	**Great**	**Great**	Medium
Added value potential	Medium	**Great**	**Great**	**Great**	**Limited**	Medium	Great
Cost efficiency	High	Medium	Medium	Low	Medium	High	Medium
Innovation potential	Medium	Medium	Medium	**Great**	**Limited**	Medium	**Limited**
Share of products with high added value	Medium	Medium	High	High	Low	Low	Low
Synergy with other chains	Medium	High	High	High	Low	High	High
Investments in R&D	Low	Medium	High	Medium	Low	Low	High
Share of innovative products	Medium	High	High	High	Low	Medium	Low
Social aspect	**Supportive**	**Supportive**	**Supportive**	**Not Supportive**	Neither-nor Supportive	Neither-nor Supportive	Neither-nor Supportive
Legal and econom-ic policies	Supportive	Supportive	Supportive	Neither-nor Supportive	Neither-nor Supportive	Supportive	Neither-nor Supportive
Market (purchasing and selling)	Supportive	Supportive	Supportive	Neither-nor Supportive	Neither-nor Supportive	Neither-nor Supportive	Not Supportive
Infrastructure and financial resources	Not Supportive	Not Supportive	Neither-nor Supportive	Not Supportive	Neither-nor Supportive	Not Supportive	Neither-nor Supportive

and wood chains in the region that are facing similar climatic (environmental) challenges and are looking for optimal solutions (following the example of the sustainable Mediterranean agri-food value chain (PRIMA, 2023).

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