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CATWOOD – REVERSE LOGISTICS PROCESS MODEL FOR QUANTITATIVE ASSESSMENT OF RECOVERED WOOD MANAGEMENT

ABSTRACT

Modern environmental and economic challenges in waste management require transition from linear to circular economic flow. In practice, this entails considerable challenges that include the change of material circle flux, the application of mathematical modelling and the use of life cycle thinking – also in the field of recovered wood (RW). To this end, the reverse logistics process model CATWOOD (CAscade Treatment of WOOD) with mechanistic modelling for detailed planning of the RW reverse flow with regular collection, innovative (cascade) sorting based on RW quality and environmentally sound recovery has been designed. As a decision support, the quantitative methods of life-cycle assessment (LCA) and societal life-cycle costing (SLCC) have been incorporated into the CATWOOD, which can choose among a few alternative scenarios. A case study has been performed in the Posavje region in Slovenia, which has discovered that reverse logistics scenarios for reuse are environmentally friendlier than those for recycling or energy recovery, but also more costly, mainly because of extensive manual labour needed and less heavy technology involved in sorting and recovery processes. Sensitivity analysis has exposed that modifying the values of the input parameters may change the final LCA and SLCC results in scenarios observed.

KEYWORDS

reverse logistics; transportation; mechanistic modelling; LCA; societal LCC; recovered wood.

1. INTRODUCTION

Due to the uncertain political and economic situation, limited access and increased demand, there is a threat of shortage of natural resources in the near future – including wood [1]. In the middle of the 1990s, Sirkin and ten Houten [2] already presented a system for cascading, seeking to sequentially prolong the lifespan of different discarded products, based on material quality and utilisation over time; recovered wood (RW), consisting of industrial residues, packaging, construction and demolition (C&D) and municipal wood waste as well. In the 21st century, cascading has been followed by legislative support as implementation of five-step hierarchy of waste management options [3], efficient circularity with the highest targets for municipal RW recycle and reuse [4–5] recommendations, and the best applications of cascading [6]. Cascading has been gaining significant attention among academics in recent reviews [7–10] and original studies. The latest and most encouraging findings are as follows: (1) because wood stores carbon and mitigates climate changes, it is better to save it than use it as a fuel [11], (2) remarkable share of wooden packages, furniture, C&D wood can be reused or recycled [12–15], (3) particle board using RW recyclates shows sufficient mechanical properties and fulfils the stressed exposures [16].

In parallel with the development of cascading use of wood, the idea of reverse logistics (RL) was evolved, mainly due to increasing legislative incentives, environmental awareness and cost reductions [17, 18]. RL is the continuous inverse logistic process through which discarded products transition from the consumer back to the sorting and recovery entities for possible reuse, recycling, remanufacturing or disposal [19, 20]. Thus, the implementation of the RW cascading philosophy requires contemporary technology and concepts for effective process management in the RL, e.g. regular collection and transportation, sorting based on resource quality, environmentally sound recovery, which ensures resource returns, accelerate and close life cycle of the RW. Nevertheless, this is related to different environmental and economic concerns. Therefore, ecological and economical impacts in RL in previous research studies have been planned and optimized employing different quantitative methods, mostly operation research (OR), life cycle assessment (LCA) and life cycle costing (LCC) were used as decision support [see e.g. 21, 22].

In order to provide detailed insight into the RL and RW management, we have reviewed and classified the most important 19 articles according to the quantitative methodology applied, the RL process employed and the technical aspect of the transportation system involved. The literature review reveals that mainly OR, LCA and LCC have been used in this field. OR is an analytical method of problem-solving and decision-making where problems are broken down into basic components and then solved in defined steps by mathematical analysis. The authors applied mathematical optimisation, such as mixed-integer linear programming (MILP) [19, 22], MILP under uncertainty [23], multi-objective MILP [24], multi-objective stochastic model [25], mostly in the RL network designing or mechanistic modelling for decision making [26]. For instance, the multi-objective MILP has been used to minimise the costs and greenhouse gas emissions of cascaded utilisation of wood in Lower Saxony in Germany [24]. Mechanistic modelling has been applied in the sorting and manipulation process of the RW for efficiently planning of cascading in Slovenia [26]. In several papers OR was also combined with LCA [22, 24]. LCA is a scientific tool for the methodical and objective evaluation of all the essential influences that a product or a service has on the environment within its life cycle [see e.g. 27]. It is devoted to the comparison of various products with several sequential steps: (1) goal and scope definition, (2) life cycle inventory analysis (LCI), (3) life cycle impact assessment (LCIA) and (4) interpretation, compliant with the ISO 14040/44 standards [28, 29]. In the field of RW, it was applied in many studies [30–40]. Even though LCA is a technique designed to study environmental impacts, it can be very well connected to the LCC [41, 42]. The LCC involves all costs associated with the life cycle of a product or service that are directly covered by one or more actors [43] and can follow the same four steps as the LCA with the aim of giving decision support. The literature distinguishes three LCC approaches, namely conventional LCC (CLCC), environmental LCC (ELCC), and societal LCC (SLCC) [44]. CLCCs usually have a single actor perspective and assess decisions over financing high initial capital costs [45]. The ELCC, aiming to link costs with the LCA, can involve a multiple stakeholders' outlook and externalities, too [46]. The SLCC can also be connected to the LCA, including the actor's costs and externalities, society's larger welfare impacts, e.g. accidents, air pollution, noise etc. due to individual or organisational effects on other participants [47]. When researchers wants to show higher level of technical precision and detailed knowledge about specific cost item and have access to extensive data, they can apply the bottom-up approach to calculate the LCC [48]. On this field, material flow analysis, the LCA and ELCC were used to evaluate the management of the C&D RW in Finland [41]. Joint analysis of the LCA and the ELCC of a C&D RW recycling concept (glued laminated timber-glulam) to a conventional treatment option (incineration in a combined heat and power plant) was applied in Germany [42].

The literature review also reveals that a wide range of the RL processes has been used in the RW management. The input RW material in the RL processes originates from different sources, e.g. industry [22], packaging [26], C&D [26, 38, 40, 41] and municipal RW [26, 30]. Among the RL processes, transportation is one of the most important because of its network connectivity. It starts with collection, e.g. at households [31] or industry [23, 25], and continues with transition to recycling or recovery centres [e.g. 22, 24, 41, 42]. In the sorting process, the RW is sorted into three [23, 25] or four different classes according to contamination [22, 24, 26, 36, 37]. Studies seldom divide the RW by resource quality (e.g. condition; e.g. dry/wet, (un)damaged) [26], which ensures reuse and high quality recycling. The recovery process provides sundry outputs, mostly for recycling [e.g. 22–25, 30, 32–34, 37] followed by energy generation [e.g. 23, 31, 34, 36, 38, 42], and rarely for reuse [19, 26, 40].

Finally, among the authors examined, there are different technical characteristics, including technology and inventory in the RW transport management applied. In the transition of the RW, two modes of transportation have been found, namely road [23, 25, 30, 35, 36] or road and rail [22, 24]. Road vehicles applied are vans, forklifts [30] and trucks [e.g. 22], all largely use diesel fuel [e.g. 30-31]. The capacity of the RW transportation with road vehicles is defined as (1) the capacity of the vehicle, e.g. 16 tonnes [24, 35], 12–24 tonnes [24], 32 tonnes [35]; (2) the capacity of the container, e.g. 20 tonnes [23, 25] and 40 tonnes [25] or (3) the average load, e.g. 2.5 and 17 tonnes [30]. Fuel consumption of the forklift is assigned as 3.2 l/t and trucks as 0.02 l/tonne-km, 0.24 l/tonne-km [30] or 36 l/100 km [36]. Therefore, transport models also apply assumptions or mathematical formulas to calculate fuel consumption or emission generation based on the weight of transported cargo [e.g. 25, 31, 36]. In the results, the sensitivity analysis of fuel consumption of trucks is also involved with increased or reduced fuel consumption to reveal the changes of the overall RL network emissions [36]. While the transport distances of the RW holders to the collection centres are estimated shorter, e.g. 2 km [e.g. 31], the transport to recovery plants are longer, e.g. ≤ 100 km [23, 30, 31], ≤150 km [22] or 160 km [36]. Train distances are usually larger than road distances, e.g. >150 km [22]. Data regarding the environmental assessment is usually obtained from Ecoinvent [22, 24, 30, 31, 36], Defra [36] or ADEME and MELCC [25] LCI databases. Emissions in the studies often comprise both fuel production and fuel consumption [e.g. 31]. Transportation cost data is obtained from scientific data, depending on mode of transport, travelled distances and weight of cargo [24]. The results of the greenhouse gas emission of the transport process in all RL network is very disparate: ≤ 10% [24, 30, 35], 18% [42], 18–24% [31], 36–43% [24] and >75% [22]. The transportation cost of the RW has been lower in comparison to fresh wood due to higher moisture content in the latter [22]. Nevertheless, the results of the calculated costs of the transport process in all RL network is also very contrasting, ranging from 8% [24], 30% [41] to >90% [22].

Based on literature review, we expose the following research gaps. Firstly, while several previous studies on the RW applied the quantitative methods MILP, LCA and logistics costs [22, 24], or joined the LCA with the LCC [41, 42], the combination of the OR, LCA and LCC has not been integrated and investigated before. Moreover, the costs and emissions in the transport process in the studies observed are very contrasting. Data were obtained principally from scientific and generic LCI databases (e.g. Ecoinvent) and were not calculated based on time and fuel consumption. Thus, detailed mechanistic and bottom-up methods are not included nor are externalities involved. This is an important field because time consumption in relation to vehicle driving, loading or idling or in relation to manual labour with mechanistic modelling can give more accurate results [see e.g. 26, 49, 50] and allows easier decision-making and waste management planning [51]. Next, the technology cost is not presented nor is the curb side collection system included. Finally, the RW quality (condition) and reuse as the top priority behind waste prevention in the waste hierarchy is included only in rare occasions.

Therefore, the objectives and novelty of this research are: (1) combining quantitative methods OR, LCA and societal LCC (SLCC) and illustrating the decision-making process, (2) selecting scenarios, RL technology and RL processes involved, (3) implementing mechanistic modelling with main and support sub models in the LCI to obtain detailed time, fuel and electricity consumption, and distance travelled, (4) performing a case study of the Posavje Region.

2. METHODS

2.1 Development and application of the CATWOOD model

For this research, a computer-based mathematical RL process model CATWOOD (CAscade Treatment of WOOD) in Microsoft Office Excel ® spreadsheet has been built. Since modelling assumes that external constraints and internal relations are very well known, the type of the model was deterministic in a mechanistic way. This means that all natural phenomena and mechanisms are illustrated in detail. A computer-based model has been used to calculate environmental (LCA) and economical (LCC) parameters in the management of the RW. While modelling with the LCA has been carried out using ISO 14040/44 standards [28, 29], modelling with LCC has been accomplished according to the steps proposed by SETAC [46].

The basis for obtaining the results has been the use of several tools: (1) LCA, (2) internal LCC, (3) external LCC. While the internal LCC identifies costs of the RL actors, the external LCC characterises externalities. For modelling purposes in the LCI phase of the LCA, detailed sub-models for the RL processes that provide the LCA and internal LCC sources for input data have been built. Detailed sub-models in the LCA serve as a mechanistic use of the tool. Hereinafter of the assessment, the results of the LCI phase in the LCA model provide a data source for the external LCC, the first source

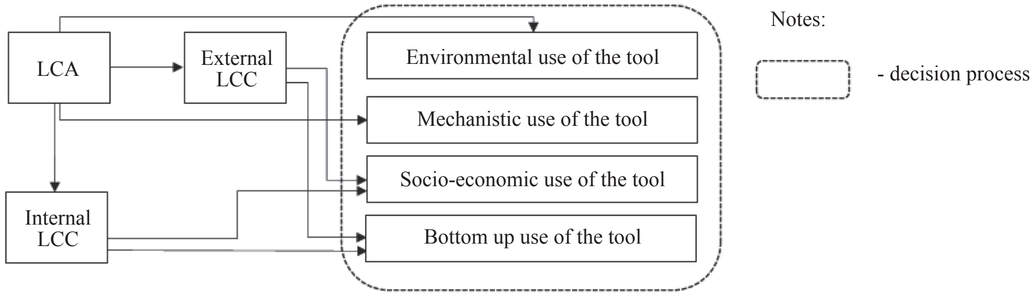

Figure 1 – Mode and types of tools used to support the decision-making process in CATWOOD model

of results in the decision-making process of the socio-economic use of the tool and the internal LCC as another source. In this case, internal and external costs have been summed and implemented in the SLCC. Both provide bottom-up use of the tool in the decision-making process. LCA modelling represents the environmental use of the tool (*Figure 1*).

2.2 Modelling with LCA

Goal and scope definition

CATWOOD comprises the following RL processes: (1) collection and transportation (C&T); (2) sorting and manipulation (S&M), (3) transition 1 (T1), (4) recovery (R) and (5) transition 2 (T2), all illustrated in *Figure 2*. These processes are included within the system boundaries. New utilisation of the RW by the end-users and production of wood-based panels or energy has been out of the scope of this research. Through RL processes four different scenarios of RW management were studied, specifically: (1) preparation for the reuse for the same purpose (PRSM), (2) preparation for the reuse for another purpose (PRAP), (3) processing of wood chips for recycling (PWCR), (4) processing of wood chips for incineration (PWCI) (*Figure 2*). The material used is clean or contaminated RW from packaging (e.g. boxes, pallets) and municipal waste (e.g. furniture). The functional unit (FU) is defined as the amount of the RW, which is allocated for each of the four scenarios in the selected region for a period of one year (tonnes per year).

Life cycle inventory

Description and calculation of the mechanistic sub-models in the CATWOOD model. In all of the processes of CATWOOD, a detailed approach to the sub models has been taken. Each process thus includes at least one or two sub-models of the RW. The total number of sub-models is 11, consisting of the main and support part if necessary. While the main sub-model represents the characteristics of the individual process (e.g. collection, transportation,

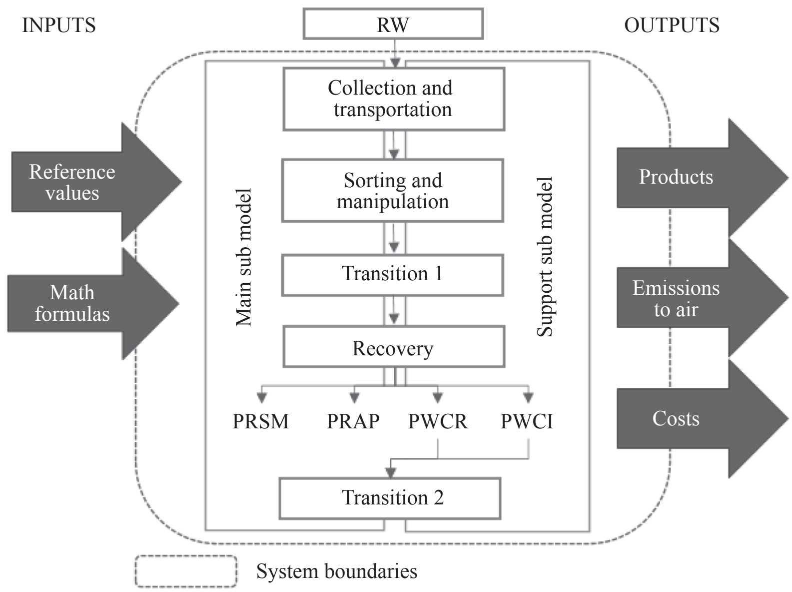

Figure 2 – Illustration of sub models and scenarios in the CATWOOD RL process model

category inspection, disassembly, etc.), the support sub-model concerns the machine manipulation, where needed. The inputs in sub-models are reference values and math formulas. The total number of inputs is 321. The calculation of multiple input parameters provide mid outputs of main and support sub models. The sum of one or both parts gives the sum of the output for time $\sum T_{ps}$, fuel $\sum F_{ps}$ and electricity consumption $\sum E_{ps}$, and distance traveled $\sum D_{ps}$, as presented in *Equations 1–4*.

$$\sum T_{ps} = \sum T_{TMSM} + \sum T_{TSS} \quad (1)$$

where:

p – processes (C&T, S&M, T1, R, T2)
s – scenarios (PRSM, PRAP, PWCR, PWCI)
TMSM – time consumption in the main sub-model (Collection centre=T_{CC}, Transportation=T_T, Collection=T_C, Loading=T_L, Fuelling=T_F, Maintenance=T_M, Lunches and breaks=T_{LB}, Category of RW=T_{cat}, Quantity of RW=T_Q, Manual manipulations=T_{man}, Disposal in containers=T_{TD}, Disassembly=T_D, Transition=T_{Tr}, Recovery centre=T_{RC}, Production centre=T_{PC}, Cleaning and maintenance=T_{CM}, Cleaning, sawing, maintenance=T_{CSM}, Loading, shredding, sowing=T_{LSS})
TSS– time consumption in support sub model (Machine manipulation=TM_{MM}, Fuelling=TM_F, Maintenance=TM_M, Lunches and breaks=TM_{LB})

$$\sum F_{ps} = \sum F_{FMSM} + \sum F_{FSS} \quad (2)$$

where:

FMSM – fuel consumption in the main sub-model (Transportation=F_T, Collection centre=F_{CC}, Collection=F_C, Between stops=F_{BS}, Transition=F_{Tr}, Recovery centre=F_{RC}, Production centre=F_{PC}, Loading=F_L, Shredding=F_{Sd}, Sowing=F_S)
FSS – fuel consumption in the supporting sub-model (Machine manipulation=FM_{MM})

$$\sum E_{ps} = \sum E_{EMSM} \quad (3)$$

where:

EMSM – electricity consumption in the main sub-model (Electricity consumption for cleaning and maintenance=E_{CM}, Electricity consumption for cleaning, sowing and maintenance=E_{CSM})

$$\sum D_{ps} = \sum D_{DMSM} \quad (4)$$

where:

DMSM– distance driven in the main sub-model (Distance driven for collection=D_C, Distance driven for transportation=*DT*, Distance driven for transition=D_{Tr})

All of the mid outputs along with the RL technology (3-axle hiab, diesel, 460 HP; roller container, 30–40 m^3; 3-axle mobile shredder, diesel, 450 kW; drum screen, diesel, 37 kW; 2-axle wheel loader, diesel, 137 kW, bucket capacity 6 m^3; manual work with 2 workers; 3-axle hook loader, diesel, 460 HP; 2-axle roll-off trailer; electricity) applied was exactly presented in each process in (b) section. Outputs from sub models provide data in the LCI phase and serve for a detailed calculation of environmental, internal and external LCC impacts. This gives the final outputs from the CATWOOD model such as products, emissions into air and costs (*Figure 2*).

The reference values that were used to build sub models and calculations were derived from scientific literature, e.g. [31] (e.g. waste density), [52] (e.g. speed travel, fuel consumption); national statistics, e.g. Statistical Office of the Republic of Slovenia (e.g. waste quantity, number of residents, number of buildings); online data, e.g. Google Maps (e.g. distances); interview with distributers, e.g. Eko Lux (container capacity), Volvo Trucks (e.g. tank capacity); own measurements (e.g. time consumptions for cleanings, fuelling, waiting in collection/recovery centre), estimations (e.g. participation rate); national legislation e.g. domestic Employment Relationships Act (e.g. number of working hours).

RL processes in the CATWOOD model. C&T is carried out by hiab and 30 m^3 roller container which starts at the collection centre garage, from where it is transported to the collection area, where the RW is collected in the curb side system and when filled, it is transported back to the collection centre to the RW dispose. Curb side collection is today a very common strategy to collect recyclables, e.g. plastic, paper, municipal solid waste in the urban areas. Transport by the RW holders to the collection centres is not in scope of this study. The C&T process contains one sub-model for all scenarios. It is similar to [49], including time consumption (T_{CC}, T_T, T_C, T_L, T_{LB}), but upgraded, as it has been suggested in recently reviewed research on technical assumptions in collection and transportation processes [50], incorporating also T_F, T_M. C&T also includes mid outputs for fuel consumption (F_T, F_{CC}, F_C, F_{BS}) and distance travel (D_C, D_T).

The purpose of the S&M process, which is performed at the collection centre, is to achieve the highest levels of the RW that takes into account both the grade of chemical contamination and resource quality. This has been investigated in detail earlier [26] and this process is based on this work. Therefore, we planned for the cascade sorting of the RW to follow the next successive steps: (1) primary visual quality check (RW is disassembled or not); (2) classification according to chemical contamination (CC) (AI–AIV) [53]; (3) secondary visual quality check (quality ranking, QRi–QRiv): QRi=excellently preserved RW, dry, undamaged and wholly useful, with or without CC (AI–AIV); QRii=well preserved RW, only partially damaged, dry and requires minor repairs, with or without CC (AI–AIV); QRiii=averagely preserved RW, wet or dry, less usable for reuse and with minimal CC (AI–AII); QRiv=poorly preserved RW, wet, very damaged, unusable for reuse, with or without CC (AI–AIV). S&M process contains all four scenarios in the five sub-models, using both the main and supporting model. All scenarios in the main sub-model include a number of similar mid outputs in time consumption (T_{cat}, T_Q, T_M, T_{LB}), but only a few different ones. For example, the PRSM scenario is incorporating the mid output T_{man} due to manual handling with the high quality of the RW, the rest of the scenarios are incorporating T_{TD} and T_D because of the predicted lower quality of the RW and manual decontamination of the RW solely (e.g. eliminating glass, metals, plastics etc.), which can disturb the recovery process. All of the scenarios observed include mid outputs in the supporting sub-model in time (TM_{MM}, TM_F, TM_M, TM_{LB}) and fuel consumption (FM_{MM}), due to the RW being loaded in the truck by hiab after sorting.

T1 and T2 are connecting the processes S&M→R (T1) and R → production (T2), and with the transition of the RW also RL facilities and factories: collection centre → recovery centre (T1) and recovery centre → production centre (T2). Thus, hook loader, roll-off trailer and two roller containers with 70 m^3 of capacity are used for this purpose. It is assumed that the vehicle is transported fully loaded. While T1 covers all four scenarios, T2 covers only PWCR and PWCI. Both processes include similar mid output in distance travelled (D_{Tr}), time consumption (T_{Tr}, T_F, T_M, T_{LB}), except T_{RC} (T1) and T_{PC} (T2), and fuel consumption (F_{Tr}), except F_{RC} (T1) and F_{PC} (T2).

After cascade sorting in the S&M process and the R process, four scenarios are made. Firstly, in the PRSM scenario, the RW QRi is reused for the same purpose as used in the past (e.g. chair → chair). Secondly, in the PRAP scenario, the RW QRii is reused for a different purpose than it was used in the past (e.g. door → dining table) [see e.g. 54]. Finally, in the PWCR and PWCI scenarios, the RW QRiii and QRiv are recovered into wood chips. After appropriate treatment at the recovery centre, the RW for reuse from the PRSM and PRAP scenarios remains at the same place and is prepared for sale, while the wood chips from the PWCR and PWCI scenarios are transitioned to the material or energy production. Production is not in the scope of this study. While the PRSM and PRAP include electric consumption (e.g. electric appliances, lights etc.), the PWCR and PWCI involve firstly hiab for RW loading, then the shredder for RW crushing, then, drum screen for wood chip screening, and lastly, wheel loader for wood chip loading.

In the R process, as it was previously suggested in [26], four sub-models, both main and supporting, were included. While the PRSM and PRAP scenarios contain only the main sub-model, the PWCR and PWCI include both. The PRSM and PRAP have almost similar mid outputs in time consumption, (T_M, T_{LB}), except for T_{CM} (PRSM) and T_{CSM} (PRAP), due to extended repair. Consequently, the electricity consumption for both scenarios is different: PRSM includes E_{CM} and PRAP E_{CSM}. The PWCR and PWCI are similar scenarios and include identical mid outputs: firstly, in the main sub-model of time (T_F, T_{LB}, T_M, T_{LSS}) and fuel consumption (F_L, F_{Sd}, F_S); secondly, in the supporting sub-model of time (TM_{MM}, TM_F, TM_M, TM_{LB}) and fuel consumption (FM_{MM}).

Calculation of environmental burdens. The CATWOOD model includes two types of air pollutant emissions connected to the fuel that is combusted in trucks and machines. The fuel emission computations comprise (1) the pollutants released when fuel is combusted [52] and (2) the pollutants emitted when the fuel is refined from petroleum feedstock (pre-combustion) [55]. Likewise, the emissions computations for electricity from repairing the RW involve (1) the pollutants released when the electricity is generated and (2) the pre-combustion emissions connected with the production of the fuels used to generate the electricity [55]. While data of the air pollutant emission for trucks and electricity have been obtained from the literature [52, 55], data for machines were derived from the current EU regulation [56].

Life cycle impact assessment (LCIA)

In the CATWOOD model, no burdens from previous life cycles of wood (extraction, production or distribution) were considered. Only the emissions arising from the processes of the RW (C&T, S&M, T1, R, T2) were assessed. Each generated emission in the LCI phase was assigned to the appropriate midpoint impact category in line with the literature [57, 58]. In this context, seven different categories were studied: global warming (GW100), acidification, photochemical ozone creation, marine eutrophication, particulate matter formation, human toxicity and ecotoxicity.

2.3 Modelling with SLCC

Goal and scope definition and information gathering

The goal of the SLCC modelling was to represent the lifecycle costs of the RL processes and RL technology. RL technology has been included into the RL processes as defined in the section *Life Cycle Inventory – RL processes in the CATWOOD model.* The sum of the costs of the used RL technology in an individual RL process and scenario represents the final result and vice versa, the sum of the costs of the RL processes due to the used RL technology represents the final result. In the SLCC, we obtain both internal and external costs (LCC). The internal costs (LCC) consist of investment (IC_{EUR}), operational and end-of-life costs ($EoLC_{EUR}$) [e.g. 45, 59]. Operating costs are further subdivided into explicit (OCe_{EUR}), which include the costs of consumed energy and cost of wages (covering available working time of a worker, regular or sick leave and possible overtime work) as well as implicit costs (OCi_{EUR}), related to the costs of services, repairs and cost of tire wear (including changing, centering, screwing). End-of-life costs are actually benefits due to selling equipment. In the SLCC, both are taken into account, lifetime and period of use. External costs (EC_{EUR}) are connected to the social costs that affect the impact of business on the society and include congestion, accidents, air pollution, noise, climate change, up-and-downstream processes and marginal infrastructure costs [47]. The SLCC costs are calculated per one year of use (EUR/year). All costs were summed and divided by the FU. The basic formula for the SLCC is demonstrated in *Equation 5*.

$$SLCC(EUR/year) = \frac{IC_{EUR} + OCe_{EUR} + OCi_{EUR} - EoLC_{EUR} + EC_{EUR}}{FU} \quad (5)$$

The SLCC was calculated based on the obtained results in LCI $\left(\sum T_{ps}, \sum F_{ps}, \sum E_{ps}, \sum D_{ps},\right)$ joined by online (e.g. average fuel and energy prices, social contributions for workers prices), and scientific literature data [47], interviews with experts in various processes, e.g. transportation (Volvo Trucks, Bijol, Avto Krka, Kostak, Vulkanizerstvo Furlan), temporary storage (Eko Lux) and recovery (Petrol). In the LCC bottom-up calculation, the approach was used to obtain results for the RL technology and RL process.

2.4 Case study

The case study was carried out in the Posavje Region in Slovenia, covering 968 km^2, comprising 6 municipalities with 75,694 inhabitants, which makes a population density of 78 inhabitants/km^2. The RW was clean or contaminated from packaging (e.g. boxes, pallets) and municipal waste (e.g. furniture). The amounts of the RW was 22.3 kg/capita/year. While almost all processes were carried out in the Posavje Region, T2 includes wood chip transition for particle board production to Carinthia Region (244 km) or energy production to the Savinja Region (120 km). The RL technology was the same as presented in the LCI.

3. RESULTS

3.1 Modelling with LCA

The results of the LCA modelling with the CATWOOD in the Posavje Region showed the greatest potential for environmental pollution in all impact categories arising from the C&T process. This has illustrated the hotspot, e.g. processes most contributing to the environmental performance of the system [41]. On the other hand, the S&M process presents six of seven categories with the lowest values, except for the GW category, where lower recorded values appear in the T2 process.

Among the selected scenarios, the highest potential for environmental pollution in all impact categories is shown in the the PWCI scenario. On the other hand, the PRSM scenario has identified the

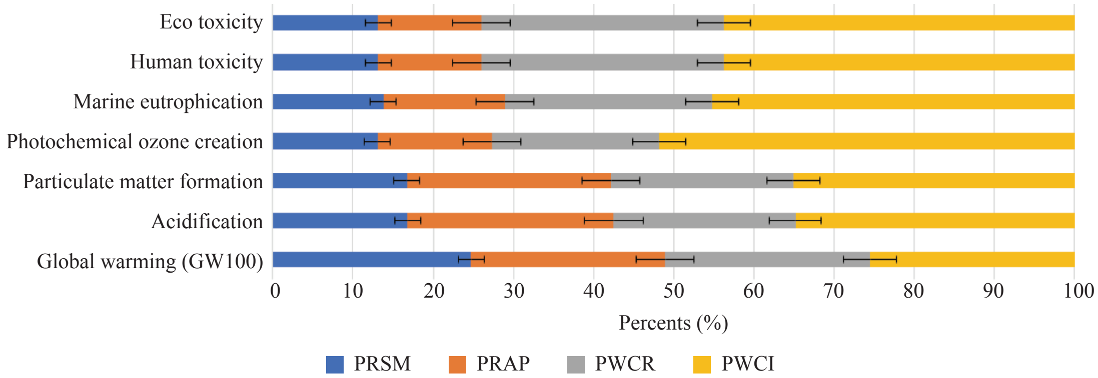

Figure 3 – The share of environmental burdens of individual impact categories in the studied scenarios

lowest values in four impact categories (acidification, particulate matter formation, photochemical ozone creation and marine eutrophication), while the PRAP scenario identified three (GW, human and ecotoxicity). The PWCR scenario did not show the highest or the lowest values in any of the categories. Nevertheless, the study proved that the PWCR scenario was an important counterbalance to the PWCI scenario, since it mostly showed significantly better results (*Figure 3*).

3.2 Modelling with SLCC

The lowest costs of all processes were recorded in the PWCR scenario (349 EUR/t), followed by the PWCI (360 EUR/t) and PRSM (367 EUR/t); the costs almost twice the amount of all of the studied scenarios was recorded in the PRAP (629 EUR/t) (*Figure 4 and 5*).

The costs of the C&T process are almost equal in all scenarios examined (172–173 EUR/t), but the charges of the processes in the involved scenarios more or less differ: T1 between 1.7 (PRAP) and 2.8 EUR/t (PWCR and PWCI), T2 from 15 (PWCR) to 27 EUR/t (PWCI), S&M from 69 (PRSM) to 223 EUR/t (PRAP) or R between 12 (PWCR and PWCI) and 232 EUR/t (PRAP) (*Figure 4*).While the costs of the RL technology are the same in some scenarios, e.g. roller container 0.8 EUR/t (all scenarios), shredder 5 EUR/t (PWCR and PWCI), drum screen 1.5 EUR/t (PWCR and PWCI), wheel loader 0.7 EUR/t (PWCR and PWCI), or with small differences, e.g. cost for hiab range from 174 (PRAP) to 179 EUR/t (PWCR and PWCI), electricity consumption from 0.2 (PRSM) to 0.9 EUR/t (PRAP), roll-off trailer from 0.06 (PRAP) to 2.2 EUR/t (PWCI), there are some drastic differences among the rest, e.g. while the costs for the hook loader range from 1.6 (PRAP) to 28 EUR/t (PWCI), the manual labour

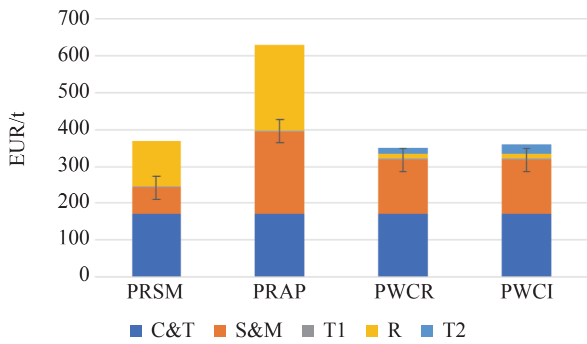

Figure 4 – Costs of the RL processes in studied scenarios

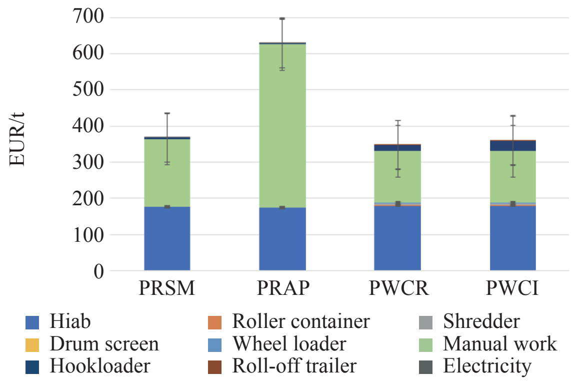

Figure 5 – Costs of the RL technology in the studied scenarios

ranges from 143 EUR/t (PWCR and PWCI) to 451 EUR/t (PRAP) (*Figure 5*). The latter also represents the hot spot – part of the RL technology assigning most to the system.

4. DISCUSSION

4.1 Sensitivity analysis in LCA modelling

As we have noticed, among all of the processes, the C&T is the most problematic from the environmental point of view and is thus considered a hotspot: 93–99% of the GW in the studied scenarios arise from the C&T process. Consequently, in the sensitivity analysis, we tried to reduce GW emissions. We tested the CATWOOD model with different input values of collection frequency: number 6, representing the case study value, was added to 4, 2, 1, and 0. Emission values were then assessed in the LCI and LCIA. The results in *Figure 6* show total values of the GW for all studied processes and scenarios. We found out that the results have been proportionally decreasing, with the PRAP scenario always presenting the lowest GW value, and the frequency of four transportations per year represents a reduction in GW emissions by 31–33%, two by 62 65% and zero by 93–98% (*Figure 6*). A completely reduced frequency can lessen the material use of the RW for the reuse so it is not recommended. Since this is also not in line with the policy objectives, we propose the use of alternative fuels [e.g. 60] to drastically minimise GW.

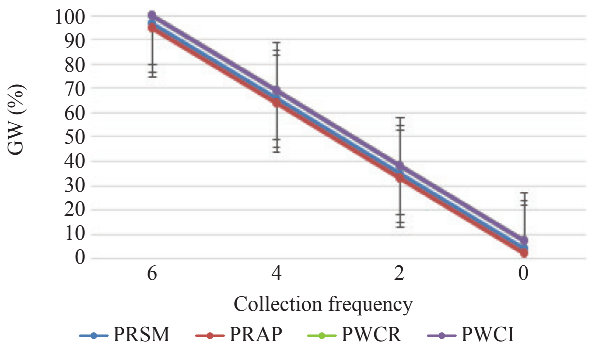

Figure 6 – Total GW emissions of the RW management in the observed scenarios with different collection frequency rates in the C&T process (kg CO_2-eq/t)

4.2 Sensitivity analysis in SLCC modelling

In the study, we found out that the most expensive process in almost all of the processes is the C&T and it represents 27–50% of the total costs. This is twice as low as the costs in the curb side collection of plastic packaging waste referred to in [61]. The other studies on the RW collection have not used this collection system. The reason for higher prices in the previous study [61], compared to our study, is involvement of waste bags and household bins, as well as the transportation of lighter material per unit, compared to the RW, which makes it more difficult to utilise the vehicle's maximum capacity. While [61] used CLCC, with narrower system boundaries, included only internal costs, in our study we applied SLCC, with wider system boundaries, and included internal and externally costs as well. Besides, the [61] accounted for an imaginary CO_2 tax, without publishing the value, we have internalised external costs. In this context, it appears that the collection of the RW may be more cost-justifiable than plastic packaging waste, which is a common practice in the EU Member States.

Another hotspot is expensive manual work as part of the RL technology. This is contrary to [42], where it was found that the sorting process had only a minor effect on the LCC; probably because the model presented was based mostly on assumptions and technological process was not in practice at that time. Since manual labour costs can be reduced via cooperation with schools, apprenticeships and employment of disabled people, for which the EU Member States in most cases cover a certain share of costs, thus providing a financial incentive, we have tested the CATWOOD with the effect of varying values of applicable input parameters for manual labour in each scenario (*Figure 7*). We found that if the costs for manual labour were reduced: (1) from 100 to 60%, the lowest total cost would remain for the PWCR scenario, (2) from 59 to 1%, the lowest total cost would come from the PRSM scenario and (3) from 1 to 0%, the lowest total cost would be from the PRAP scenario. In order to reduce the costs of manual labour and accelerate realisation, we suggest the use of more energy-efficient machines and putting bigger emphasis on better employee training.

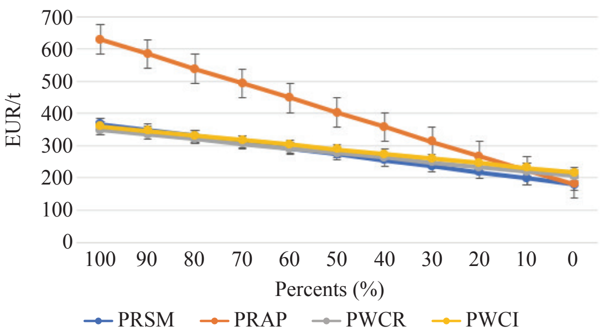

Figure 7 – Total cost of the RW management in the observed scenarios with different rates for manual labour (EUR/t)

5. CONCLUSION

In order to provide the systemic view into the RL in RW management and highlight the research gaps, firstly, literature review and classification of the most important papers were presented. Secondly, the research goals were proposed and accomplished through a series of methodical steps: (1) designing and combining quantitative methods OR, LCA and

SLCC, (2) selecting and defining four scenarios, five RL processes and nine RL technology types, (3) building and presenting mechanistic modelling in the LCI to obtain detailed time, fuel and electricity consumption as well as distance travelled. The achievement was implementation of the RL process model CATWOOD. The demonstrated combination of quantitative methods represents novelty, because previous studies did not combine all three methods. In addition, the contribution of this work also delivers detailed insight into modelling in the RL processes and RL technology. This way of modelling provides more authentic results since the smallest details allow precise calculation and can present the reasons for possible deviations. Moreover, the CATWOOD is also able to respond to changes of inputs in the LCI, thus enabling more sustainable RW planning. Thirdly, the CATWOOD was verified in a case study of the Posavje Region, Slovenia, which has revealed that the processes and scenarios for reuse, which use less heavy equipment technology, are environmentally friendlier than others, but are also more expensive, mainly because of the very high labour costs, and vice versa. Therefore, finally, in the sensitivity analysis, various input values were investigated and the results explained: (1) if the transportation frequency in the C&T process is changed, the GW will be proportionality changing, but the best scenario will always remain the same and (2) if the costs of manual labour are reduced from 59 to 0%, the total costs in the results of all scenarios will be reduced, and this will change which scenario is the best. Future work of combining these methods can be done in technically different and complex RL processes with other technology and waste fractions.

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CATWOOD – RAZBREMENILNI LOGISTIČNI PROCESNI MODEL ZA KVANTITATIVNO OCENITEV GOSPODARJENJA Z ODSLUŽENIM LESOM

POVZETEK

Sodobne okoljske in gospodarske težave na področju ravnanja z odpadki zahtevajo prehod iz linearnega v krožno gospodarjenje. V praksi to predstavlja precejšnje izzive, ki zahtevajo spremembo smeri materialnega toka, uporabo matematičnega modeliranja in integriranje metod življenjskih ciklov – tudi na področju odsluženega lesa (OL). Z namenom reševanja omenjenih izzivov smo se poslužili mehanističnega modeliranja in implementirali razbremenilni logistični procesni model CATWOOD (CAscade Treatment of WOOD), ki vključuje redno zbiranje, inovativno (kaskadno) sortiranje glede na kakovost in okolju prijazno predelavo OL. Kot podpora pri odločanju sta bili izbrani kvantitativni metodi analiza življenjskega cikla (AŽC) in družbeni stroški življenjskega cikla (DSŽC), ki izbirata med različnimi alternativnimi scenariji. Študija primera, ki je bila izvedena v Posavju v Sloveniji, je odkrila, da so scenariji na področju ponovne uporabe OL okolju prijaznejši od tistih za recikliranje ali energetsko predelavo, a tudi dražji, predvsem zaradi obsežnega ročnega dela in manj prisotne težke tehnologije v procesih sortiranja in predelave. Analiza občutljivosti je prikazala, da lahko spreminjanje vrednosti vhodnih parametrov v opazovanih scenarijih spremeni končne rezultate AŽC in DSŽC.

KLJUČNE BESEDE

razbremenilna logistika; transport; mehanistično modeliranje; AŽC; DSŽC; odslužen les.

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