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Improving the Environmental Sustainability of Pallet Logistics through Preemptive Remanufacturing: an Integer Linear Optimization Model

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***Abstract* — The use of pallets is crucial in handling and transportation processes and wooden pallet represent the most common packaging type in the US and in Europe. This work focuses on the environmental impact of wooden pallet reverse logistics, exploring the advantages of preemptive remanufacturing policies. Preemptive schedules allow the service provider to allocate transportation emissions across multiple pallet components, increasing the environmental efficiency of the transportation process. This advantage has to be compared to the lost opportunity of repairing a usable component earlier than required. An integer linear optimization model analyzes this trade-off and the benefits of a preemptive remanufacturing schedule are described. The impact of transportation distance on the efficiency of preemptive policies is explored through a sensitivity analysis.**

Keywords—pallet management; preemptive remanufacturing; closed-loop model; reverse logistics; integer linear programming.

I. Introduction

Wooden pallets are the most widespread packaging type used for material handling and transportation, representing economically and environmentally critical assets in logistics systems. About 500 million new pallets are manufactured annually. Roughly 2 billion and 280 million pallets, mostly wooden, circulate in the US [1], and the EU [2], respectively. Moreover, the pallet industry is a leading consumer of hardwood lumber in the US, consuming between 33-50% of the total produced (3.8 billion board feet) [1]. Despite the fact that most wooden pallets can be reused or recycled, pallets are responsible for 2–3% of all waste landfilled in the US [3]. As companies strive to reach sustainability goals, the need for environmental assessment and improvement of pallet operations increases. However, only a few efforts in the literature focus on effective pallet management models for sustainability [4].

Closed-loop pallet management systems strive to recover pallet assets at the end of the use phase for repair and reuse. A closed-loop strategy allows the pallet provider to recover a still valuable asset, with economic and environmental benefits. However, to ensure the sustainability of closed-loop strategies, these benefits have to be compared to pallet reverse logistics environmental and economic costs [5]. Focusing on the remanufacturing phase, the transportation of pallets from a customer's location to the remanufacturing facility represents a significant source of carbon dioxide equivalent (CO_2-eq) emissions [6]. A unique feature intrinsic to pallet reverse logistics is that pallets fail (and can be repaired), component by component. These pallet component failures typically occur in different trips (or cycles) and depend on the loading and handling conditions. This requires component level repairs which, in turn, generates additional transportation to remanufacturing facilities. All this contributes to an increase in CO_2-eq emissions. Thus, an opportunity exists to reduce CO_2-eq emissions and costs associated with the transportation to the remanufacturing facility by preemptively repairing some pallet components prior to failure. While this truncates the useful life of some components, it has been shown to reduce transportation emissions and the overall carbon footprint [6]. This work explores optimal preemptive remanufacturing policies, where repair or replacement of pallet components can occur earlier than required (if pooled with other component's repair) to achieve a reduction in CO_2-eq emissions.

II. Background: Pallet Reverse Logistics

As shown in Figure 1, a closed-loop pallet supply chain typically includes a pallet manufacturer, a logistic service provider and a remanufacturer, while the pallet-users can be any actor involved in the production and distribution of a product or material delivered on pallets (e.g. product manufacturers, distribution centers, retailers). In a pallet pooling system, the logistic service provider may also oversee pallet manufacturing and remanufacturing, either performing or outsourcing these processes. During the use phase, when a pallet is in need of remanufacturing (i.e. component repair or replacement), the pallet is then collected and transported to a remanufacturing facility. There, the pallet undergoes remanufacturing and is injected back into the system to start another cycle. This detour to remanufacturing repeats every time a component fails (which is highly dependent on how severely the pallet is loaded or treated) and until the pallet practical end of life, that is when the pallet can no longer be repaired back to the original specification [6]. To define a pallet cycle, we refer to the FasTrack protocol [7], which indicates a pallet handling cycle as a sequence of 16 tasks. We assume that one cycle encompasses all the activities performed during a trip between echelons in the supply chain.

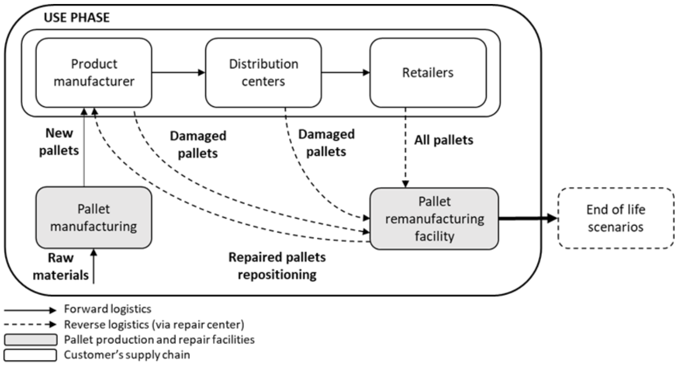

Fig. 1: Closed-loop pallet supply chain [5]

Literature about pallet reverse logistics is not vast, but in the last decade some efforts have explored this sector. Closed-loop schemes have been studied, and in some cases compared to the open-loop configuration to understand their relative economic and environmental performance [3], [5], [6], [8]–[13]. A few efforts analyze specifically the environmental impact of pallet operations, stressing the need for sustainable pallet management systems [14]–[17]. The implementation of traceability tools to analyze the possible benefit tracking devices can bring to pallet management has also been evaluated. [18]–[20].

Costs and emissions due to transportation to and from the remanufacturing facility are significant. These depend mainly on the distance between the user (e.g. the echelon where it fails) and the remanufacturing facility, but are independent from the severity of the damage, that is the type and number of components needing repair or replacement [6]. Consequently, this work explores preemptive repair and replacement policies where repair or replacement of components are allowed to occur before the actual failure if such premature action indeed reduces overall transportation emissions. Preemptively repairing or replacing a component has advantages in that the transportation emissions can be allocated across multiple components and has the potential to reduce overall transportation emissions. However, if a component is prematurely repaired or replaced, its remaining useful cycles at that point of the component lifecycle are wasted. Thus, a "loss" of usable cycles due to the opportunity to prematurely repair or replace a functional component for the sake of reducing overall emissions arises. Given this trade-off, we develop an integer linear program that determines the preemptive repair and replacement schedule that balances the benefits gained from reducing transportation emissions with the lost opportunity of use associated with early replacement and or repair.

III. Methodology

A. *Remanufacturing emissions for block pallets in a non-preemptive schedule*

Previous work [6] estimated the remanufacturing emissions for wood pallets under different handling and loading scenarios.

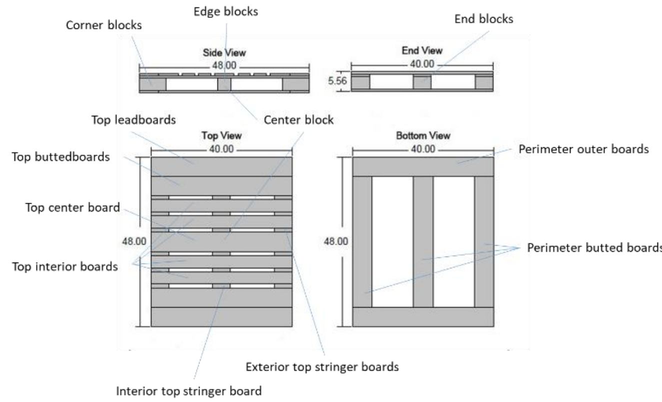

Fig. 2: Pallet components of 40x48'' block pallets (adapted from PDS®)

TABLE 1: Repair and replacement emissions per component for block pallets

Component	Repair emissions [kg CO_2 eq.]	Replacement emissions [kg CO_2 eq.]
Top leadboard [TL]	0.09	0.29
Top buttedboard [TB]	0.02	0.22
Top interior board [TI]	0.02	0.14
Top center board [TC]	0.09	0.29
Perimeter outer board [PO]	0.09	0.24
Perimeter butted boards [PB]	0.09	0.15
Exterior top stringer board [ET]	0.09	0.24
Interior top stringer board [IT]	0.09	0.24
Corner block [BCO]	N/A	0.12
Edge block [BEG]	N/A	0.12
End block [BED]	N/A	0.08
Center block [BCE]	N/A	0.08

An initial analysis of a pallet life cycle was performed using the Pallet Design System (PDS®) software, which elaborates data on pallet type, wood type, handling conditions and weight of the loads, to estimate the pallet components' service life (expressed in number of cycles) as well as the type of failures and ensuing remanufacturing activity (repair or replacement). The components of a standard 40x48'' block pallet are illustrated in figure 2. The emissions for the repair or replacement of each pallet component were calculated, based on data collected from industry visits, time studies and the PDS service life analysis (Table 1). It is worth noticing that blocks are only replaced, not repaired.

Five handling and loading scenarios conditions were considered:

- S1: good handling and treatment, light-duty loads (1000 lbs.);
- S2: average handling and treatment, medium-duty loads (2000 lbs.);
- S3: rough handling and treatment, heavy-duty loads (3000 lbs.);
- S4: good handling and treatment, heavy-duty loads (3000 lbs.);

- S5: rough handling and treatment, light-duty loads (1000 lbs.).

Transportation emissions were also included, considering a distance between the user and the remanufacturing facility of 100 km, and assuming an emission factor of 0.107 kg CO_2 eq./ton-km for a 32-ton EURO5 diesel truck [21]. The detailed methodology is described in [6].

B. Pallet failure profiles

The total remanufacturing emissions are based on the pallet expected service life and frequency/type of remanufacturing needed, obtained for each of the handling/loading scenarios. The pallet breakdown profile indicates for each cycle which component needs repair or replacement operations (Table 2).

Based on these profiles, the total remanufacturing emissions for the non-preemptive remanufacturing schedule (i.e. remanufacturing performed upon component failure) were estimated (Table 3). This represents the baseline to which the preemptive schedule will be compared.

C. The optimization model

To identify the remanufacturing schedule that minimizes the carbon footprint of the remanufacturing phase, an integer linear program is developed. The following assumptions are made.

- The component repair and replacement activities are assumed to deterministically follow the schedules elaborated through the PDS software and shown in the previous section. These activities are time-varying, in that not every cycle requires the same repair or replacement activities.
- The planning period is the expected number of cycles a pallet can be used for prior to the end of life scenario, as calculated and shown in Table 2. This number varies by scenario.
- The emissions related to the opportunity loss of pre-emptively repairing or replacing a component are included in the objective function, calculated as the share of repair/replacement emissions that get "lost" by moving remanufacturing activities to an earlier cycle.
- The opportunity loss emissions and the transportation emission coefficients, hpsjc and A, are constant over time.
- All repair and replacement activities must occur before or during the scheduled cycle. No backorders for repair and replacement activities are allowed.

Sets

- S, set of scenarios, which include s=1(good handling with light loads), s=2 (average handling with medium loads), s=3(rough handling with heavy loads), s=4 (good handling with heavy loads), and s=5(rough handling with light loads).
- P, set of components, indexed on p = 1,…12
- J, set of job types, where j=1 (repair) and j=2(replace)
- C, set of cycles, indexed on c = 0…|Ts|, where Ts denotes the number of cycles that a pallet will last given a scenario s treatment (data given in Table 2).

Parameters

- A denotes the transportation emissions produced if a pallet is sent to the remanufacturing facility. It is calculated as the product of the distance covered, the emission factor and the weight of a block pallet, in this case A = 100 km*0.107 kg CO_2 eq./ton-km*0.03158 ton = 0.338 kg CO_2 eq./ton.
- e_psj denotes the emission coefficient associated with job type j for component p in cycle c given scenario s (data in Table 1).
- r_psj denotes the time between job type j for component p given scenario s
- h_psj denotes the lost use per cycle of job type j for component p given scenario s and h_psj = e_psj/r_psj .
- d_psjc is 1 if component p in scenario s is normally set for job type j in cycle c; 0 otherwise (data derived from Table 2).
- M denotes a very big number

Decision Variables

- X_psjc = 1 if component p in scenario s is recommended for job type j in cycle c; 0 otherwise
- I_psjc = 1 if component p in scenario s has already had job type j completed by the end of cycle c; 0 otherwise. (I_psj0=0 ∀p∈ P,s∈ S,j∈ J)
- Y_sc = 1 if any component requires any job type in cycle c given scenario s; 0 otherwise (Y_sc = 1 if sum(j in J) sum(p in P) x_psjc > 0)

Next, we provide a separate model for each scenario s. The objective function minimizes the sum of the transportation emissions with the lost opportunity emissions from not using the component to its full potential, and the emissions associated with the repair and replacement activities. Note the last term in the objective function will be a constant and thus dropping it from the objective function will not impact the optimal solution. We include it in the objective function so that when we display results, the objective function provides a value that is consistent with non-preemptive analysis [6].

$$\min\left(\sum_{c\in C} AY_{sc} + \sum_{c\in C}\sum_{j\in J}\sum_{p\in P} h_{psj}I_{psjc} + \sum_{c\in C}\sum_{j\in J}\sum_{p\in P} e_{psj}X_{psjc}\right)$$

Subject to the following constraints:

In constraint (1) transportation is required to the remanufacturing facility if any component requires repair or replacement in cycle c. In constraint (2), we enforce that all repair and replacements need to be completed either in the cycle scheduled or before. In constraint (3), we account for the opportunity lost from repairing or replacing any component earlier than required. Finally in constraints (4) – (6), we ensure that our decision variables take on binary values.

TABLE 2: PALLET BREAKDOWN PROFILE PER SCENARIO: EXPECTED SERVICE LIFE AND CYCLES NEEDING REMANUFACTURING ACTIVITIES PER COMPONENT (REPAIR)/(REPLACEMENT)

	S1	**S2**	**S3**	**S4**	**S5**
T_s - Pallet expected service life	30	15	9	21	23
Components $p \in P$	**Cycles where (repair) /(replacement) activities are expected**				
TL (2)	--	(5, 13)/ (8, 15)	(3, 8)/ (5, 9)	(8)/ (14)	(14)/ (23)
TB (2)	(7, 19)/(12, 24, 30)	(3, 8, 13)/ (5, 10, 15)	(2, 5, 8)/ (3, 6, 9)	(4, 11, 18)/ (7, 14, 21)	(6, 16)/ (10, 20)
TI (4)	--	--	--/ (8)	(17)/--	(21)/--
TC (1)	--	(11)/--	(4)/ (7)	--	--
PO (2)	(7, 18, 29)/ (11, 22, 30)	(3, 8, 13)/ (5, 10, 15)	(3, 8)/ (5, 9)	(4, 11, 18)/ (7, 14, 21)	(5, 13, 21)/ (8, 16, 23)
PB (3)	(10, 27)/ (17, 30)	(5, 13)/ (8)	(4)/ (7)	(6, 16)/ (10, 20)	(7, 19)/ (12, 23)
ET (2)	--	(10)/--	(3, 8)/ (5)	(13)/ (21)	--
IT (1)	--	(14)/--	(4)/ (7)	(19)/--	--
BCO (4)	--/ (15)	--/ (6, 12)	--/ (4, 8)	--/ (16)	--/ (15)
BEG (2)	--/ (10, 20)	--/ (5, 10)	--/ (4, 8)	--/ (11)	--/ (10, 20)
BED (2)	--	--/ (15)	--/ (9)	--	--
BCE (1)	--/ (19)	--/ (9)	--/ (7)	--/ (21)	--/ (19)
Total n° of repair+ replacement activities	7+12 = 19	13+15 = 28	12+18 = 30	12+13 = 25	9+12 = 21

$$\sum_{j\in J}\sum_{p\in P} X_{psjc} \le M\, Y_{sc} \;\forall c \in C \quad (1)$$

$$\sum_{c'=1}^{c} X_{psjc'} \ge d_{psjc} \;\forall p \in P, c \in C, j \in J \quad (2)$$

$$I_{psjc} = I_{psjc-1} + X_{psjc} - d_{psjc} \;\forall p \in P, c \in C, j \in J \quad (3)$$

$$X_{psjc} = \{0,1\} \;\forall p \in P, c \in C, j \in J \quad (4)$$

$$I_{psjc} = \{0,1\} \;\forall p \in P, c \in C, j \in J \quad (5)$$

$$Y_{sc} = \{0,1\} \;\; c \in C \quad (6)$$

IV. RESULTS

Table 3 summarizes the results of the optimization model per scenario, comparing them to the non-preemptive schedule of the baseline and showing the percentage improvement in CO_2-eq emissions. A decrease in the total remanufacturing emissions can be observed in all scenarios, confirming that a preemptive policy can improve the environmental performance of the reverse logistics despite the opportunity loss. New values for total emissions per pallet vary between 4.34 and 6.19 kgCO_2-eq while the percent improvement varies between scenarios, ranging from 11.3% to 40.7%. The highest improvement can be found when pallets are subject to good handling and light loading conditions, resulting also in the lowest value for total emissions. On the contrary, the worst performance can be found under scenario 3 (rough handling, heavy loading), with an improvement of only 11%. This happens because pallets in scenario 3 need the highest number of repair/replacement activities (see Table 2), which results in the highest level of remanufacturing emissions, which are constant in both policies. This is evident in Fig. 3, which compares the results obtained with the two policies and highlights the weight of each source of emissions. The proposed model aims at decreasing the total emissions by optimizing the transportation phase: while transportation emissions decrease in each scenario with a preemptive policy, remanufacturing emissions do not vary, since the number and type of repair/replacement activities needed do not change. Therefore, in scenario 3, where transportation activities represent only 39% of emissions in the baseline and can be reduced only from 8 to 3 trips to the remanufacturing depot, a preemptive policy cannot be as effective as in other scenarios, where there is more room for improvement.

In Fig. 3, the opportunity loss emissions in the preemptive schedule are largely compensated by the drastic decrease of transportation emissions in all scenarios, ranging from 11% (S2 average handling/medium loading and S4 good handling/heavy loading) to 17% (S1 good handling/light loading and S5 rough handling/light loading) of the total emissions. In general, scenarios with light loading (S1 and S5) present the highest improvement compared to the baseline, and the lowest value of CO2eq emissions. This is not true with a non-preemptive policy, where transportation is responsible for a large part of the total emissions, with a share between 39% (in S3) and 65% (in S1), and the inefficiencies of this phase have a significant impact on the overall performance.

TABLE 3: SUMMARY OF RESULTING REMANUFACTURING EMISSIONS IN PRE-EMPTIVE SCHEDULE AND COMPARISON WITH THE BASELINE.

Scenarios	Emissions non-preemptive (baseline) [6] [kgCO2eq/pallet]	Emissions pre-emptive [kgCO2eq/pallet]	Percent Improvement	Cycles wit Repair/ Replace activities
S1	7.32	4.34	40.7%	7, 17, 29
S2	7.41	5.67	23.5%	3, 5, 10, 15
S3	6.98	6.19	11.3%	2, 5, 8
S4	8.05	5.21	35.2%	4, 7, 14, 20
S5	7.50	4.54	39.5%	5, 10, 19

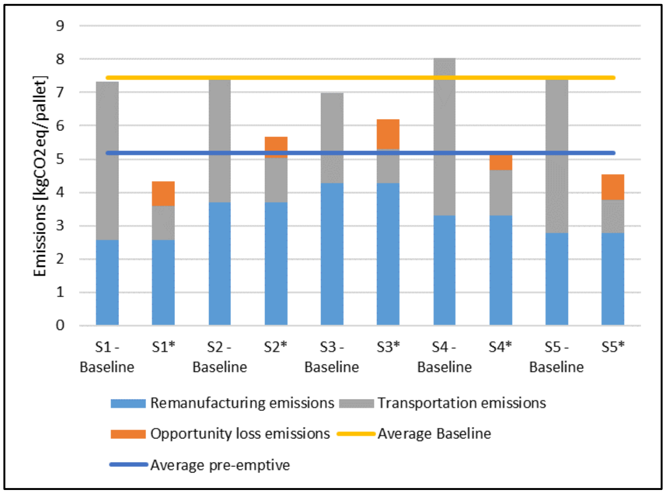

Figure 1: Results of the optimization model per scenario compared to the baseline.

V. SENSITIVITY ANALYSIS

As previously explained, the model refers to a distance of 100 km between the customer and the remanufacturing facility. This distance will vary, case by case; however, a previous study demonstrated an upper limit for this distance exists, above which a reverse logistics system for pallet recovery and remanufacturing is no longer environmentally and economically efficient, and this upper limit depends also on pallet conditions [13]. Given the significant impact of the transportation phase on the total emissions, a sensitivity analysis on distance is performed to evaluate the variability of results. Two more values are considered for distance, 50 km and 150 km, which are both coherent with industry practices and with the limits presented in [13]. The results obtained are shown in table 4 and figure 4.

Clearly, the share of transportation emissions increases with distance. This is also true for the opportunity loss emissions: table 4 shows that as distance increases, pallets are sent to the remanufacturing facility less frequently to avoid multiple trips and share transportation emissions over multiple components. Consequently, opportunity loss emissions increase, as components are usually repaired/replaced earlier than required. Overall, the sensitivity analysis confirms the results previously obtained, suggesting that pallet reverse logistics has the highest environmental impact when pallets are handled roughly and loaded heavily (S3). On the contrary, light load policies (S1 and S5) have the greatest potential improvement with preemptive policies, allowing CO2eq emissions savings compared to S3 of 28-32% with a distance of 50 km, and 25-28% with a distance of 150 km.

TABLE 4: SUMMARY OF RESULTING EMISSIONS IN PRE-EMPTIVE SCHEDULE WITH DIFFERENT VALUES FOR DISTANCE (50 KM AND 150 KM).

Scenarios	Remanufacturing emissions [kgCO2eq/pallet]	Distance = 50 km				Distance = 150 km			
		Opportunity loss emissions [kgCO2eq/pallet]	*Transportation emissions [kgCO2eq/pallet]*	*Total emissions [kgCO2eq/pallet]*	*Repair/ replace cycles*	*Opportunity loss emissions [kgCO2eq/pallet]*	*Transportation emissions [kgCO2eq/pallet]*	*Total emissions [kgCO2eq/pallet]*	*Repair/ replace cycles*
S1	2.58	0.29	0.85	3.72	7, 10, 17, 22, 29	0.74	1.52	4.84	7, 17, 29
S2	3.69	0.08	1.01	4.78	3, 5, 8, 10, 13, 15	0.99	1.52	6.20	3, 8, 13
S3	4.28	0.20	1.01	5.49	2, 3, 5, 7, 8, 9	0.90	1.52	6.70	2, 5, 8
S4	3.31	0.19	1.01	4.51	4, 7, 11, 14, 18, 21	1.03	1.52	5.86	4, 11, 18
S5	2.77	0.33	0.85	3.95	5, 10, 15, 19, 23	0.75	1.52	5.04	5, 10, 19

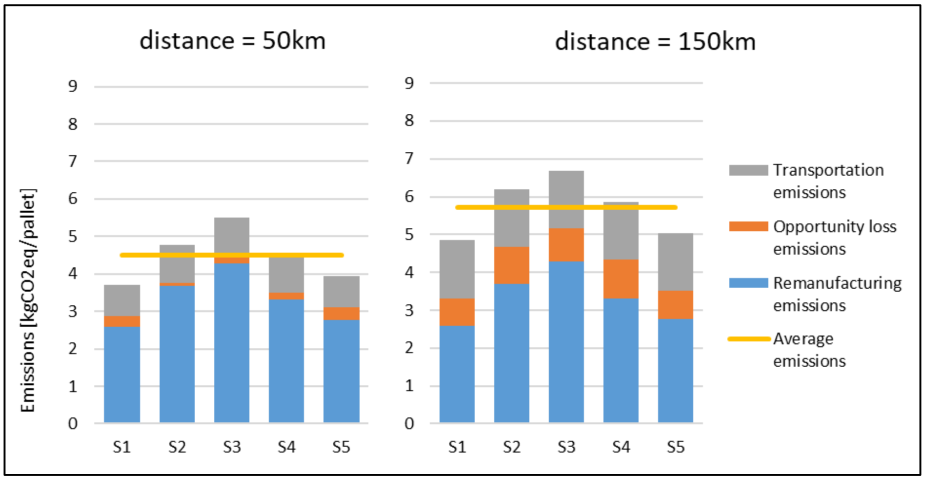

Figure 2: Results of the optimization model per scenario with different values for distance (50 km and 150 km)

VI. Conclusions

This work applies an integer linear optimization model to determine optimal preemptive repair policies that minimize CO2eq emissions for block pallets. By consolidating transportation trips to remanufacturing facilities, preemptive repair can reduce the environmental impact of pallet reverse logistics. This work finds that while pallets handled roughly and loaded heavily (S3) have the highest CO_2-eq emissions, such handling and loading conditions are less conducive to preemptive policies. Instead, good handling and treatment, light-duty loads (S1) have the greatest potential improvement with preemptive policies, allowing CO_2-eq emissions savings of 40.7% compared to a non-preemptive policy for the base case with 100 km.

A number of future research directions exist. While we focused on environmental objectives for block pallets, the analysis should be expanded (1) to other pallet types, such as stringer pallets; (2) to other objectives, specifically economic considerations, and (3) to other approaches, such as multi-objective analysis to provide decisions robust to multiple different objectives. Methodologically, we assume the pallet profile is known with certainty, this assumption should be relaxed to consider component failure to being a random variable. Finally, the effect of uncertainty of the component failure profiles as well as the impact of the mix of handling and loading conditions that are inherent in large pools of pallets should be addressed in the future. With the large number of pallets assets deployed all over the world, these approaches have the potential to make a significant impact on the environmental sustainability of logistics operations.

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