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MODELLING OF POST–CONSUMER WOOD SORTING AND MANIPULATION: COMPUTATIONAL CONCEPTION AND CASE STUDY

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ABSTRACT

Latest scientific findings and policy guidelines emphasize the importance of returning bio-based waste raw materials through cascading use, also including post-consumer wood (PCW). To accomplish the concept of cascading use it is crucial to properly sort PCW given by the quality of raw materials which is resource consuming process. For this purpose, we have *(1)* selected appropriate activities, *(2)* constructed a model with different sub models in time, fuel and energy consumption, and *(3)* defined the inputs, performed calculations and presented (mid) outputs. In the case study all sub models have been compared with each other, demonstrated on the example of Slovenia. The results show that the reuse of wood is justified and should be implemented to a greater extent. Sensitivity analysis has exposed that modifying the values of the input parameters or (mid) outputs may change the final results in time and fuel consumption among selected sub models.

KEYWORDS: Cascade use, post–consumer wood, sorting, manipulation, modelling.

INTRODUCTION

Since the early 1970s, it has been found that mass production of goods leads to material and energy depletion of natural resources, which need to be replaced by alternative stocks of increasing amounts of waste (Ashby 2021). In order to solve a complex issue the concept of cascading use of materials was developed by Sirkin and ten Houten (1994) as four-dimensional model of resource economy consisting of resource quality, utilization time, resource salvageability, and consumption rate. This concept is very appropriate for further use of bio-based materials, thus prolonging total material availability (Mair and Stern 2017, Lubke et al. 2020), in our case waste wood. Since 2008 cascading use has been identified in the waste pyramid of the European Waste Framework Directive, which places reuse before recycling and energy recovery. It was followed by further promotion of effective utilization of bio-based materials through a series of papers, including recommendations and the best applications of cascading, efficient circularity and innovative use of wood waste by European Commission (EC 2012, 2018, 2020). Meanwhile, various authors have already used different research methodologies to assess environmental impacts of wood cascading (Thonemann and Schumann 2018, Rehberger and Hiete 2020). The most promising findings follow as: Cascading can significantly lengthen carbon sequestration in wood (Franje 1997a,b), remarkable share of wooden packages, furniture, construction and demolition waste wood can be reused or recycled (Högelmeier et al. 2013, Husgafvel et al. 2018), quality over quantity in wood waste management can assure larger global warming savings, due to ability to substitute energy intensive products (steel or concrete) (Faraca et al. 2019a).

In order to achieve the cascading use with the highest possible application of waste wood, consisting of forest residues, industry by-products and disused products, e.g. post-consumer wood (PCW), it must be sorted before its further use, sorting being based on its resource quality and homogeneous composition. While forest residues and industry by-products are usually homogenous and clean, the PCW is very heterogeneous material with different levels of impurities (mechanical, chemical), origin (packaging, construction and demolition, furniture etc.) and type (solid wood and composites, pallets, boxes, furniture, upholstered etc.) (Besserer et al. 2021), which makes sorting and sustainable recovery more difficult.

To reach this target PCW sorting is taking place either on-site (Rivela et al. 2006) or off-site (Lu and Yuan, 2012), using manual, automated (direct and indirect) or combined (automated-manual) techniques. While waste triage by hand is more appropriate for reuse, automated ways with shredding along with magnets for metal rejection and X-ray fluorescence (XRF) for efficient identification of As, Cr and Cu treated wood are more suitable for recycling or energy recovery of PCW (Gundupalli et al. 2017). Machine manipulation by hoist or cranes is also used for easier material sorting, especially for larger and volumized items (Yuan et al. 2013). Therefore, sorting remains a time consuming and energy intensive working process that needs to be prudently planned.

Planning in waste management processes, e.g. collection and transportation, sorting and recovery of different kind of waste, is a common topic in literature on mathematical modelling, using different methodology, namely mixed integer linear programming (Mohammadi et al. 2019, 2021, Burnard et al. 2015, Li and Tee 2012), dynamics methodology (Ghisolfi et al. 2017), geographic information system software and analytical hierarchy process (Farahbakhsh and Forghani 2019), cost–benefit analysis (Achillas et al. 2013), fuzzy mixed integer location-allocation model (Kusakci et al. 2019), and mechanistic, mostly for decision support or facility choices and network design. In some of these studies time has been included as production time to process various municipal waste (Mohammadi et al. 2019), or working time (Mohammadi et al. 2021), or disassembly time (Ghisolfi et al. 2017, Achillas et al. 2013), or service time (Farahbakhs and Forhani 2019). Greenhouse gases and lead emissions (Li and Tee 2012), or CO_2 emissions (Farahbakhs and Forhani 2019, Mohammadi et al. 2021, Burnard et al. 2015) have also been incorporated in some models. Nevertheless, to the best of the authors' knowledge time, fuel or energy consumption in sorting processes of municipal waste or PCW have not been presented in detail in the literature before. On the other hand, mechanistic modelling has been included in limited number of academic works on collection and transportation of municipal waste, where certain authors used a large number of input parameters to computate the total distance and fuel consumption of the fleet vehicles in the road network (Gentil et al. 2010). While the earliest studies, Sonesson (2000) defined very detailed transport (hauling) time, driving time during collecting, and loading time, recent studies, Jaunich et al. (2016a,b) have added unloading time in transfer facility, lunch time and breaks as well. Likewise, these studies have examined energy expending for driving and idling (Vimpolšek et al. 2019). Emissions could be subsequently obtained from these calculated values in life cycle inventory and the environmental impacts using life cycle assessment modelling revealed. Certain studies also used mechanistic (Jaunich et al. 2016a,b) or comprehensive models to calculate life cycle costs based on the hours spent, using bottom-up approach (Groot et al. 2014, Martinez-Sanchez et al. 2015).

Detailed calculations are very important for accurate data acquisition, which allows easier decision-making in waste management planning (Christensen et al. 2020). Because transfer of mechanistic modelling into sorting process represents a novelty in waste management planning, the objectives of this research are: *(1)* determination of activities in the technological process of PCW sorting and manipulation, *(2)* defining decision support model by sub models, *(3)* composition of formulas, input parameters and (mid) outputs for time, fuel and energy consumption, *(4)* performing case study Slovenia.

MATERIAL AND METHODS

Defining activities in technological process

The system boundaries of technological process have been from gate to gate, which means that the study has been made exclusively in the sorting and manipulation process. Collection and recovery of PCW has been out of scope. PCW has been collected from households or companies and temporarily stored at waste management centres for further various activities: quality inspection (primary inspection), (not) disassembly, category assessment (AI-AIV), and mechanical and manual manipulation for further recovery (Fig. 1).

The wood has been checked visually and by hand touching the material, and classified according to quality into four groups, which condition further recovery: *(1)* excellent (dry, undamaged, whole – usable for its purpose), *(2)* good (dry, damaged – minor repairs needed), *(3)* average (wet or dry, quite damaged – less useful) and *(4)* poor quality (wet, very damaged – unusable). Only exceptionally well-preserved PCW of excellent quality has not been disassembled, the rest of PCW was disassembled. The goal of dismantling the well-preserved PCW was to eliminate contaminants (paper, textiles, metals) which do not have the special function in further re-use. We have assumed only non-timber parts of well-preserved PCW were transported by wheelbarrows from the disassembly site to separate collection containers. To this day advanced transport technologies in PCW sorting facilities have been very rare in Europe (Jarre et al. 2020), and none in Slovenia.

The goal of dismantling average or poorly preserved PCW was to reduce volumized composite materials to basic wood panels that allow better utilization of space during loading. All of the contaminants in average or poorly preserved PCW were expected to be removed later by machines in PCW processing plants. Disassembly was carried out by hand tools, e.g. hammers and pliers, whereby the disassembly of well-preserved PCW was more careful and slower than the one of average or poorly preserved PCW, so the required longer disassembly times were determined appropriately.

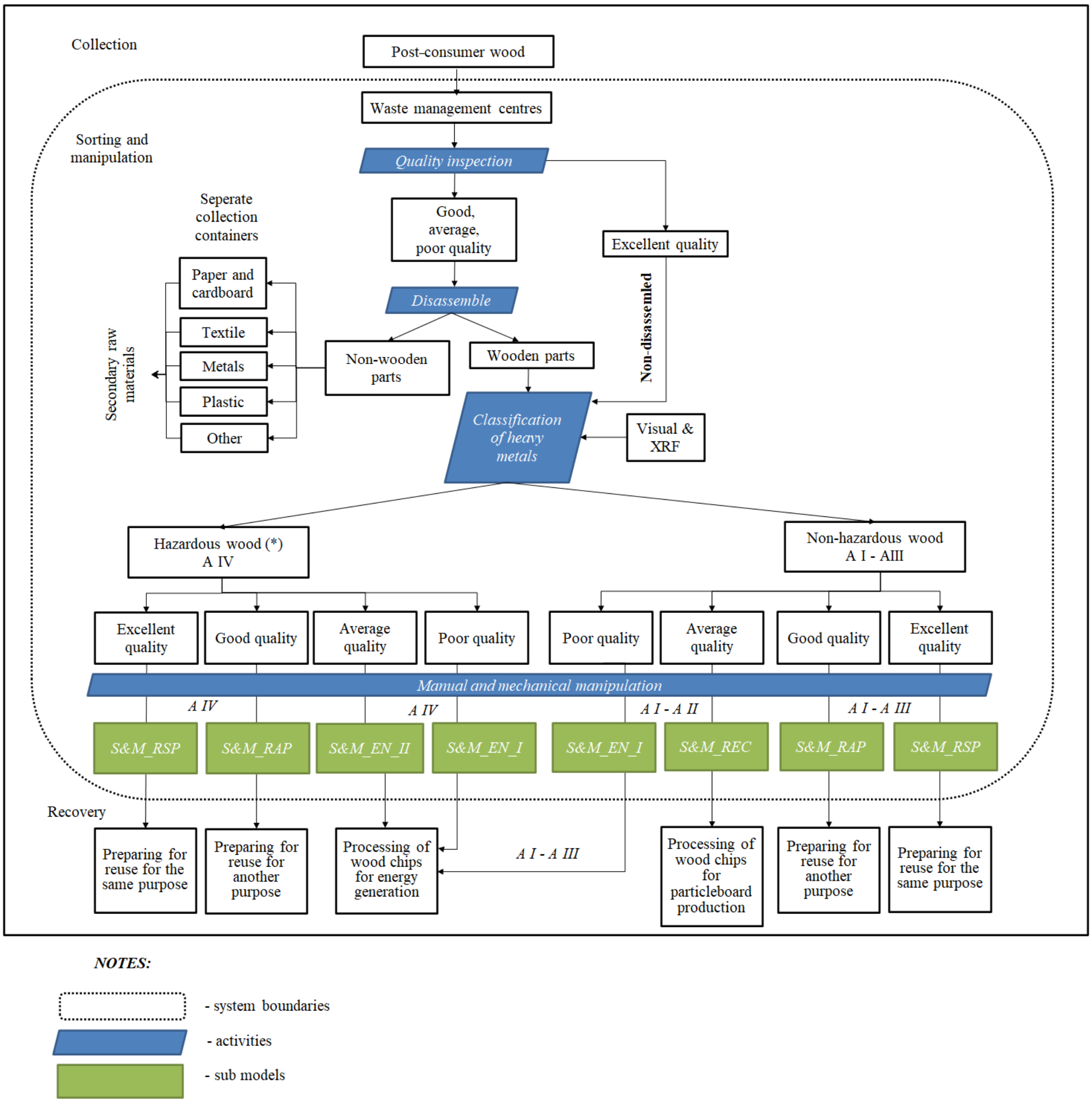

Fig. 1: Activities in sorting and manipulation process.

Afterwards, the chemical contamination of PCW was assessed visually and with handheld XRF (Hassan et al. 2011). Online sorting techniques (XRF or LIBS) have not been successfully applied in PCW recycling facilities yet (Lesar et al. 2018). On this basis PCW was classified according to AltholzV (2002) and European Panel Federation standards into four groups AI -AIV, which conditioned further recovery (Tab. 1). Non-hazardous (AI–AIII) and hazardous (AIV) PCW included all qualities of wood (excellent, good, average and poor). This makes sorting easier, since it requires chemically pure wood. Due to wood composite manufacturers waste oriented strand boards, plywood or medium density fibreboard, which were included in class AIII (Vis et al. 2016, Faraca et al. 2019a), were restricted as input. At the end it was planned for PCW with lower quality to be downcycled – dilapidated into their constituent materials and remade into new wood composites (Ihnát et al. 2020) or energy generated in plants (Corona et al. 2020).

Presentation of the sorting and manipulation model

Activities in sorting and manipulation configure a model. In modelling we assume that external limitations and internal relationships are very well known. All events or mechanisms are calculated in detail. Based on this outlook and described activities, 5 sub models with mechanistic approach, which uses data on physical properties, have been built. Sub models, consisting of main and support part, which have quantitatively defined procedures, have been designed. While the main segment represents the basic characteristic of the (manual) sorting process, the support section concerns the (machine) manipulation (Fig. 2).

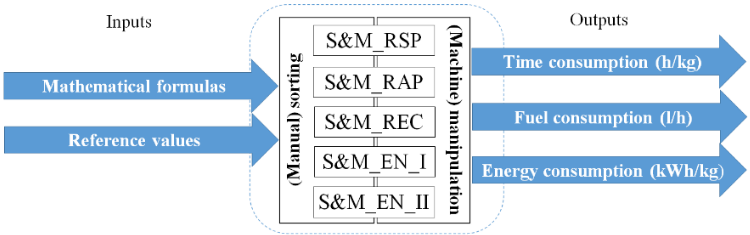

Fig. 2: Sorting and manipulation model.

The quality of PCW in the sub models is divided as follows: excellent PCW, groups AI–AIV, has become a part of the sub model S&M_RSP, and good PCW, groups AI–AIV, a part of the sub model S&M_RAP; average PCW has been split in two: groups AI–AII have become a part of the sub model S&M_REC, and groups AIII–AIV a part of the sub model S&M_EN_II. This is because entire preserved PCW of average quality cannot be recycled due to chemical contamination. At last, poor PCW, groups AI–AIV, has become a part of the sub model S&M_EN_I. These sub models ensure appropriate recovery, namely: S&M_RSP – preparing for reuse for the same purpose, S&M_RAP – preparing for reuse for another purpose, S&M_REC – wood chip processing for particleboard production, S&M_EN_I and S&M_EN_II – wood chip processing for energy recovery (Fig. 1). The input parameters of the sub models are reference values and mathematical Eqs. 1-15. 17 input parameters with reference values are used in the sorting (Tab. 1) and 9 in the manipulation part (Tab. 2). Due to different methodological and technological processes not all of the sub models include all of the listed inputs. Consequently, there are also minor differences between the sub models and the values of inputs due to different expected share of wood quality, (non) wooden parts, required time for disassembly and weight or density of the loaded fractions per truck, resp. The reference values are derived from literature, expert estimations or own measurements at recycling centre of Kostak Company Krško, where 11000 tons of waste are collected annually. A detailed view of the values is presented in Tabs. 1 and 2.

Mathematical formulas allow inputs through computations to be converted into calculated values or (mid) outputs in time, fuel and energy consumption, resp. 7 mid outputs and 2 outputs in sorting part, 4 mid outputs and 2 outputs in the manipulation part are presented (Tabs. 3 and 4). The sub models also include time consumptions such as time for fuelling and the maintenance of the vehicle (Vimpolšek et al. 2019). In the first phase the total data on consumption of time ($h \cdot year^{-1}$), fuel ($l \cdot year^{-1}$) and energy ($kWh \cdot year^{-1}$) in (mid) outputs have been obtained. In the second phase the results of all (mid) outputs (dividends) have been divided by the amount of sorted material in each of the five individual sub models for a period of one year ($kg \cdot year^{-1}$) (divisors). Divisor is actually a functional unit. The results for time ($h \cdot kg^{-1}$), fuel ($l \cdot kg^{-1}$) and energy ($kWh \cdot kg^{-1}$) are presented in results. The modelling has been performed in Microsoft Excel® and the calculation of the first phase is described below.

(Mid) outputs calculation in sorting and manipulation model

Time to evaluate the PCW category (TT_{cat}) in the sub models has been calculated differently. While the sub models S&M_RSP, S&M_REC, S&M_EN_I and S&M_EN_II have included Eqs. 1a,b,c, the sub model S&M_RAP included slightly different Eqs. 1a,c,d:

$$Q_{SQ} = P_{SQ} \cdot Q_{PCW} \tag{1a}$$

$$T_{cat\_i} = Q_{SQ} \cdot P_{cat\_i} \cdot T_{cat\_det} \tag{1b}$$

where: Q_{SQ} = estimated quantity of selected quality, ($kg \cdot year^{-1}$); T_{cat_i} = time to evaluate PCW category *i* (AI, AII, AIII, AIV), ($h \cdot year^{-1}$).

$$TT_{cat} = \sum T_{cat\_i} \tag{1c}$$

$$T_{cat\_i} = Q_{SQ} \cdot P_{wood} \cdot P_{cat\_i} \cdot T_{cat\_det} \tag{1d}$$

Time to evaluate the quality of PCW (TQ_{SQ}) in the sub models S&M_RSP, S&M_RAP and S&M_EN_I consists of Eq. 2a, and in the S&M_REC and S&M_EN_II of Eq. 2b:

$$TQ_{SQ} = Q_{SQ} \cdot T_{quality} \tag{2a}$$

$$TQ_{SQ} = \sum Q_{cat\_i} \cdot T_{quality} \tag{2b}$$

where: $\sum Q_{cat\_i}$ = total quantity of PCW category *i* (AI, AII, AIII, AIV), ($kg \cdot year^{-1}$).

Time for manual manipulation (T_{MM}) is included by Eq. 3 in the S&M_RSP sub model only. Due to similarity, the Eq. 3 is derived from the Eq. 10 in the sorting part:

$$T_{MM} = T_{loadings} \quad (3)$$

Time for driving and dumping to containers ($T_{T\&D}$) is included exclusively in the S&M_RAP sub model by Eq. 4:

$$T_{T\&D} = \frac{Q_{SQ} \cdot P_{nonwood}}{Q_{wheelbarrow}} \cdot T_{individ\_T\&D} \quad (4)$$

Time to disassemble the PCW ($T_{disassemble}$) in the sub models S&M_RAP and S&M_EN_I is included by Eqs. 5a,b in the sub models S&M_REC and S&M_EN_II:

$$T_{disassemble} = Q_{SQ} \cdot T_{disassemble\_wood} \quad (5a)$$

$$T_{disassemble} = \sum Q_{cat\_i} \cdot T_{disassemble\_wood} \quad (5b)$$

As part of sorting time for maintenance (TS_M) by Eq. 6, time for lunches and breaks ($TS_{L\&B}$) by Eq. 7, total sorting time ($\sum TS$) by Eq. 8 and energy consumption of XRF ($\sum E_{XRF}$) by Eq. 9 were also calculated in all sub models:

$$TS_M = \frac{\sum j}{N_{h/week}} \cdot TS_{individ.cleaning} \quad (6)$$

where: j = sorting time in mid outputs ($TT_{cat}, TQ_{SQ}, T_{MM}, T_{T\&D}, T_{disassemble}$).

$$TS_{L\&B} = \frac{\sum j + TS_M}{N_{h/shift}} \quad (7)$$

$$\sum TS = \sum_j + TS_M + TS_{L\&B} \quad (8)$$

$$\sum E_{XRF} = TT_{cat} \cdot E_{XRF} \quad (9)$$

As part of the manipulation, all the studied sub models have the same formulas, namely time consumption for loading ($T_{loadings}$) (Eq. 10) and time for fuelling (T_{fuel}) (Eq.11):

$$T_{loadings} = \frac{Q_{SQ}}{AUTO_V \cdot WOOD_\rho} \cdot T_{individ\_loading} \quad (10)$$

$$T_{fuel} = \frac{T_{loadings} \cdot F_{loading}}{AUTO_V\ tank} \cdot T_{fuelling} \quad (11)$$

The manipulation part like sorting includes time for maintenance (TM_M) and time for lunches and breaks ($TM_{L\&B}$) in Eqs. 12 and 13, resp. Total manipulation time ($\sum TM$) includes Eq. 14 and fuel consumption for loading ($\sum F_{loadings}$) is obtained by Eq. 15:

$$TM_M = \frac{(T_{loadings} + T_{fuel})}{N_{h/week}} \cdot TM_{individ.cleaning} \quad (12)$$

$$TM_{L\&B} = \frac{(T_{loadings} + T_{fuel} + TM_M)}{N_{h/shift}} \quad (13)$$

$$\sum TM = T_{loadings} + T_{fuel} + TM_M + TM_{L\&B} \quad (14)$$

$$\sum F_{loadings} = T_{loadings} \cdot F_{loading} \quad (15)$$

Tab. 1: Sorting input parameters for selected sub models.

No	Sorting input parameters	S&M_RSP	S&M_RAP	S&M_REC	S&M_EN_I	S&M_EN_II	Unit	Abbreviation	Source
1.	Estimated share of category AI	0.69	0.69	0.69	0.69	NO	-	$P_{cat\ i}$	Merl et al. (2007)
2.	Estimated share of category AII	0.12	0.12	0.12	0.12	NO	-		Merl et al. (2007)
3.	Estimated share of category AIII	0.11	0.11	NO	0.11	0.11	-		Merl et al. (2007)
4.	Estimated share of category AIV	0.08	0.08	0.08	0.08	0.08	-		Merl et al. (2007)
5.	Time to evaluate PCW category	0.001	0.001	0.001	0.001	0.001	$h \cdot kg^{-1}$	$T_{cat\ det}$	Own measurements
6.	Estimated share of selected quality	0.315	0.29	0.29	0.105	0.29	-	P_{SQ}	Own measurements
7.	Quantity of PCW annually	60000	60000	60000	60000	60000	kg	Q_{PCW}	Expert estimations
8.	Time for visual and XRF assessment of PCW quality (*)	0.001	0.001	0.001	0.001	0.001	$h \cdot kg^{-1}$	$T_{quality}$	Expert estimations
9.	Weekly working hours	40	40	40	40	40	h	$N_{h/week}$	Expert estimations
10.	Time of individual cleaning of platoon (*)	2	2	2	2	2	h	$TS_{individ.cleanin}$	Own measurements
11.	Daily working hours per shift	8	8	8	8	8	h	$N_{h/shift}$	Expert estimations
12.	Estimated share of wooden parts	NO	0.98	NO	NO	NO	-	P_{wood}	Faraca et al. (2019a,b)
13.	Estimated share of non-wooden parts	NO	0.02	NO	NO	NO	-	$P_{nonwood}$	Faraca et al. (2019a,b)
14.	Average weight of loaded wheelbarrow	NO	30	NO	NO	NO	kg	$Q_{wheelbarrow}$	Own measurements
15.	Average trip and sorting time (**)	NO	0.008333	NO	NO	NO	h	$T_{individ\ T\&D}$	Own measurements
16.	Time to disassemble the PCW (*)	NO	0.005	0.0025	0.0025	0.0025	$h \cdot kg^{-1}$	$T_{disassemble\ woo}$	Own measurements
17.	Energy consumption of XRF	0.012	0.012	0.012	0.012	0.012	kWh	E_{XRF}	Expert estimations

Tab. 2: Manipulation input parameters for selected sub models.

No	Manipulation input parameters	S&M_RSP	S&M_RAP	S&M_REC	S&M_EN_I	S&M_EN_II	Unit	Abbreviation	Source
1.	Available volume in transport vehicle	70	70	70	70	70	m^3	$AUTO_V$	Expert estimations
2.	Density of wood	86	176	176	176	176	$kg \cdot m^{-3}$	$WOOD_\rho$	Puy et al. (2010)
3.	Individual loading time	0.75	1.5	1.5	1.5	1.5	h	$T_{individ\_loading}$	Vimpolšek et al. (2019)
4.	Fuel consumption for loading	5.18	5.18	5.18	5.18	5.18	$l \cdot h^{-1}$	$F_{loading}$	Sandhu et al. (2015)
5.	Loader's tank capacity	450	450	450	450	450	l	$AUTO_{V\ tank}$	Expert estimations
6.	Time for individual fuelling	0.17	0.17	0.17	0.17	0.17	h	$T_{fuelling}$	Vimpolšek et al. (2019)
7.	Weekly working hours	40	40	40	40	40	h	$N_{h/week}$	Expert estimations
8.	Time for individual cleaning of the vehicle (**)	1	1	1	1	1	h	$TM_{individ.cleaning}$	Vimpolšek et al. (2019)
9.	Daily working hours per shift	8	8	8	8	8	h	$N_{h/shift}$	Estimated

Tab. 3: (Mid) outputs in sorting part of a model.

Num.	Sorting	(Mid) output	S&M_RSP	S&M_RAP	S&M_REC	S&M_EN_I	S&M_EN_II	Abbreviation	Units	
1.	Time to evaluate the PCW category	Mid output	Yes	Yes	Yes	Yes	Yes	TT_{cat}	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
2.	Time to evaluate the quality of selected PCW	Mid output	Yes	Yes	Yes	Yes	Yes	TQ_{SQ}	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
3.	Time for manual manipulation	Mid output	Yes	No	No	No	No	T_{MM}	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
4.	Time for driving and dumping to the containers	Mid output	No	Yes	No	No	No	$T_{T\&D}$	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
5.	Time to disassemble the PCW	Mid output	No	Yes	Yes	Yes	Yes	$T_{disassemble}$	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
6.	Time for maintenance	Mid output	Yes	Yes	Yes	Yes	Yes	TS_{M}	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
7.	Time for lunches and breaks	Mid output	Yes	Yes	Yes	Yes	Yes	$TS_{L\&B}$	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
8.	Total sorting time	Output	Yes	Yes	Yes	Yes	Yes	$\sum TS$	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
9.	Energy consumption of XRF	Output	Yes	Yes	Yes	Yes	Yes	$\sum E_{XRF}$	$kWh \cdot year^{-1}$	$kWh \cdot kg^{-1}$

Tab. 4: (Mid) outputs in manipulation part of a model.

Num.	Manipulation	(Mid) output	S&M_RSP	S&M_RAP	S&M_REC	S&M_EN_I	S&M_EN_II	Abbreviation	Units	
1.	Time for loading	Mid output	Yes	Yes	Yes	Yes	Yes	$T_{loadings}$	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
2.	Time for fuelling	Mid output	Yes	Yes	Yes	Yes	Yes	T_{fuel}	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
3.	Time for lunches and breaks	Mid output	Yes	Yes	Yes	Yes	Yes	$TM_{L\&B}$	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
4.	Time for maintenance	Mid output	Yes	Yes	Yes	Yes	Yes	TM_{M}	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
5.	Total manipulation time	Output	Yes	Yes	Yes	Yes	Yes	$\sum TM$	$h \cdot year^{-1}$	$h \cdot kg^{-1}$
6.	Fuel consumption for loadings	Output	Yes	Yes	Yes	Yes	Yes	$\sum F_{loadings}$	$l \cdot year^{-1}$	$l \cdot kg^{-1}$

Notes: * - the work is done with two workers, ** - the work is done with one worker.

Case study

The case study modelling has been performed in Slovenia, in the area of 20271 km² with 2100126 inhabitants. The country annually generates 8.4 million tons of all types of waste, municipal waste being just over 1 million tons (509 kg per capita). The amount of waste wood packaging, wood from construction and households is about 60000 tons per year. System boundaries in the modelling have been gate to gate and functional unit the amount of PCW, which is allocated for each of the five sub models for a period of one year (kg per year). We have assumed sorting and manipulation in Slovenia have been carried out in 159 local waste management centres.

RESULTS AND DISCUSSION

Results

The results show the highest time consumption for sorting ($\sum TS$) has been spent in the S&M_RAP sub model (8.32E^{-03}), followed by S&M_REC, S&M_EN_I and S&M_EN_II (5.32E^{-03}), and the lowest in S&M_RSP (3.25E^{-03}). Contrary, the longest time consumption for manipulation ($\sum TM$) has been recorded in the S&M_RSP sub model (1.31E^{-04}), followed by S&M_REC, S&M_EN_I and S&M_EN_II (1.28E^{-04}), and the lowest in S&M_RAP (1.26E^{-04}). While the energy consumption of XRF ($\sum E_{XRF}$) in all the sub models has been identical (1.2E^{-05}), the highest fuel consumption for loading **(**$\sum F_{loadings}$**)** among the studied sub models has been recorded in the S&M_RSP sub model (6.46E^{-04} l·kg^{-1}), followed by S&M_REC, S&M_EN_I and S&M_EN_II (6.31E l·kg^{-1}), and the lowest in S&M_RAP (6.18E^{-04} l·kg^{-1}).

Discussion

By making certain changes to the input parameters and mid outputs, the sub models described in this paper give deeper insight into the sorting and manipulation system, and provide more detailed understanding and better support in further decision making. For this purpose, the inputs and mid outputs in time and fuel consumption with determined changes have been tested in the sensitivity analysis.

The mid outputs of time for manual manipulation (T_{MM}) and time for driving and dumping to containers ($T_{T\&D}$) are located solely in the sub models S&M_RSP and S&M_RAP, where they cover 22.19% and 0.66% of the total time consumption ($\sum TS$+$\sum TM$). This represents a relatively small amount of total time ($\sum TS$+$\sum TM$) and in the case of reducing an individual mid output 0-100% the total time is not significantly reduced: in this event time for manual manipulation (T_{MM}) is reduced by 7.50E^{-04} h·kg^{-1} and time for driving and dumping to the containers ($T_{T\&D}$) for 5.56E^{-05} h·kg^{-1} (Fig. 3). Nevertheless, there are certain ways to use sophisticated technologies to reduce the presence of workers when loading sensitive material or replace workers with wheelbarrows by conveyor belts in the removal of secondary fractions (Infiesta et al. 2019). A challenge may arise in this area because the material at the source has to be collected separately, which would either require more conveyor belts or someone to sort the material properly.

Among the studied mid outputs time to disassemble the PCW ($T_{disassemble}$) covers the largest share of time consumption except in the sub model S&M_RSP, where it is not included: in the sub models S&M_RAP (59%), S&M_REC, S&M_EN_I and S&M_EN_II (46%). Therefore, we have gradually reduced the time required for PCW disassembly ($T_{disassemble}$) (100-0%). We have found out that the lowest final values have been recorded in the sub models S&M_REC, S&M_EN_I and S&M_EN_II, if the required time was reduced by 83% or more. On the other hand, in the sub model S&M_RAP a 100% reduction of the disassembly time ($T_{disassemble}$) does not change the final results, as the value of the sub model remains the highest. Fig. 4 clearly illustrates the movement and changes in the ratios of the reduction of time to disassemble the PCW ($T_{disassemble}$) in relation to the total time ($\sum TS+\sum TM$). In practice, full shortening of time to disassemble the PCW ($T_{disassemble}$) is nearly impossible, but with appropriate tools and well-trained workers it is possible to do work faster.

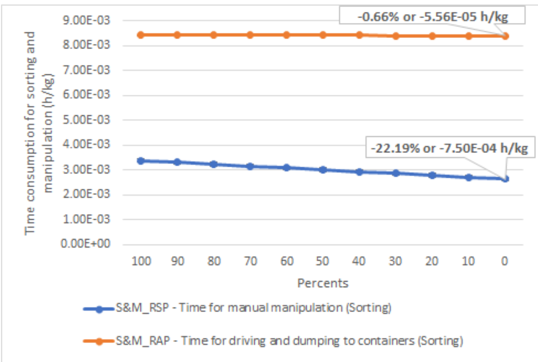

Fig. 3: Decrease of time parameters in the selected sub models.

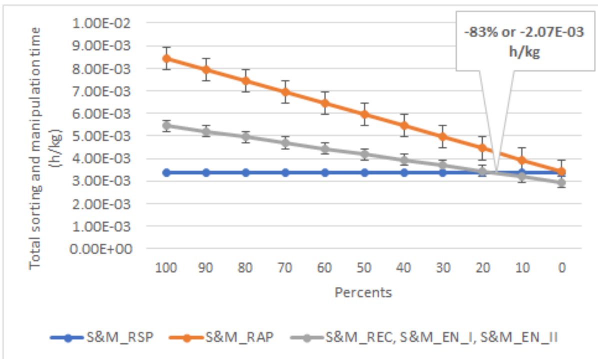

Fig. 4: Reduction of the parameter time to disassemble the PCW ($T_{disassemble}$) in the considered sub models.

Fuel consumption for loadings ($\sum F_{loadings}$) is the highest in the S&M_RSP sub model ($6.46E^{-04}$ $l{\cdot}kg^{-1}$) despite the lowest time consumption input due to poorer utility of the vehicle due to volumized loads (undisassembled cabinets, tables, chairs, etc.), large number of loads, and longer total vehicle loading time. On the other hand, the lowest values are recorded in the S&M_RAP sub model, which is due to exactly opposite reasons as stated for the S&M_RSP sub model. Therefore, if any value among the selected inputs in the S&M_RAP sub model were changed, this would be reflected in fuel consumption. Since the S&M_RSP sub model has the greatest cascading potential, we searched for lower result than has been recorded in S&M_RAP ($6.18E^{-04}$ $l{\cdot}kg^{-1}$) by changing the inputs. In order to achieve the lowest fuel consumption for loadings ($\sum F_{loadings}$) ($6.17E^{-04}$ $l{\cdot}kg^{-1}$) in the S&M_RSP, at least one of the following input values should be changed: *(1)* increase the density of wood ($WOOD_{\rho}$) from 86 $kg{\cdot}m^{-3}$ to 90 $kg{\cdot}m^{-3}$ (Fig. 5), *(2)* reduce fuel consumption for loading ($F_{loading}$) from 5.18 $l{\cdot}h^{-1}$ to 4.95 $l{\cdot}h^{-1}$, *(3)* reduce individual loading time ($T_{individ\_loading}$) from 0.75 h to 0.717 h (Fig. 6). In practice, greater use of solid wood, more economical engines and well-trained drivers could shorten manipulation times and reduce fuel consumption.

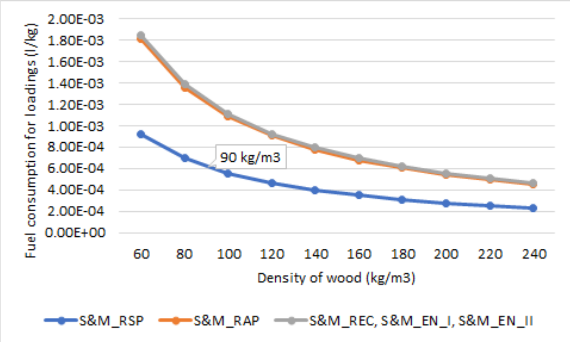

Fig. 5: Influence of wood density ($WOOD_\rho$) on total fuel consumption for loading ($\sum F_{loadings}$).

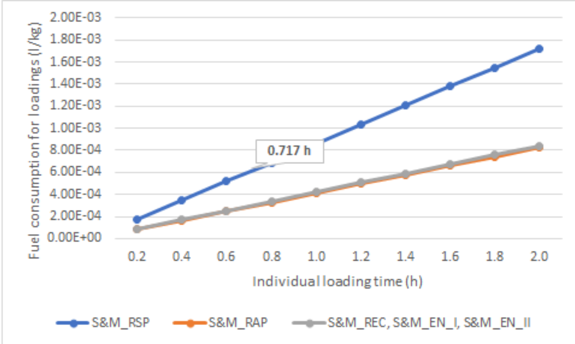

Fig. 6: Influence of individual loading time ($T_{individ\_loading}$) on fuel consumption for loadings ($\sum F_{loadings}$).

CONCLUSION

In this article we present the activities in sorting and manipulation process (model) for PCW, define the input parameters and (mid) outputs for time, fuel and energy consumption, explain the system boundaries and a functional unit. This is followed by the preparation of five different mechanistic sub models, based on cascade use of wood, namely S&M_RSP, S&M_RAP, S&M_REC, S&M_EN_I and S&M_EN_II. Mathematical formulas and reference values, which enable relevant calculations and predictions, have been created in all the sub models. In the case study of waste management centres in Slovenia we have found out that the lowest time consumption arises in the S&M_RSP sub model, the lowest fuel consumption has been recorded in the S&M_RAP, while energy consumption among the models has been equal. Based on the results obtained, we conclude that waste management hierarchy, which encourages reuse of material over recycling and energy recovery, is relevant in the sorting and manipulation process. The concept of cascade use of PCW is therefore completely justified.

Mid outputs and inputs in time and fuel consumption, including changes in certain values, have been tested in the sensitivity analysis. We have discovered that a 100% reduction in time for manual manipulation (T_{MM}) and time for driving and dumping in containers ($T_{T\&D}$) could reduce the total time ($\sum TS+\sum TM$), but the sequential order of the sub models from best to worst are not changed. Quite the contrary, testing of the mid output time consumption for disassembly ($T_{disassemble}$) showed: if this parameter is reduced by 83% or more, the lowest final values are recorded in the S&M_REC, S&M_EN_I and S&M_EN_II sub models. We have also learned that fuel consumption for loading ($\sum F_{loading}$) could significantly reduce final result in the S&M_RSP sub model if inputs for fuel consumption for loading ($\sum F_{loading}$) are increased, i.e. density of wood ($WOOD_\rho$), or reduced, i.e. time of individual loading ($T_{individ\_loading}$). Further researches are possible by extending the sub models for time, fuel and energy consumption in the field of preparation of PCW for reuse or recycle.

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