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Environmental Impact of EPAL Pallets: A Comparative LCA of Standard Exchange and Nolpal System.

TESI DI LAUREA MAGISTRALE IN
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Abstract

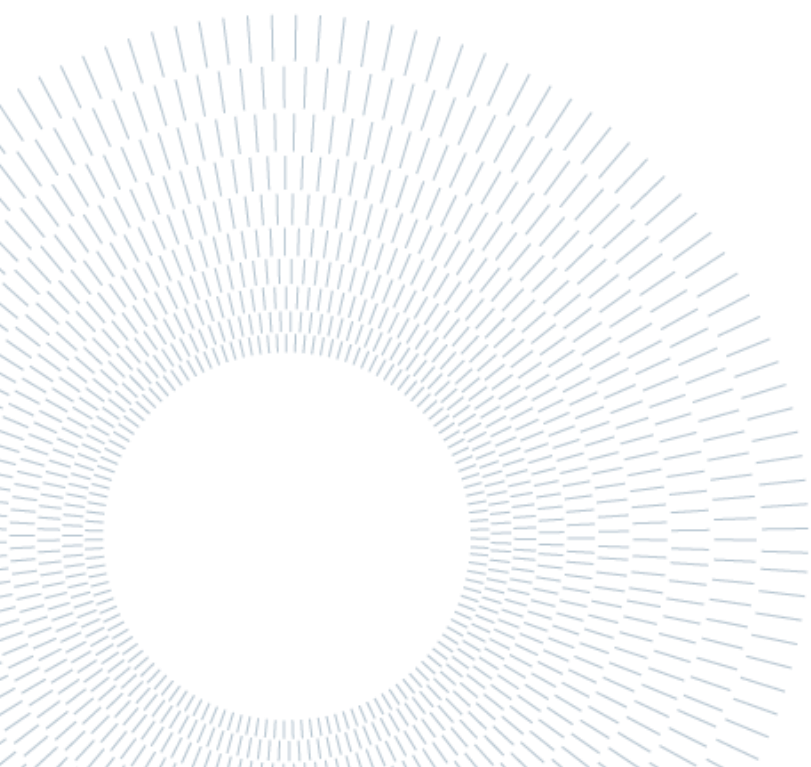
Pallets play a pivotal role in the growing global market, as they are essential for the transportation of goods worldwide. The continued expansion of trade has led to an increase in distances travelled, and the inevitable consequence is an exponential growth in costs, consumption, and greenhouse gas emissions. This is particularly true for EPAL pallets, which are the most widely used type of pallet in Italy and Europe. Conventional pallet management practices are among the primary drivers of this escalation in both emissions and operational costs. This study presents a comparative LCA of the environmental impacts of two different management methods: the standard pallet exchange method and the alternative pallet system proposed by Nolpal. Instead of the conventional buy-and-sell model, Nolpal retains ownership of its pallets and circulates them through a rental pool powered by a nationwide network of hubs across Italy. The comparison between these two systems has been conducted using a cradle-to-grave approach, by means of the openLCA software, which allows for a study of the environmental impacts of the pallet's entire life cycle. The primary data for the analysis have been provided directly by Nolpal, while the secondary data have been collected from existing literature on the topic. Based on the results obtained, the best pallet management system has been identified. Furthermore, suggestions about future improvements in the end-of-life treatment of wooden pallets have been given as well.

Key words: LCA; pallet; sustainability; logistic operations; pallets' pooling; End-of-Life; Nolpal; climate change.

Abstract in italiano

Il pallet è uno dei protagonisti di un mercato globale sempre in crescita in quanto essenziale per il trasporto di merci e prodotti in tutto il mondo. Il continuo ampliarsi dei commerci ha portato ad un aumento sempre più considerevole delle distanze percorse, e la conseguenza inevitabile è l'aumento esponenziale di costi, consumi e emissioni di gas serra nell'atmosfera. Questo vale in particolar modo per il pallet EPAL, che risulta essere la tipologia di bancale più utilizzata in Italia e in Europa. La gestione dei pallet è il principale ambito su cui operare per andare a ridurre questo impatto ambientale. Questo studio presenta un'analisi comparativa degli impatti ambientali di due diversi tipi di gestione alternativi: il metodo standard di compravendita dei pallet e un nuovo sistema di interscambio dei bancali proposto dall'azienda Nolpal. L'azienda si propone infatti come proprietaria principale dei pallet, che vengono immessi in circolazione tramite un modello basato sui prestiti invece che sul convenzionale approccio di acquisto e rivendita. Questo sistema di noleggio è facilitato dalla distribuzione in tutta Italia di hub dedicati di Nolpal. Il confronto tra questi due sistemi è stato portato a termine adottando un approccio di tipo Cradle-to-grave tramite il software OpenLCA che ha permesso di realizzare lo studio sugli impatti ambientali dell'intero ciclo di vita del pallet. I dati primari dell'analisi sono stati forniti direttamente da Nolpal, mentre i dati secondari sono stati ricavati dalla letteratura preesistente sull'argomento. Alla luce dei risultati ottenuti, è stato stabilito il miglior sistema di gestione dei pallet, provvedendo inoltre a suggerire miglioramenti futuri nell'ambito dei trattamenti di fine vita dei bancali di legno.

Parole chiave: LCA; bancali; sostenibilità; logistica; noleggio; fine vita; Nolpal; cambiamento climatico.



Contents

Abstract.....	i
Abstract in italiano.....	iii
Contents.....	v
Introduction	1
1 Wooden Pallets: characterization and management strategies.	2
1.1. Materials characterization	2
1.2. Current management strategies	3
2 Methodology: Life Cycle Assessment	6
2.1. LCA framework.....	6
2.2. Software and database	8
2.3. Existing LCA on the topic.....	8
3 NOLPAL company	10
3.1. EPAL rental and pooling system	10
3.2. Environmental aspects of the system	11
3.3. Comparisons with current management strategies.....	11
3.4. The Nolpal's model	13
3.4.1. The exchange model.....	13
3.4.2. Restoration of pallets.....	13
4 Goal and Scope.....	14
4.1. System boundaries	14
5 Life cycle inventory analysis	16
5.1. Data collection	16
5.1.1. Primary data by Nolpal	16
5.1.2. Secondary data from literature.....	16
5.2. Comparative analysis of two scenarios	18
5.2.1. Direct exchange without Nolpal	18
5.2.2. Direct exchange with Nolpal	19
5.3. End of Life.....	19
5.3.1. EoL Scenarios applied to the case study.....	21

6	Life Cycle Impact Assessment.....	22
6.1.	Results for the scenario without Nolpal.....	22
6.2.	Results for the scenario with Nolpal	25
6.3.	End-of-Life treatments implementation.....	27
	6.3.1. Alternative solutions for EoL of EPAL pallets.....	28
7	Interpretation.....	29
8	Conclusion and future developments.....	31
	Bibliography	33
	List of Figures	39
	List of Tables	41
	Acknowledgments	45

Introduction

Since their invention, pallets have occupied a very important role in industrial applications. As global markets continue to expand, the demand for seamless transport of products and materials makes pallets more vital than ever. Studies like the one conducted by Freedonia World Pallets [1] predict, based on historical data, an annual increase in pallet production and use of over 4% by 2028. However, the value of pallets lies not only in their practical applications but also in their low cost and simple manufacturing process. In fact, they are easily produced from readily available materials: wood selected for specific structural needs, steel nails, and protective chemical or heat treatments designed to prevent bacterial decay.

Along with the increase in the production and use of pallets, the environmental impacts and costs at every stage of their life cycle have also increased: one of the most relevant issues is the exhaust emissions from transport from producer to customer and vice versa. In this regard, Nolpal [2] plays a very important role, being the first Italian firm to introduce a disruptive nationwide EPAL pallet rental service. Established in 2011, Nolpal has reconfigured traditional logistics via an open pooling system. In Nolpal's alternative management system, clients lease EPAL pallets for product distribution, while this company assumes full responsibility for the most sensitive phase of the supply chain loop: the pallet return process. Nolpal's operational model spans a nationwide network of hubs called Nolpal points. This strategic positioning facilitates a localized return process: companies receiving goods can deliver empty pallets to the closest Nolpal site, avoiding the logistical inefficiency of long-distance repositioning. Such a system yields substantial environmental benefits by minimizing fuel consumption and atmospheric pollutants through the optimization of reverse logistics flows. Ultimately, the pallet is repaired directly at the Nolpal hub, simplifying another vulnerable stage in the EPAL pallet lifecycle.

The aim of this thesis is to compare and analyze the environmental impact of two possible scenarios: the standard EPAL management system and the one implemented by Nolpal across Italy. The analysis is performed using openLCA. Using a tailored model, the software evaluates the environmental footprint of pallets from raw material collection through their end use.

1 Wooden Pallets: characterization and management strategies.

1.1. Materials characterization

The origins of wooden pallets date back to the first half of the 20th century. The outbreak of World War II was a major impetus for their development, and as the global economy grew, pallets were adapted not only to the requirements of handling equipment but also to the dimensions of containers and trucks [3]. EPAL wooden pallets are the most common devices used to perform logistics operations all over the world, therefore they must present some very important mechanical properties and resilience. The choice of proper materials can, in part, guarantee these properties, as wood is known for its rigidity, durability, and longevity; that said, EPAL wooden pallets must undergo some chemical or heat treatments to prevent issues like the presence of bacteria in the wood that can affect the mechanical behavior of the device.

Pallet production is a straightforward process, relying primarily on two materials: softwood and steel nails. The first is wood from gymnosperm trees, such as conifers, which is widely available at relatively low cost; all such materials must first be tested to ensure they possess the mechanical properties necessary for their application. The testing is performed according to SAM 50 machine and measuring apparatus and so the modulus of elasticity under bending, bending strength, and destructive force under bending are carried out according to EN 408 [4], used to determine raw physical parameters (specifically stiffness and bending strength), which are subsequently normalized via EN 384 [5] to assign the timber to its definitive strength classes. Considering, for instance, non-destructive testing of pine wood [6], the results indicate high strengths for the sapwood of the pith zone, reaching C35 grade, and comparable strength properties (C20) have been obtained for the wood of the top zone and the sapwood of the middle zone part of the tested logs. The weakest is the heartwood material of the pith zone (C14) and middle zone (C16). Starting from these results, it is possible to achieve a wider vision of the mechanical properties of the materials used to create pallets performing a comparative study on density, mechanical strength and elastic modulus (MOE) of different samples.

As shown in Figure 1, by varying the composition and density of the timber, it is possible to tune the mechanical properties of pallets to the function it is required to perform. It is important to note that EN 338 [7], the normative that regulates the production of pallets, does not specify any minimum strength class but only regulates design and construction specifics, leaving it to the pallet manufacturer and the customer to agree on the mechanical characteristics based on the application.

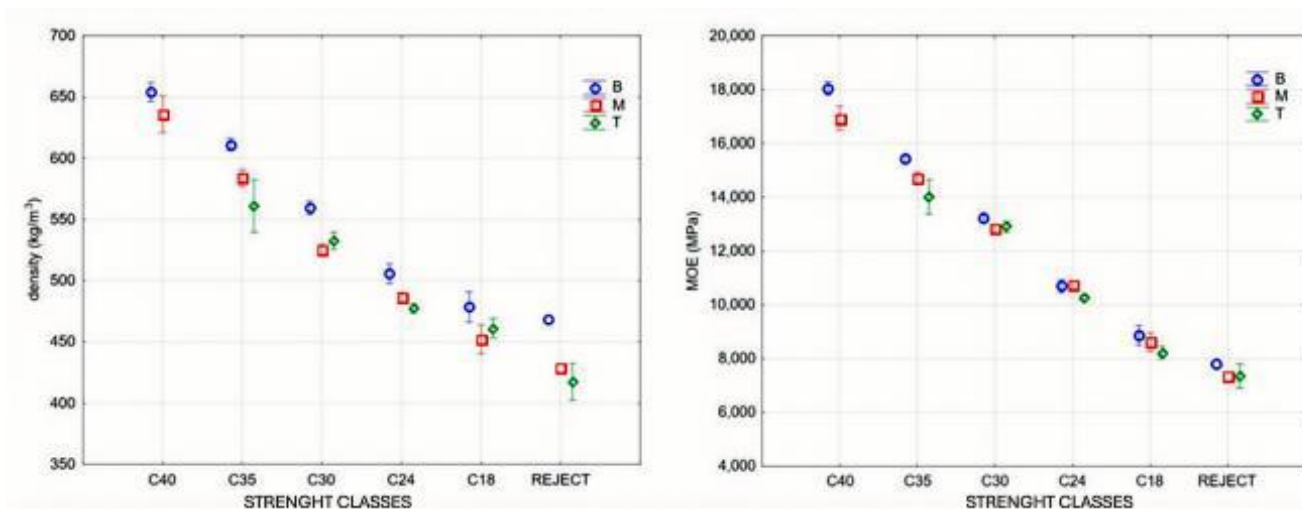


Figure 1: Comparative analysis of wood density and elastic modulus distribution within strength classes.

1.2. Current management strategies

The performed LCA study considered the 1200x800 mm EPAL wooden pallet shown in Figure 2. While many types of pallets are available today, including plastic and metal options, the focus of this study is shifted on EPAL1 pallets. For these, management prioritizes maintaining a highly resilient asset that can complete numerous trips before requiring repair or final disposal. The materials selected are boards of quality timber, woodchip, along with approximately 78 nails. The weight of an EPAL1 pallet is listed as 25 kg. The importance of EPAL pallets nowadays is also underlined by the European pallet association [8], as it states:

“The EPAL brand is widely recognized as a benchmark for quality, safety, and sustainability within the global logistics sector. With an estimated 675 million EPAL Euro pallets and approximately 20 million EPAL pallet boxes currently in circulation, the EPAL exchange pool constitutes the largest open pooling network worldwide.”

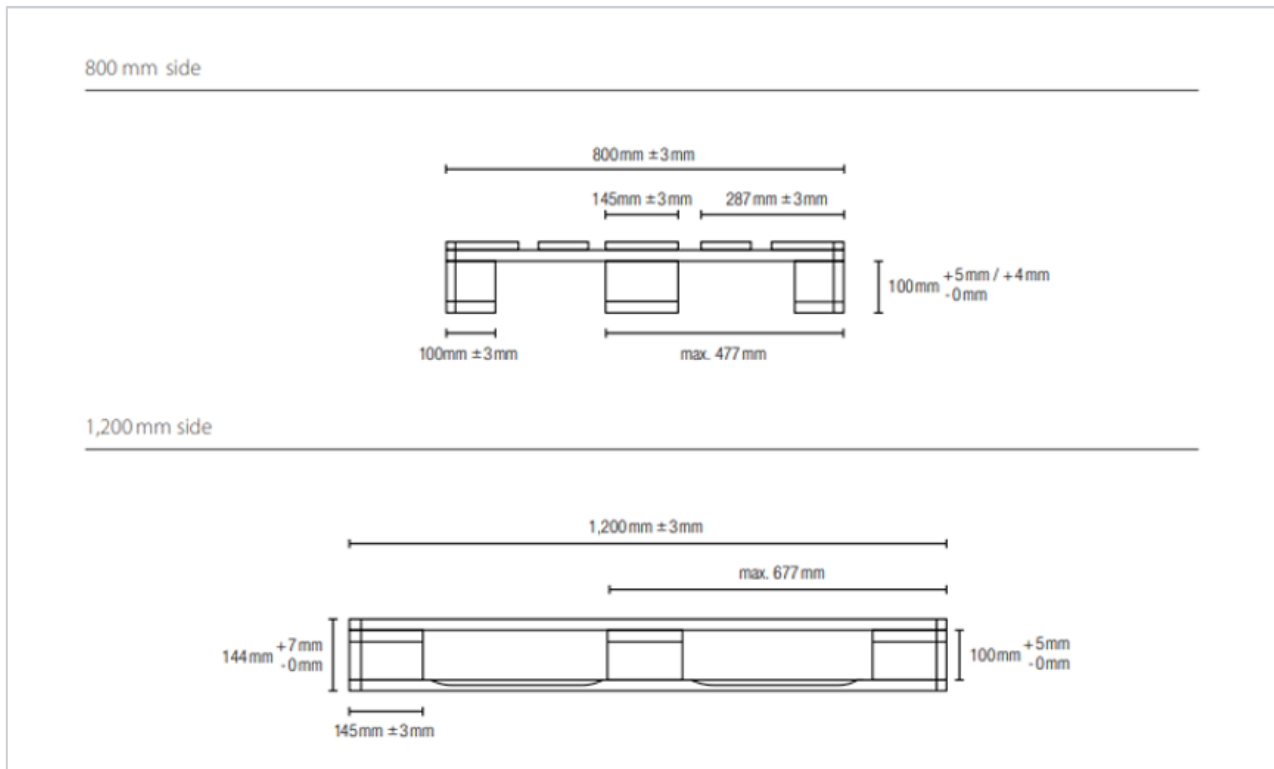


Figure 2: EPAL1 pallet specifications

Regarding the different management strategies for pallets, it is possible to distinguish between:

- Single use system;
- Buy/sell system;
- Pooled system.

The single-use strategy is designed to last only one trip, after which the pallet is typically disposed of, either to a landfill or for incineration; this strategy is not relevant to the current case study, since EPAL pallets are designed to last for several trips. The buy/sell system is surely the most common for long-lasting pallets: in this case, the producer sells the pallet to the customer, who can use it and eventually resell it. The last management strategy is the closed-loop or pooling one, which relies on leasing pallets; this is the case of companies like Nolpal, which are heavily focused on increasing the adoption rate of pallet rental systems among transport and logistics firms, shifting the industry away from traditional purchasing models. This transition not only yields an overall reduction of costs, as illustrated in Table 1, but also drives a substantial reduction in environmental pollution by curbing greenhouse gas emissions from transport vehicles [9].

Table 1: Comparison between management strategies' costs.

	Open loop (no salvage) Single use expendable	Open loop (salvage) Buy/sell	Closed loop (rental) Leased pallet pooling
Purchase costs	\$5/pallet	\$9/pallet	\$0/pallet
Salvage value	\$0/pallet	\$3/pallet	\$0/pallet
Cost of lost pallet	N/A	\$3/pallet	\$22/pallet
Ordering costs (transportation)	\$52,5/transport batch	\$52,5/transport batch	N/A

2 Methodology: Life Cycle Assessment

2.1. LCA framework

As established in the preceding sections, this research provides a comparative analysis of the environmental impacts associated with various End-of-Life (EoL) scenarios for EPAL pallets. This assessment is conducted using the Life Cycle Assessment (LCA) framework, the primary analytical tool for evaluating the environmental performance of the disposal pathways examined. LCA is nowadays one of the most used methodologies to inspect climate change and environmental problems due to the production, usage, and dismantling of products. The inception of the Life Cycle Assessment methodology can be traced back to the period between 1970 and 1990, a period in which environmental issues like resources and energy efficiency, pollution control, and solid waste became issues of broad public concern but it was only in the period between 1990 and 2000 (the so-called decades of standardization) that the International Organization for Standardization (ISO) has organized groups to give a standardization to the LCA method [10]. Finally, two international standards, still currently used, have been set:

- **ISO 14040 (2006E):** “Environmental management - Life cycle assessment - Principles and framework” [11]
- **ISO 14044 (2006E):** “Environmental management - Life cycle assessment - Requirements and guidelines” [12]

These are simple guidelines that provide a proper framework and terminology for LCA analysis, but, as noted in ISO 14040, the aim was never to standardize the method itself, since “there is no single method for conducting LCA” [13]. The ISO 14040 standard provides the fundamental principles and the overall framework for Life Cycle Assessment. The standard presents the core of the methodology, along with suggestions, depending on the defined scope and the logical structure to be followed, to provide a solid assessment. Complementarily, the ISO 14044 standard serves as the operational guide. It delineates the technical requirements and guidelines for conducting an LCA study, prescribing the minimum criteria for each phase, data management protocols, methodologies for allocation in multi-output processes, and the strict standards necessary for the critical review of the findings. The two standards

together define that all LCA studies must follow this iterative process to be considered valid, shown in Figure 3:

- **Definition of goal and scope:** defining the goal of an LCA involves clarifying its primary objectives, the motivations driving the study, the intended audience, and any comparative claims. Concurrently, establishing the scope requires a detailed specification of the product system, its operational function, the functional unit (i.e. 1kg of product), and the system boundary (a delimitation of which unit processes are part of an LCA and must be in line with the objectives of the study) must be in line with the objectives of the study [11] [12].
- **Life Cycle Inventory (LCI):** inventory analysis data should be collected for all unit processes contributing to the system boundary. The data may be measured, calculated, or estimated and will be used to quantify inputs and outputs for each unit process [11] [12].
- **Life Cycle Impact Assessment (LCIA):** this phase operates on a relative basis linked to the functional unit and is integrated with the other LCA steps to reduce uncertainties and eventual omissions. During this phase, environmental impact categories are selected based on their relevance to the product system under analysis, with the option to define new categories if necessary. The inventory results are then classified by allocating them to the appropriate impact categories (recognizing that some flows may contribute to more than one category) and characterized using category indicators [11] [12] [13].
- **Interpretation:** results are analysed, and the important issues that must possess completeness, sensitivity, as well as consistency are identified to define the so-called “environmental hotspots” (unit processes with the higher environmental impact) and so provide a solution to mitigate the undesired effects [13].

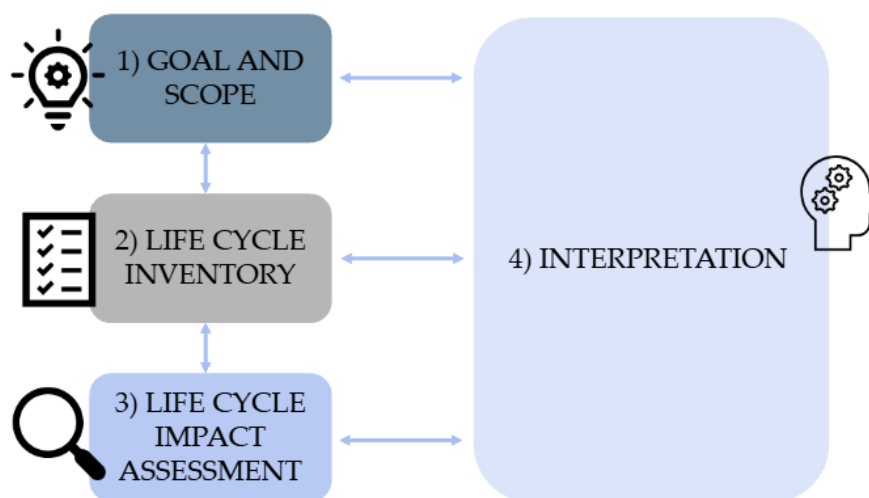


Figure 3: general methodological framework for LCA.

2.2. Software and database

The software used for this study is openLCA, developed by GreenDelta in 2006. OpenLCA is one of the most widely used tools for LCA analysis in both industrial and academic applications, thanks to its flexibility and compatibility with the ISO 14040/44 standards previously described. Open LCA relies on some key elements to perform data analysis:

- **Flows:** inputs and outputs of each process and are divided into elementary flows (obtained directly from nature without human interference), product flows (goods and services obtained by human elaborations) and waste flows (waste of the stage described by the process).
- **Processes:** units in which all the flows (inputs and outputs) are collected and accounted in order perform the analysis.
- **Product systems:** is the feature of Open LCA designed to generate automatically the supply chain (many processes connected to define all the stages of life of the desired product), connecting all inputs and outputs and allowing to assess the environmental impact of the case of study.
- **Projects:** allow to perform a comparison between different product systems and so to analyse different scenarios.

A key strength of OpenLCA lies in its database independence: rather than relying on a native database, the software serves as a neutral platform that can import and process major global datasets. Among these, Ecoinvent (version 3.11) is widely recognized as one of the most comprehensive and frequently utilized, and it has consequently been selected as the database for this study. First published in 2003, this database aims to facilitate Life Cycle Assessment (LCA) by providing comprehensive background data. It strengthens the technological and methodological foundation of LCI databases, offering modern capabilities, flexibility, and the scalable structure needed to become a truly global resource [14].

Nevertheless, there are limitations to the applicability of this software. While it offers highly precise assessments of industrial operations, it has a limited capacity to integrate social and economic variables. Consequently, when utilizing openLCA with an arbitrarily defined functional unit, the derived results are always classified as 'potential impacts' rather than definitive facts [15].

2.3. Existing LCA on the topic

This analysis is based on a cradle-to-grave approach, from raw materials selection through to the use and subsequent disposal of EPAL pallets, and the aim is certainly to drastically reduce the environmental impact of transport emissions, while also having the secondary benefit of reducing the management costs of each pallet.

As Ataee et al. [16] present in their article, land transport represents an important category of transport infrastructure assets (TIA) adding that LCA is one of the most used systems to assess the environmental impact of this type of transport infrastructure. Chhugani et al. [17] and Browne et al. [18] have analyzed the problem of computing an LCA analysis to define the best option in terms of emissions from different heavy-duty vehicles (trucks, buses, etc.) powered by different energy sources. They conclude that the adoption of alternative powertrains fuelled by "greener" energy sources can represent a preferable solution over conventional internal combustion engine vehicles (ICEVs), even when considering long-haul transport scenarios, all evident by adopting the Well-to-Wheel (WTW) life cycle framework, in which the overall environmental burden is shared between two distinct phases: the Well-to-Tank (WTT) stage, which encompasses the impacts associated with energy/fuel production and distribution, and the Tank-to-Wheel (TTW) stage, which quantifies the direct tailpipe emissions during vehicle operation. In this context, Chhugani et al. state that deploying hydrogen fuel cell electric vehicles (FCEVs) alongside battery electric vehicles (BEVs) is the most effective strategy for minimizing Global Warming Potential (GWP).

When it comes to environmental impact assessments for pallet management systems, two studies can be conducted using a cradle-to-grave approach: one focused on analyzing the impacts of different management strategies, and the other comparing pallets made from different materials.

Anil et al. [19] have performed a comparative analysis of the environmental impacts of plastic and wooden pallets applied in the grocery industry. The results are controversial: wooden pallets are the worst option compared to plastic ones in logistics operations and transport due to their higher weight, but the best option in terms of life-cycle environmental impacts. Khan and colleagues [13] added to this type of study the possibility of a wood-polymer composite pallet, which is significantly better than a plastic one across all environmental impact indicators, except for Global Warming Potential, when compared with wooden pallets.

In the article presented by Bengtsson and Logie [20] the comparison between different management systems is presented, resulting in achieving the best possible option in the case of the pooling system with respect to all the other strategies that have been previously presented.

3 NOLPAL company

Nolpal is a Casadei Group company founded in Emilia Romagna in 2011 as an innovative start-up focusing on pallet management. After a few years of structural calibration and shareholder alignment to perfect its complex business model, Nolpal officially proposed its standard EPAL pallet management service in Italy in 2015. Since then, the company has experienced rapid growth and now ensures full logistics coverage across all Italian regions, including the islands.

3.1. EPAL rental and pooling system

As a startup focused in implementing new management systems for EPAL standard pallets, Nolpal has introduced in Italy the concept of pooling or rental strategy. Operating through a network of strategically located sites at major transportation hubs, this organization serves as a critical enabler of sustainable logistics. On one hand, it guarantees the high availability of certified pallets nationwide; on the other hand, it optimizes reverse logistics flows. Specifically, this strategic positioning of the hubs minimizes transport distances, enabling companies to achieve significant cost savings by reducing expenditures on empty pallet repositioning, warehousing, inventory management, and structural reconditioning. This management system is surely a significant improvement over the standard management strategy, which requires producers to buy their own EPAL pallets, handle eventual repairs, and decide where to stack them.

The improvements brought by Nolpal do not stop at mere management systems; in fact, given the enormous number of Pallets to be managed, they have integrated an advanced electronic tracking system, based on vouchers like the one illustrated in Figure 4, that enables monitoring of the entire lifecycle of their logistics assets. The implementation of electronic vouchers digitalizes transaction records, facilitating seamless exchange processes and enforcing strict accountability among supply chain actors. Consequently, this transition from traditional paperwork to a digital framework drastically reduces process lead times and optimizes overall management efficiency. [2]

Mittente o Destinatario		Emititore	Transportatore
THE COMPANY spa P.IVA: 789123456 Nodo Mittente:		SAMPLE FACTORY spa P.IVA: 123456789	LOREM IPSUM LOGISTICA srl P.IVA: 9876543210 Targa: Autista:
Buono dematerializzato Token 1234567 del 1/1/2024			
LASCIA IN DEPOSITO (IN) - INGRESSO Riferimento At Doc 3456/5 - 1/1/2024 Pallet (PAG) usato conforme all'intercambio (A-B-C) nr. 20		RITIRA DA DEPOSITO (OUT) - USCITA Riferimento:	
Firma per conto di SAMPLE FACTORY spa:		Firma per conto di LOREM IPSUM LOGISTICA srl:	- id 1234 Operatore: lorem ipsum generalist Operazione modificata: lorem ipsum generalist 1/1/2024
Voucher51		Buono gestito elettronicamente da Voucher51 Questo documento è inviato elettronicamente a Voucher51 Utilizzabile solo come ricevuta	

Figure 4: Example of Voucher 51 provided by NolPal

3.2. Environmental aspects of the system

The rental system adopted by Nolpal not only offers cost advantages, as already presented, but also brings important improvements in the company's environmental sustainability. In fact, the management strategy promoted by Nolpal promotes the implementation of a circular economy, incrementing the lifespan and the reuse of a single pallet while also reducing the environmental impacts of their usage as well as reparation and disposal, since the company also provides a dismantling and recovery of waste service for pallets that have reached the end of their life cycle. The waste is transformed into pallet blocks, which are then used for repairs or directly to produce new pallets.

3.3. Comparisons with current management strategies

In the standard management systems, all pallets are treated in the same way, the usage stage of their life always consists in the delivery of pallets from the trademark industry to the large-scale retailers and then they must be immediately returned, regardless of their condition, whether intact, in need of repair or too damaged to be used again. A critical limitation of this traditional management strategy is the inherent necessity for long-distance empty transit, leading to high fuel consumption, extremely high emissions, and long transportation times, as well as high costs. In this situation, the management strategies of single-use expendable pallets, to avoid the return trip, sending pallets directly to disposal, and the pooling-rental system provided by companies like Nolpal have gained more ground.

Figure 5 shows the standard direct exchange system (scenario A), in which the complete round trip of pallets is presented. There is also the possibility of a deferred

exchange, in which the retailer can't return the pallet immediately, so the transportation company must make two additional trips to close the loop.

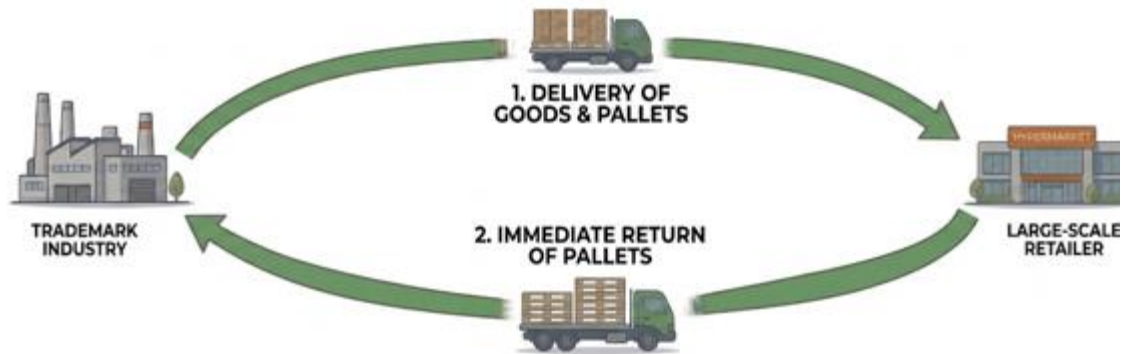


Figure 5: Schematic representation of current management strategy.

Tornese and her colleagues [21], in their study on the logistics operations in the pallet supply chain, presented this issue as inherently controversial because the optimal strategy varies depending on the supply chain node analysed, and so on the interaction between the different stakeholders that take part in the chain, as shown in Figure 6. Pallet suppliers typically favour a single-use strategy to leverage low purchasing costs and operational simplicity. Conversely, other supply chain stakeholders face a detrimental economic impact due to reduced operational turnover, thereby preferring conventional management systems. Consequently, a closed- or open-loop pooling network represents the most balanced alternative; in fact, by transitioning from asset ownership to a service-based model (Rental/Pooling), suppliers benefit from reduced transportation and management costs, while other network participants maintain their role in the circular economy through continuous inspection, maintenance, and redistribution activities.

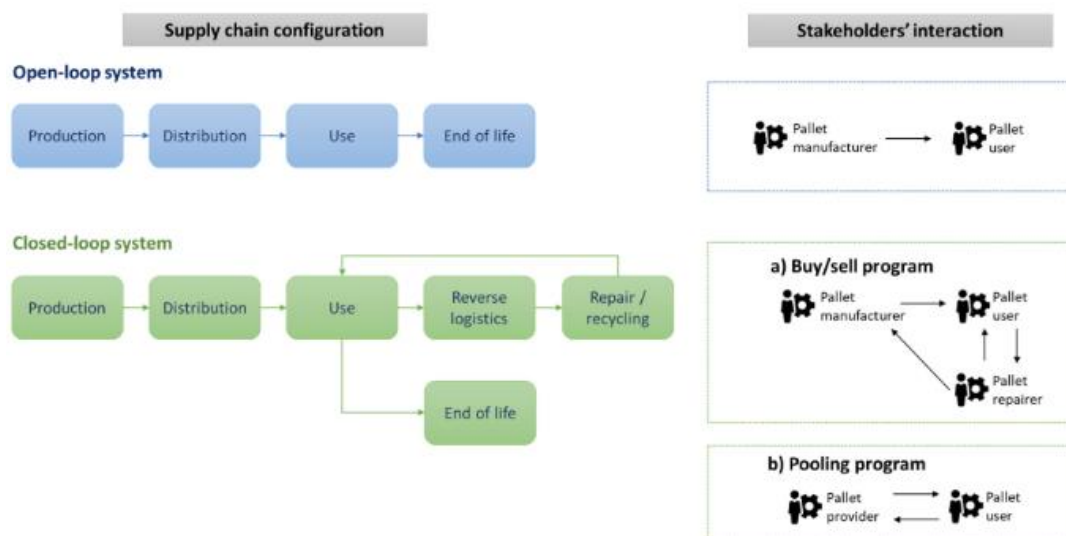


Figure 6: Open and closed loop models with stakeholders' interaction.

3.4. The Nolpal's model

As already mentioned, Nolpal has established in Italy in the sector of logistic operations in the pallet's supply chain, bringing innovative ideas and strategies to reduce the costs and simultaneously enhance the environmental sustainability of the standard management strategies.

3.4.1. The exchange model

This scenario, as illustrated in Figure 7, consists in the pallet as not directly purchased from the manufacturer by the trademark industry but as rented from one of the Nolpal's hubs, called Nolpal points. After completing the delivery trip to the large-scale retailer, there is no need to send it back since it can be easily returned to one of the other Nolpal points located near the retailer, thus reducing both transportation costs and emissions. The company has studied the hubs' locations, usually placing them in areas where major retailers are concentrated, to facilitate the exchange of rented pallets.

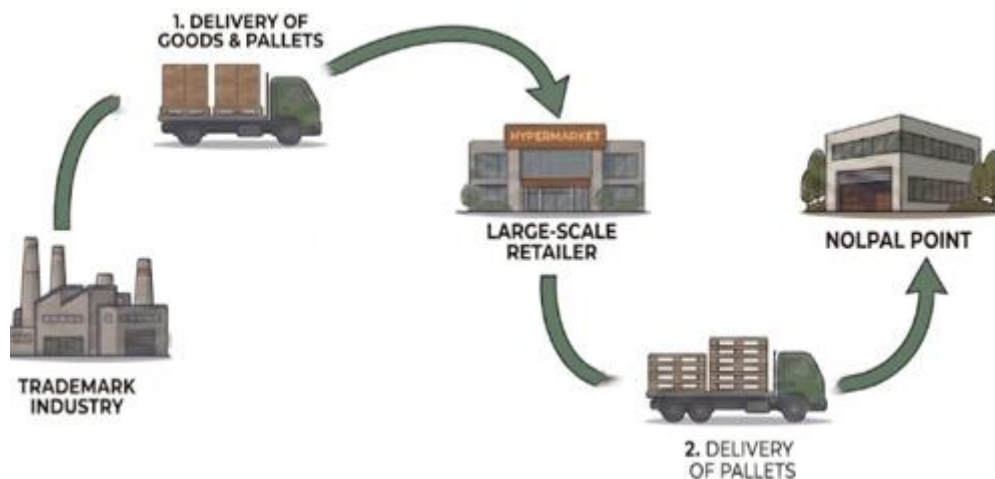


Figure 7: Schematic representation of Nolpal's exchange system

3.4.2. Restoration of pallets

The standard buy/sell system is often affected by situations in which returned pallets are structurally too compromised to be used again unless they undergo a restoration process. Nolpal offers a solution that is even more eco-friendly than repairing them: repair stations directly within their local warehouse facilities (Nolpal points). This decentralized maintenance strategy avoids reverse logistics, thereby reducing transport costs and emissions associated with the round trip to refurbish a pallet.

4 Goal and Scope

The aim of this study is to define the environmental impacts of the model proposed by Nolpal and then compare them with those of the standard methodology, with reference to the direct exchange system.

The study is based on an LCA analysis and so the very first step to be achieved is the definition of the correct functional unit (FU), which is used to normalize the material inputs and outputs and environmental impacts of the system based on the function of the product. Determining the functional unit is one of the most critical and complex challenges in LCA methodology, as it requires balancing strict mathematical standardization with the multidimensional operational realities of the system under analysis. The functional unit is defined as “The Delivery of 75000 kg of product loads by means of EPAL pallets”. The number of pallets required to fulfil the selected FU has been calculated using the load carrying capacity and reference service life (RSL) of the pallet analysed, seen as the estimated number of trips a pallet can perform before reaching the end-of-life phase [22]:

$$= \frac{75000 \text{ kg of product delivered}}{\text{RSL} \left(\text{number of } \frac{\text{trips}}{\text{pallet}} \right) \times \text{load bearing capacity} \left(\frac{\text{kg}}{\text{trip}} \right)}$$

Assuming a maximum load capacity of 1500 kg per trip, the total transport requirement is calculated at 50 trips. Since a single EPAL pallet has an estimated lifespan of 25 trips, two pallets are needed to transport the total product volume. The study used a cradle-to-grave approach to evaluate the environmental impact of these two pallets across their entire life cycle, from raw material extraction to final disposal.

4.1. System boundaries

As previously stated, this analysis considers all stages involved in EPAL pallets' life cycle, as shown in figure 8. Starting from the collection and processing of raw materials heading to assembly, usage and end-of-life phases. The purpose of this study is to compare the environmental emissions generated by the two different possible

scenarios, analysing how the change in the management system affects the overall impacts of the entire pallets' life cycle. With this fixed boundary condition, variation in the environmental indicators can be associated with the exclusively attributed to the differences in the logistics and transport management strategies being evaluated.

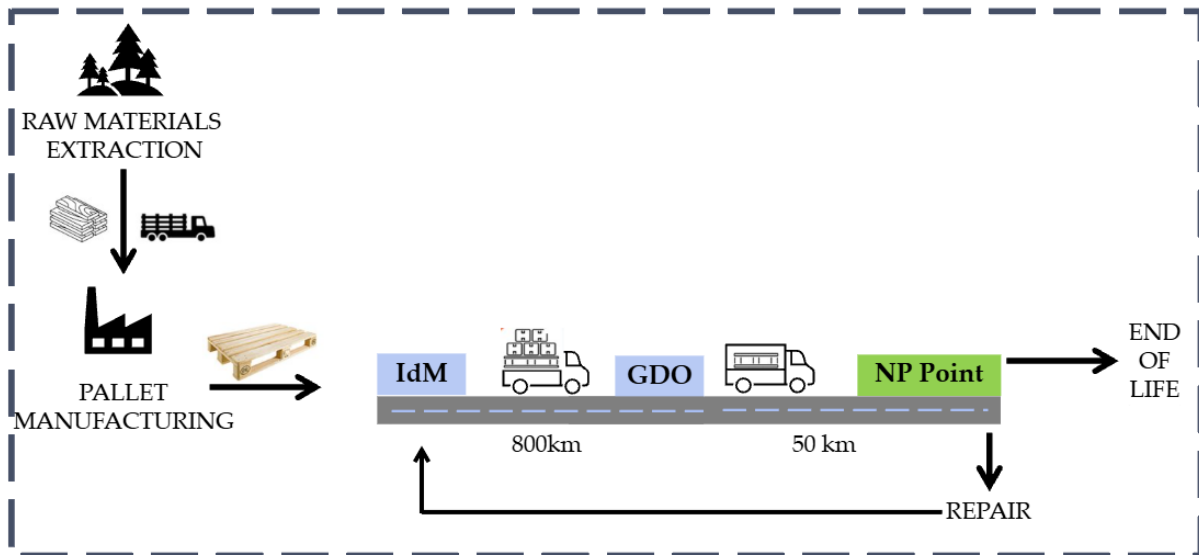


Figure 8: System boundaries in life cycle of pallets (with Nolpal)

The study is geographically limited to the country of Italy, accounting the distribution of Nolpal points. The data provided by the company cover a six-month period, while, for secondary data, an average value from recent data available in literature have been used.

5 Life cycle inventory analysis

5.1. Data collection

The focus of the study is the comparison of the use and transport phases in two different scenarios:

- Scenario A: direct exchange of EPAL pallets without Nolpal
- Scenario B: direct exchange of EPAL pallets with Nolpal

The primary data for this study have been directly provided by Nolpal: they cover a six-month period and pertain to a specific trademark industry that executed shipments. The industry managed the outbound distribution of goods utilizing EPAL pallets, executing truckload shipments to 937 mass-retail locations characterized by high geographical dispersion across Italy. The operational loop and reverse logistics cycle of the pallets have been completed by leveraging 38 dedicated NolPal points distributed throughout the national territory. This network density ensured the continuous collection, sorting, and balance-reconciliation of the pallet fleet. Secondary data, such as those on raw materials for the production stages and on end-of-life treatments, have been instead derived from the literature.

5.1.1. Primary data by Nolpal

The primary data provided by the company allows for the comparison at fixed distances:

- 800 km = average distance between the trademark industry and the retailer.
- 50 km = average distance between the retailer and the nearest Nolpal point.

As shown in Chapter 4, the functional unit chosen for the study assumes that two EPAL pallets (each approximately 25 kg) and their respective loads need to be carried during the trip. Since there are no specific indications of the type of truck involved in the logistics, the study is modelled using EURO 6 lorries fuelled by diesel. The analysis itself considers only emissions from the use of this type of truck (carbon dioxide or monoxide, methane, etc.), not emissions related to their production stage.

5.1.2. Secondary data from literature

The production stage of EPAL pallets has been divided into three steps:

- Sawing: wood logs are cut into green lumber.
- Drying: green lumber is dried to obtain rough dry lumber
- Planing: elaboration of lumber to obtain wooden boards for pallets.

In addition, a process called "boiler" is introduced, reusing all sawing by-products to generate industrial heat needed for drying, planing, and in the assembly stage for Phytosanitary treatments [23]. The overall boundary system for the production stage is shown in Figure 9:

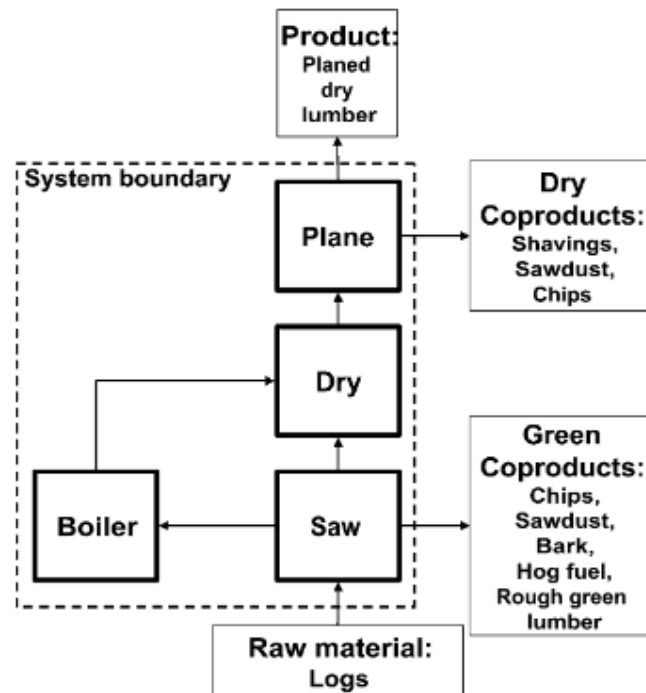


Figure 9: System boundaries of the production stage

The production stage starts with 1343 kg of logs, including bark, that must undergo the three processes just presented, obtaining finally the so called “planed dry lumber” necessary for the assembly of EPAL pallets. All consumption values, such as electricity and thermal energy, have been collected from previous LCA studies and the literature [24]. The boiler process has been modelled using data from CORRIM, incorporating findings from the work of Ipina [25] and Milota et al. [26].

All providers used are limited to the territory of Italy or Europe, in the case of providers generalized across all countries.

5.2. Comparative analysis of two scenarios

5.2.1. Direct exchange without Nolpal

The traditional exchange system is based on the arrange of shipment of pallets of goods from the trademark industry to the large-scale retailer's location. After arriving at the destination, carriers are unloaded and immediately return to the trademark industry with pallets used for the delivery.

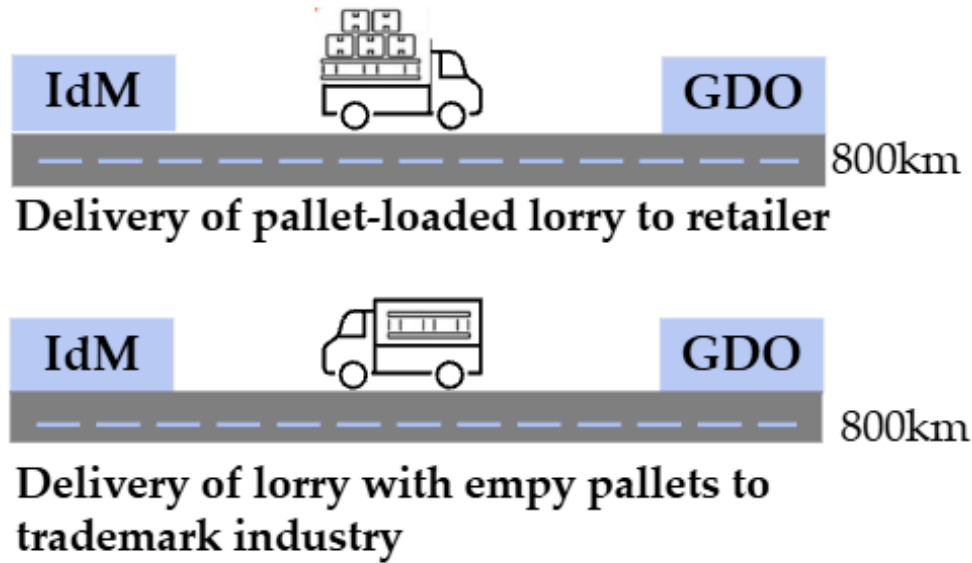


Figure 10: Unit processes for direct exchange without Nolpal

As shown in Figure 10, shipments of goods with pallets directly provided by Nolpal must be considered. To perform the correct analysis for the functional unit selected, the number of necessary trips has been set to 50 so, accounting an average value of 25 trips per pallet life cycle, each shipment involves the usage of 2 pallets weighing 25 kg each and the chosen approach is to define two different trips, one loaded and one empty:

- Loaded pallet delivery evaluated as $25 \text{ kg} \times 800 \text{ km} \times 25 \text{ trips} \times 2 \text{ pallets}$
- Empty pallet delivery evaluated as $25 \text{ kg} \times 800 \text{ km} \times 25 \text{ trips} \times 2 \text{ pallets}$

This calculation entails 25 round trips of approximately 800 kilometres, assumed constant for both loaded and empty transit. Given a pallet weight of 25 kg, the total is multiplied by two to account for both pallets evaluated in the study. It is important to underline that, being this study fully focused on the impact of pallets logistic operation, we do not account also the weight of the goods transported in the delivery trip to perform the assessment, but only the weight of the pallet. This approach has been chosen by following other studies focused on this subject [27]. In this case, impact

due to the necessity of an average of two restorations in a life cycle of one pallet have been evaluated on the basis of a round trip of around 150 km to the repairer

5.2.2. Direct exchange with Nolpal

In this scenario, shown in Figure 11, after goods are dispatched from the trademark industry and unloaded at the retailer site, the empty vehicle is redirected to the nearest Nolpal facility, averaging 50 km away, rather than returning 800 km to its origin. Moreover, since restoration is conducted on-site at the Nolpal hub, supplementary transport to an external repairer is entirely bypassed.

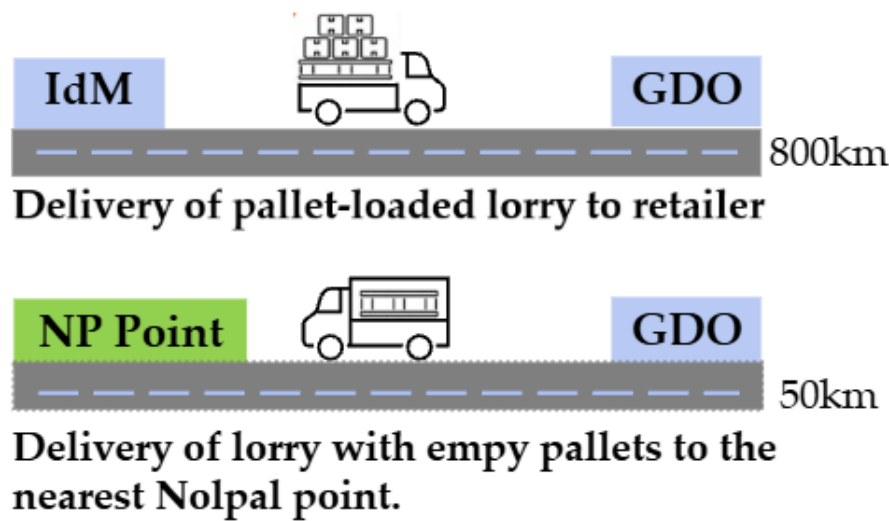


Figure 11: Unit processes for direct exchange with Nolpal

5.3. End of Life

In a cradle-to-grave approach, a relevant role in assessing environmental impacts is played by End-of-Life (EoL) treatments, specifically the pallet's disposal. For this reason, the EoL stage has been added to the model.

The structural composition of the EPAL pallet consists of 97% wood and 3% metallic components [28]. Regardless of their classification (single-use, EPAL-standard, or manufactured from alternative materials), all pallets inevitably reach the end of their operational lifecycle, necessitating appropriate disposal or end-of-life management. The end-of-life scenario, as shown in Figure 12, can be modelled utilizing empirical data provided by Rilegno, the Italian national consortium for wood packaging recycling, and relies on four different possible scenarios [29]:

- Landfill
- Incineration and industrial heat production
- Recycle
- Composting

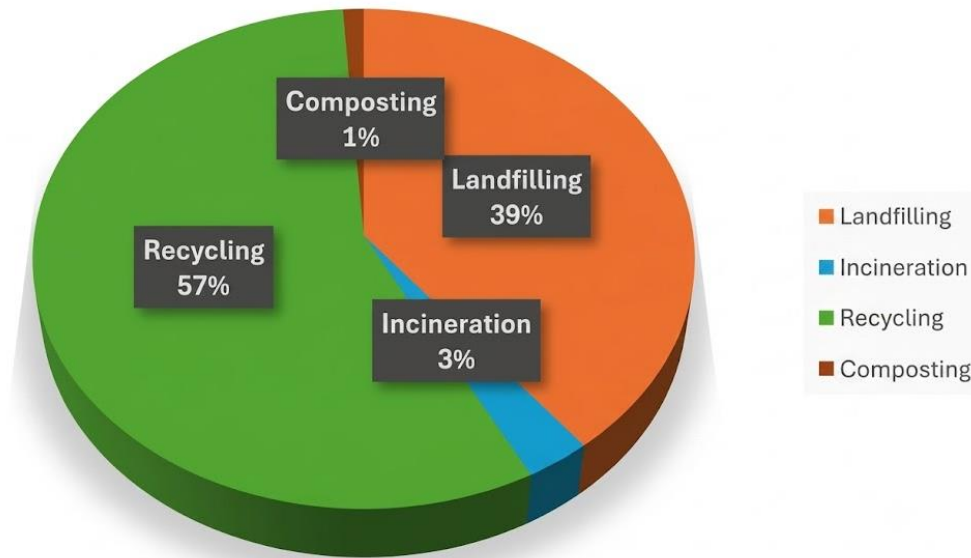


Figure 12: Possible End-of-Life scenarios for wooden pallets.

Each one of them holds aspects to be deeply evaluated, especially in conducting an LCA study like in this case. The ecological impact of landfilling several pallets, alongside their incineration, is a particular case study, for which several critical emission patterns emerge depending on combustion efficiency and material composition. First, elevated carbon monoxide (CO) levels are a direct indicator of incomplete combustion in the incinerator. Furthermore, comparative analyses reveal that the thermal degradation of engineered or composite wood yields significantly higher nitrogen oxide emissions than that of raw wood, a phenomenon primarily attributed to the presence of nitrogen-based resins utilized during industrial processing. From an atmospheric perspective, the resulting acid gases and NO emissions contribute substantially to acid rain generation; moreover, they act as a primary reactant in the formation of photochemical smog resulting in severe public health risks through the generation of fine respirable particulate matter, which is characterized by prolonged airborne retention times and high toxicity [30]. The most widely investigated impact categories are usually global warming (climate change), acidification, eutrophication, human toxicity, ozone layer depletion, and ecotoxicity and they can be all quantitatively evaluated using specialized software such as OpenLCA, which is anticipated to perform the analysis and return the results regarding the critical impacts of the various scenarios analysed.

5.3.1. EoL Scenarios applied to the case study

This study evaluates the environmental impacts of three out of the four identified end-of-life (EoL) treatments: landfilling, incineration, and composting. These three scenarios have been modelled using the robust background datasets available in the Ecoinvent database. The recycling scenario, however, has been excluded from the current quantitative assessment due to a lack of specific, representative data for the recycling process of this particular wooden product. Unlike landfilling or incineration, accurately modelling wood recycling requires highly specific primary data on downstream conversion processes and material flows. Furthermore, under the Ecoinvent "Allocation, cut-off by classification" system model, the primary life cycle boundary ends at waste collection, and the system does not grant burden credits for the provision of secondary materials (which would instead require a substitution or system expansion approach). Properly assessing the full climate impact of the recycling pathway requires precise data on the specific secondary operations, as well as a meticulous accounting of biogenic carbon flows across extended life cycles. While not feasible within the data constraints of the present study, assessing the recycling treatment represents a key direction for future research, provided that specific data on the recycling processes are obtained. [31].

6 Life Cycle Impact Assessment

This chapter presents the results of the performed assessment. These results are derived using the globally recognized EF v3.1 no LT method, where EF stands for Environmental Footprint and “no LT” means that Long Term emissions are not accounted, a method overseen by the European Commission. The impact is evaluated across multiple categories, including climate change, ozone depletion, human toxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication.

6.1. Results for the scenario without Nolpal

As the primary objective of this study is to compare the two distinct scenarios, the analysis begins by detailing the direct-exchange baseline, which evaluates supply chain operations prior to Nolpal's involvement. After a comprehensive screening across all 25 analysed impact categories, the focus has been shifted directly to the Climate Change indicator to evaluate the environmental implications of these baseline data. This targeted analysis enables a clearer understanding of the drivers of the carbon footprint and the potential mitigation strategies offered by alternative logistics models.

In Table 2, the results for the 16 principal categories are presented, allowing the definition of the overall impacts of the pallets' life cycle in the scenario without Nolpal. According to the impact results shown in Figure 13, the transport and use of the pallets is the most impactful stage, compared with the repair and production stages. This trend confirms the importance of providing solutions that reduce the impacts of pallet logistics and thus underscores the importance of companies like Nolpal.

Table 2: Impact category results for the scenario without Nolpal

Impact category	Reference Unit	Result
Acidification	Mol H ⁺ -Eq	0,89417
Climate change	Kg CO ₂ -Eq	412,084
Ecotoxicity: freshwater	CTUe	1622,19
Energy resources: non-renewable	MJ, net calorific value	5781,72
Eutrophication: freshwater	kg P-Eq	0,00464
Eutrophication: marine	kg N-Eq	0,21357
Eutrophication: terrestrial	Mol N-Eq	2,35889
Human toxicity: carcinogenic	CTUh	3,1E-06
Human toxicity: non-carcinogenic	CTUh	3,7E-06
Ionising radiation: human health	kBq U235-Eq	1,34061
Land use	Dimensionless	12442,1
Material resources: metals/minerals	kg Sb-Eq	0,00136
Ozone depletion	kg CFC-11-Eq	8,1E-06
Particulate matter formation	disease incidence	2,9E-05
Photochemical oxidant formation: human health	kg NMVOC-Eq	1,46370
Water use	m ³ world Eq deprived	33,8767

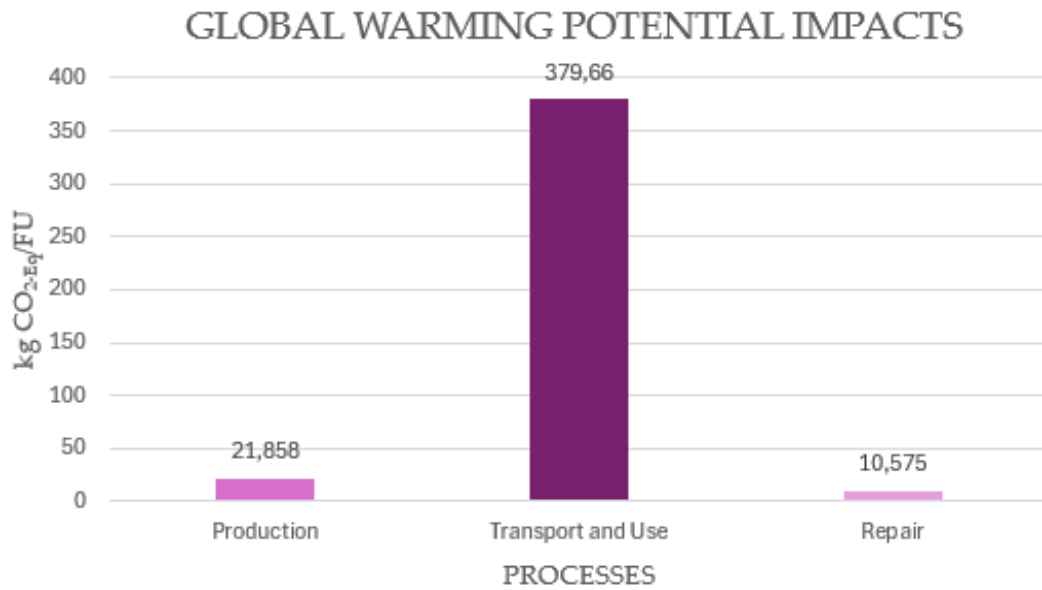


Figure 13: Processes' contributions to climate change, without Nolpal system.

Table 3: Share of impacts without Nolpal

NO NOLPAL SCENARIO	Production	Transport and use	Repair
Percentage of incidence	5,30%	92,13%	2,56%

Results show how the climate change is one of the most detrimental categories, especially when analysing the transport and use stage, since, as shown in Table 3, 92,13% of the overall impacts are from thus life phase; specifically, this impact category quantifies the release of greenhouse gases (GHGs) into the atmosphere. Because individual GHGs possess varying global warming potentials, the method standardizes these emissions by converting them into a single reference unit: kilograms of carbon dioxide equivalent (kg CO₂-Eq). Furthermore, the EF v3.1 characterization method reports both the cumulative total and a detailed breakdown across three sub-indicators: fossil, biogenic, and land use and land transformation. In the context of this study, while the biogenic and fossil sub-categories represent the most relevant metrics, the fossil component exerts the most significant weight on the total Climate Change score. This dominance is primarily driven by fossil-derived emissions (specifically diesel combustion during truck transport) underscoring that the overall carbon

footprint is heavily dictated by distribution and reverse logistics rather than the initial pallet manufacturing phase.

6.2. Results for the scenario with Nolpal

In this section the same table (Table 4) with results for each impact category is presented but with the implementation of the Nolpal system.

Table 4: Impact category results for the scenario with Nolpal

Impact category	Reference Unit	Result
Acidification	Mol H ⁺ -Eq	0,51194
Climate change	Kg CO ₂ -Eq	228,522
Ecotoxicity: freshwater	CTU _e	942,760
Energy resources: non-renewable	MJ, net calorific value	3200,49
Eutrophication: freshwater	kg P-Eq	0,00322
Eutrophication: marine	kg N-Eq	0,12406
Eutrophication: terrestrial	Mol N-Eq	1,36787
Human toxicity: carcinogenic	CTU _h	1,8E-06
Human toxicity: non-carcinogenic	CTU _h	2,1E-06
Ionising radiation: human health	kBq U235-Eq	0,76924
Land use	Dimensionless	10882,1
Material resources: metals/minerals	kg Sb-Eq	0,00075
Ozone depletion	kg CFC-11-Eq	4,4E-06
Particulate matter formation	disease incidence	1,6E-05
Photochemical oxidant formation: human health	kg NMVOC-Eq	0,82866
Water use	m ³ world Eq deprived	21,2486

Table 5: Share of impacts with Nolpal

NOLPAL SCENARIO	Production	Transport and use	Repair
Percentage of incidence	9,57%	88,26%	2,17%

As shown in Table 5 the percentage of impacts of the use stage is reduced, and this is because the alternative provided by Nolpal optimizes the transportation distances, facilitating the logistics and reducing the emissions.

In Figure 14 the comparisons of the effects of the two scenarios are presented in terms of climate change for the stage of transportation, use and repair:

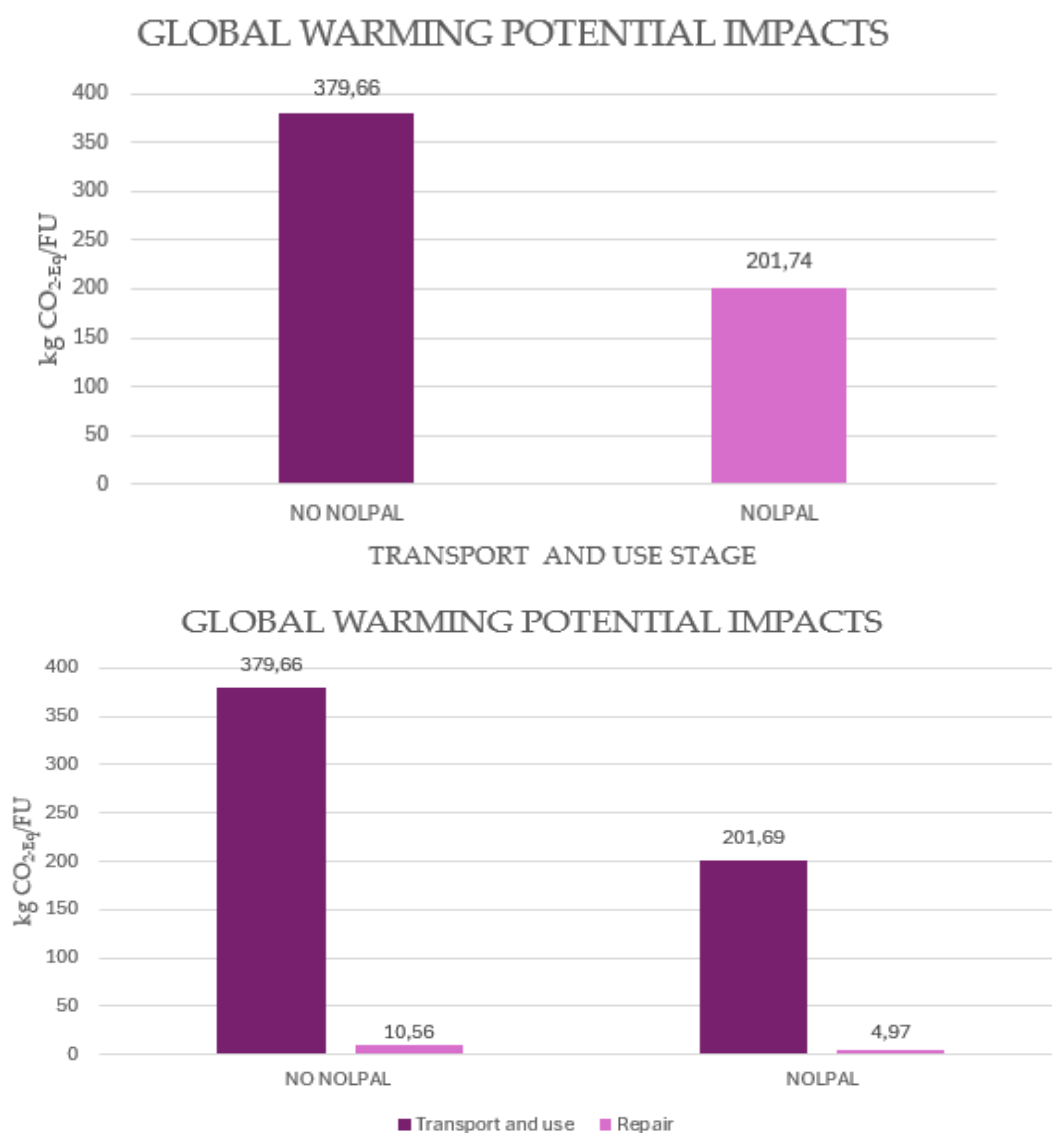


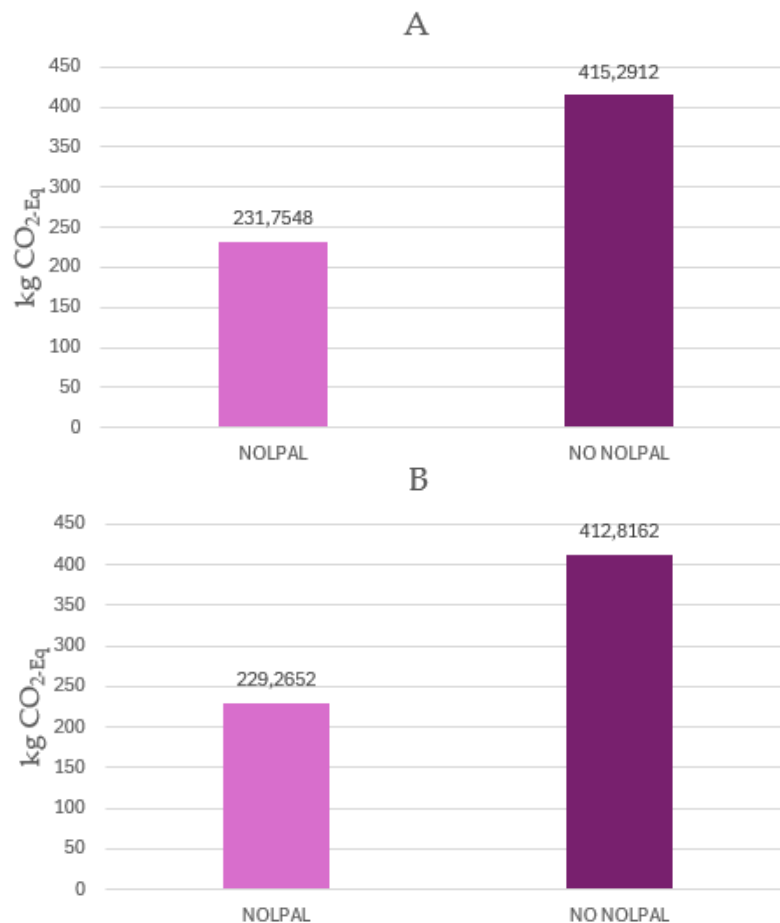
Figure 14 Climate change results for the two scenarios

Specifically, the scenario involving the implementation of Nolpal method represents a reduction from 379,66 kg CO₂-Eq to a value of 201,69, meaning that the emissions of greenhouse gases are reduced by more than the 53%. These results in climate change, but also in the others impact categories, confirm that Nolpal provides a system that is, ecologically speaking, way better than the standard systems.

6.3. End-of-Life treatments implementation

In a cradle-to-grave approach the assessment is performed considering processes from the collection of raw materials for the production stages till the very ending stages of the life cycle of the product considered. As already mentioned in the previous chapters, this study analyses the EoL treatments of landfilling, incineration and composting for both the scenarios presented and compares the results obtained.

The results obtained, shown in Figure 15, are referred to the treatment of the two pallets necessary to compute the analysis of the selected functional unit and are useful to underline how, also in this case, the overall impacts are drastically reduced when a company like Nolpal takes over by promoting a pooling/ rental system instead of the conventional ones. The reduction percentage is always around 55-56%, equal as previously seen for the transport and use stage, showing again how this stage of the pallet life cycle is the most detrimental one.



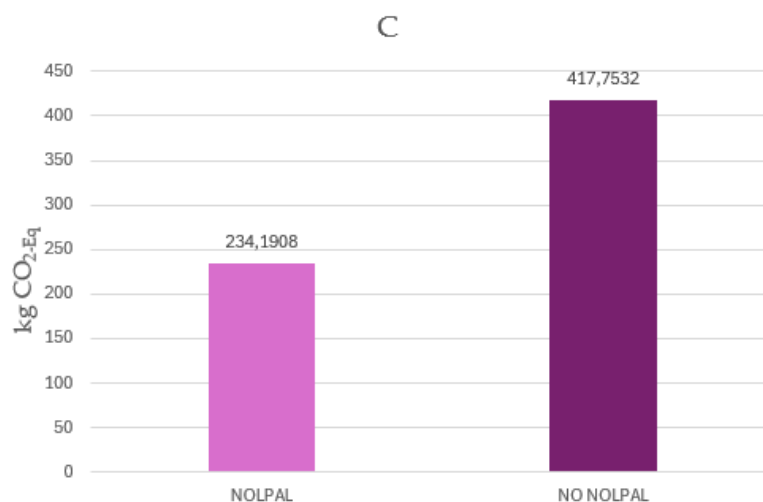


Figure 15: Climate change results for EoL scenarios: A-Landfilling; B-Incineration; C-Composting

6.3.1. Alternative solutions for EoL of EPAL pallets

In addition to the standard End-of-Life treatments there is also the possibility to adopt the innovative concept of circular economy: the objective is to decouple the economic growth and industrial production from consumption of finite resources, keeping materials and components to their highest value and utility as long as possible. The purpose is to eliminate waste and pollution derived from the EoL treatment of products like damaged pallets; this means using materials from damaged pallets to form new products avoiding the research of other raw materials and so facilitating the regeneration of natural systems. Within circular economy, the just presented approach is one of the most powerful and is named Industrial Symbiosis (IS). Normally, the term “symbiosis”, refers to a biological interaction between two different organisms that take benefits mutually one from the other and so is for industrial symbiosis, where residues, by-products and waste of one company become new resources and raw materials for the production of another.

Industrial symbiosis not only allows the restoration of natural systems but also reduces drastically the costs of end-of-life treatments and the emissions derived from them, leading to an even more “green” management system of EPAL pallets.

7 Interpretation

The aim of the study is to obtain an environmental impact assessment both for the scenario of the standard management system and the pooling/rental one proposed by Nolpal, in the case of EPAL pallets.

The characterization results obtained for the conventional pallet lifecycle clearly demonstrate that the transport and use phase represents the primary source of environmental impact. This insight is made accessible by adopting a comprehensive cradle-to-grave boundary condition, which captures the full timeline of the asset. For the reasons just presented there is undoubtedly the need to provide new solutions to reduce the impacts of the transport and use stage, especially accounting for the ever-increasing distances that the pallet supply chain must cover, even outside of Italian territory. The model proposed by Nolpal results to be more sustainable, acting to reduce drastically the distances covered, both for the return trip of pallets and the eventual trips to the repairer, and so the resulting emissions.

In comparison with the standard approach, Nolpal's system results in a reduction in the overall emissions of more than 53%. This result shows the effectiveness that the alternative strategy proposed has on the environmental footprint of pallet's supply chain, especially with articulated and large vehicles. Evaluating the results of this research and comparing them with existing literature a notable trend is revealed [32]; studies report an environmental impact reduction of approximately 35–40% for transport routes of an average of 300 km. When compared with the 56% reduction achieved in this analysis, which considers trips of approximately 800 km, the efficacy of Nolpal's logistical model increases proportionally with transport distances. In other words, the environmental and operational benefits of this optimized pooling network become increasingly pronounced as the total mileage of the logistics loop expands.

The cradle-to-grave approach adopted allows the assessment of environmental impacts also for the End-of-Life stage, this analysis not only can provide information for the transport and use stage but also can set the fundamental basis for alternative strategies also for the very end stages of pallets life cycle. Incorporating the principles of industrial symbiosis, specifically through the continuous cascading reuse of severely compromised pallets and their constituent raw materials, presents a highly effective strategy to be added to the already effective one proposed by Nolpal. This integrated approach is critical for mitigating the escalating environmental burdens generated by a rapidly expanding logistics sector. Furthermore, using this strategy to

encompass alternative material and configurations for pallets, such as composite or advanced polymer-based or the metallic ones, would allow the model to capture broader supply chain networks and optimize the lifecycle efficiency of diverse transport asset typologies.

8 Conclusion and future developments

The continuous expansion of the global industrial apparatus intrinsically accelerates the demand for material handling assets, establishing a direct correlation between macroeconomic growth and pallet production. In this situation, traditional management strategies are becoming ecologically and logistically unsustainable, necessitating a shift toward innovative distribution strategies. Nolpal occupies a prominent position within the European logistics landscape, as the first company in Italy to operationalize a comprehensive, decentralized pooling model, it represents a pioneering framework that demonstrates how targeted structural optimization can effectively separate the concepts of ever-growing industry and supply chain emissions. Indeed, Nolpal introduces a comprehensive reconfiguration of the conventional pooling system by deploying a network of regional hubs, designated as "Nolpal Points," strategically positioned adjacent to primary freight corridors and transport junctions. This decentralized network architecture constitutes the core strength of the proposed model. By significantly narrowing the physical distance between retailers and pallet suppliers, the system effectively optimizes transit routes, thereby drastically reducing greenhouse gas emissions by eliminating long-haul empty-trip inefficiencies.

The assessment has been performed by computing an LCA analysis. The data, collected both by direct contact with Nolpal and by making average values of the one reported in pre-existing articles, have been inserted in the software only as input and output and this enabled the software, based on the database Ecoinvent, to process the life cycle inventory data and successfully compile the final impact assessment results.

Selecting a comprehensive cradle-to-grave boundary condition (rather than the more restricted cradle-to-gate or gate-to-gate frameworks) proved essential for conducting a comparative analysis across all lifecycle stages. This total-system perspective reveals two critical points: first, that the transportation and operational use phase must be prioritized for structural modifications to achieve immediate greenhouse gas reductions, and second, that future iterations should incorporate advanced End-of-Life strategies, with a specific emphasis on leveraging industrial symbiosis to close the material loop.

To conclude, this study is aimed to estimate the environmental impact of pallets life cycle, analysing the current alternatives to the standard management and obtaining

results on the best option for the process of transport and use but, at the same time, proposes to reduce even further the impacts by operationalizing the concept of industrial symbiosis and enlarging the methodology to all types of pallets in circulation.

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List of Figures

Figure 1: Comparative analysis of wood density and elastic modulus distribution within strength classes.	3
Figure 2: EPAL1 pallet specifications.....	4
Figure 3: general methodological framework for LCA.	7
Figure 4: Example of Voucher 51 provided by NolPal.....	11
Figure 5: Schematic representation of current management strategy.....	12
Figure 6: Open and closed loop models with stakeholders' interaction.	12
Figure 7: Schematic representation of Nolpal's exchange system	13
Figure 8: System boundaries in life cycle of pallets (with Nolpal)	15
Figure 9: System boundaries of the production stage	17
Figure 10: Unit processes for direct exchange without Nolpal.....	18
Figure 11: Unit processes for direct exchange with Nolpal	19
Figure 12: Possible End-of-Life scenarios for wooden pallets.	20
Figure 13: Processes' contributions to climate change, without Nolpal system.....	24
Figure 14 Climate change results for the two scenarios	26
Figure 15: Climate change results for EoL scenarios: A-Landfilling; B-Incineration; C-Composting.....	28

List of Tables

Table 1: Comparison between management strategies' costs.....	5
Table 2: Impact category results for the scenario without Nolpal.....	23
Table 3: Share of impacts without Nolpal	24
Table 4: Impact category results for the scenario with Nolpal	25
Table 5: Share of impacts with Nolpal	26

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