Circular Transformation of the American Wood Packaging Industry

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This thesis is dedicated to my two brothers:

Aiden, who I will love and support for life, no matter what happens. I hope you understand that, contrary to conventional wisdom, potential can be a curse, and a wandering mind can be a blessing. We are merely the eyes of the world -- don't blink or you'll miss it! I'm proud of you.

Nate, who taught me that love is free and life is short. May he rest in peace.

I would like to thank the following people for helping make me the person I am today:

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And you, the reader, who has taken an interest in my obsession. I hope that by the end of this document, at least one of you will feel the same spark of passion I first had when I started working on this problem over three years ago. Unlike these acknowledgements, the circular transformation of the American wood packaging industry ends with neither me nor you, so read your heart out – we're only trying to change the world here!

Abstract

Introduction:
Wood packaging consumes over twenty percent of industrial timber harvests in the United States. Organised reuse of wood packaging can reduce timber consumption but is not widely practised. Existing research on circular wood packaging systems is limited in scope, focusing on individual design and process interventions at the firm level. This thesis constitutes a novel investigation of the circular transformation of the American wood packaging industry at a strategic level.

Research Objectives:

1. Examine the case for circular transformation under an ecological modernisation framework.
2. Assess the degree of circularity of the industry as it operates today through the lens of the seven operational principles of a circular economy.
3. Generate practical recommendations and strategies to increase the circularity of the American wood packaging industry.

Methods:
The effects of circular practices on the economic and environmental performance of the industry were examined at firm and national scales using quantitative modelling and analysis techniques supported by secondary data. Information about the practices of American wood pallet businesses was obtained using a questionnaire. Case studies and a barriers and drivers analysis concerning circular transformation were constructed from interviews and document analysis.

Results:
The model demonstrates that a universal circular wood pallet scheme can reduce national timber consumption by up to 10% (25 million tonnes/year) while reducing annual costs by up to $20 billion. The economic competitiveness of circular pallet systems is sensitive to new manufacturing costs, loss and damage rates, and freight costs, suggesting a need for supporting economic policy incentives. Disparities in capacities for circular practices between small and large wood pallet producers are seen across all phases of the wood packaging life cycle.

Conclusions:
A producer responsibility model for the wood packaging industry supported by producers' participation in a common, decentralised reuse scheme and complementary economic policy incentives is proposed.

Keywords: circular economy, packaging, producer responsibility, wood, waste

Executive Summary

"The Wood Packaging Industry Problem"

The claim that wood packaging moves the world is no exaggeration. Wood packaging is the backbone on which physical supply chains operate, carrying over eighty percent of all commerce worldwide. Demand for wood packaging, particularly pallets, places considerable stress on American forest resources, consuming more than one fifth of total industrial roundwood harvests. Meanwhile, the southeastern United States has recently undergone deforestation at a rate four times that of the Amazon rainforest, resulting in a release of sequestered carbon equivalent to 9.2 billion tonnes of CO_2 between 2001 and 2021. One purpose-built reusable wood pallet can replace the function of forty one-way pallets, but as of 2021, only twelve percent of pallet users in the United States participate in organised reuse schemes. Displacing the demand for one-way pallets with reusable alternatives would significantly reduce the environmental burden placed on American forests by the wood packaging industry.

Existing research attempting to reduce the costs and/or environmental impacts of the wood packaging industry mainly focuses on mechanical design and performance of wood packaging products ("The wood packaging design problem"), optimisation of loading and handling conditions ("The wood packaging handling problem"), or isolated improvements to logistics and product life cycle activities ("The wood packaging life cycle problem"). Invariably, these problems are investigated at the scale of the individual packaging user or producer. No publication to date has investigated the impacts of these optimisations in combination, nor developed strategies to implement them at an industry-wide scale.

This thesis examines the potential for a wide array of actors to combine their respective capacities towards the goal of reducing the costs and environmental impacts of the entire American wood packaging industry via the holistic optimisation and widespread adoption of returnable wood pallet systems. This approach can be conceptualised as an attempt to solve a new kind of problem – "The wood packaging industry problem."

Building the Case for Circular Transformation

Research Aim

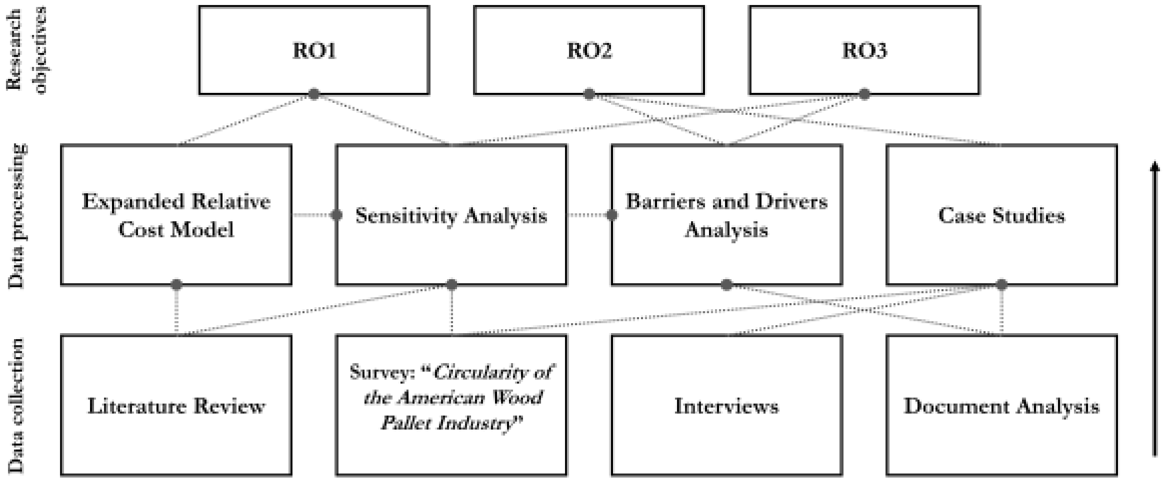
This research aims to build economic and environmental cases for a circular wood packaging industry in the United States and construct actionable strategic recommendations supporting industry transformation.

Research Objectives

1. Examine the case for circular transformation under an ecological modernisation framework.
2. Assess the degree of circularity of the industry as it operates today through the lens of the seven operational principles of a circular economy.
3. Generate practical recommendations and strategies to increase the circularity of the American wood packaging industry.

Research Design and Methods

The thesis employs a mixed methods, multi-stage research design to fulfill its three research objectives. Quantitative data obtained from literature review and survey responses was processed using an expanded relative cost model and breakeven, sensitivity, and risk analyses. Qualitative data obtained from survey responses, interviews, and document analysis was used alongside quantitative results to build case studies and inform a barriers and drivers analysis. Finally, a practical model for circular transformation was conceptualised, addressing RO3. The diagram below illustrates the research design and methods used to fulfill the research objectives:



Key Findings

Results from the expanded relative cost model demonstrate that a circular wood packaging system can drastically reduce the American wood packaging industry's resource consumption while reducing user and social costs. A universal circular wood packaging scheme can reduce annual costs by up to $20 billion while reducing annual timber consumption by up to 25 million tonnes (10% of the total national consumption), though this result is sensitive to new manufacturing costs, loss and damage rates, and freight costs. Nationally aggregated results are summarised in the table below:

Scenario	Baseline	Existing reuse improved	Universal improved reuse
User cost	$42 385 000 000	$35 898 000 000	$32 004 000 000
Social cost	$14 194 000 000	$12 475 000 000	$4 198 000 000
Total costs	$56 579 000 000	$48 373 000 000	$36 202 000 000
Total emissions (t CO2-eq.)	34 700 000	16 100 000	40 700 000
Total timber (t)	31 500 000	29 500 000	5 500 000
Total steel (t)	1 200 000	1 200 000	50 000

Eight representatives of American wood pallet producers answered a 53-item questionnaire about their practices in each phase of the wood packaging life cycle. Key findings from the questionnaire are summarised in the table below:

Industry practices	Key Findings
Design	• There is a low degree of standardisation in product dimensions – a barrier to reuse. • Despite the prevalence of software-aided product design in the industry, these tools' eco-design capabilities are rarely utilised.
Raw material procurement	• Wood raw material is purchased in a variety of forms. • Small organisations tend to be located farther from the raw material source. • Most organisations import some fraction of their wood, typically from Canada. • Forest certification schemes are used by a growing fraction of organisations.
New manufacturing	• Large organisations report a higher degree of process automation. • Grid electricity and natural gas are the predominant energy sources used. Biomass energy is generated by a minority of organisations.
Delivery & retrieval	• All organisations surveyed reported using diesel, heavy duty trucks. The use of gasoline, medium duty trucks for smaller orders is less prevalent. • Order quantities fulfilled range from 11-50 pallets to 500+ pallets. Smaller orders are more commonly fulfilled for deliveries than for retrievals. • Large organisations transport products over much greater distances than do small organisations.
Repair	• Remanufacturing, the practice of using salvaged components in repair activities, is widely practised. • More organisations refurbish components than replace components. • Grading schemes for repaired pallets are not consistent across organisations.
Closed loop systems	• Few organisations participate in closed loop systems. • Participants report a high degree of consolidation in reverse logistics, but a low prevalence of cross-docking and a lack of chain of custody and service history information.
EOL managment	• All organisations surveyed reuse components in some way. • Small organisation have a higher prevalence of undesirable EOL practices (landfilling, donation) than do large organisations.
General	• Large organisations tend to participate more in earlier life cycle phases (design, procurement, new manufacturing), while small organisations tend to participate more in later phases (retrieval, repair, EOL).

Interviews and document analysis revealed several important findings:

1. High costs, inconsistent product quality, and inventory control limitations are significant barriers to the adoption of existing wood packaging reuse schemes in the United States.
2. Existing policy addressing packaging waste is ineffective at influencing the practices of the American wood packaging industry.
3. Decentralised wood packaging reuse schemes have found success in Europe but face financial barriers to adoption in the U.S.

A Producer Responsibility Model for the American Wood Packaging Industry

The findings suggest that a producer responsibility programme can be effective in driving a circular transformation of the American wood packaging industry. Under this approach, a producer responsibility organisation sets standards of practice for the operation of a common, decentralised returnable wood packaging pool sustained by the activities of existing producers on an open market. The programme is supported by economic policy incentives that ensure participation in the system is economically viable for producers and packaging users. Responsibilities of key stakeholder groups are outlined below:

1. **Producer responsibility organisation**
   The proposed role of a producer responsibility organisation for wood packaging combines the functions of existing decentralised pools – setting standards for products and producer activities and maintenance of producers' compliance with these standards – with some of the functions of existing PROs for other types of packaging – ensuring product stewardship and penalising producers for harmful activities. Unlike a traditional PRO which penalises all production on a unit basis, participation in the PRO-managed reuse scheme is free, and only activities which deviate from the standards and requirements set by the PRO are penalised. The potential to participate in a PRO without mandatory administrative costs and penalties may make the concept of a PRO more palatable to wood packaging producers.

2. **Wood packaging producers**
   Producers are responsible for altering their existing portfolio of product designs to align with the standards set by the PRO and carry out life cycle activities according to PRO standards of practice. Unlike the EPAL system in Europe, which requires participants to use an exchange business model, producers under the proposed PRO are free to monetise their activities in whichever fashion suits them. Independent manufacturers and recyclers may freely purchase and sell cores at prices governed by market competition, and poolers may continue to work with a rental business model or transition to a buy/sell model. This approach results in the least disruption to the business activities of producers, which may reduce the industry's resistance to the establishment of a PRO for wood packaging.

3. **Regulators**
   The role of regulators is to provide initial financing for the establishment of a decentralised pallet pool, set producer responsibility obligations related to reporting and life cycle practices, and encourage the widespread use of the pool through economic incentives. They provide the "teeth" to the rules set by the PRO. Most importantly, regulators should impose a tax on all wood packaging products produced outside of the PRO programme sufficient to incentivise participation in the programme. Regulators can also take actions in adjacent areas to improve the resource efficiency of the American wood packaging industry and provide environmentally beneficial destinations for diverted material. These actions include incentivising the adoption of alternative fuels and drivetrains for road freight and incentivising the adoption of mass timber construction.

Table of Contents

List of Figures

List of Tables

Abbreviations

APCO	Australian Packaging Covenant Organisation
BAU	Business as usual
B2B	Business-to-business
bbf	Billion board feet
CHEP	Commonwealth Handling and Equipment Pool
CPC	Canadian Pallet Council
EM	Ecological modernisation
EOL	End-of-life
EPAL	European Pallet Association
EPR	Extended producer responsibility
FTL	Full truckload
GDPR	General Data Protection Regulation of the European Union
GHG	Greenhouse gas
LCA	Life cycle assessment
LLC	Limited liability company
LTL	Less-than-truckload
MTC	Mass timber construction
PPI	Producer price index
PRO	Producer responsibility organisation
RO	Research objective

1 Introduction

The claim that wood packaging moves the world is no exaggeration. As the preeminent platform for the bulk movement of goods, nearly every product consumed today relies on wood packaging to support logistics functions at some point during its life cycle. With billions of units recovered for reuse, repair, and recycling each year worldwide, wood packaging may also be the most circular product in widespread use today. Despite this, research attempting to understand and improve circular wood packaging systems at a high level is sparse. This thesis is the first published work to examine the possibilities and benefits of expanding on the wood packaging industry's strong foundation for circularity at a national scale and propose practical, strategic recommendations for a transformation of the industry toward circularity.

1.1 Problem Definition

Existing research attempting to reduce the costs and/or environmental impacts of the wood packaging industry mainly focuses on mechanical design and performance of wood packaging products ("The wood packaging design problem"), optimisation of loading and handling conditions ("The wood packaging handling problem"), or isolated improvements to logistics and product life cycle activities ("The wood packaging life cycle problem"). Invariably, these problems are investigated at the scale of the individual packaging user or manufacturer. No publication to date has investigated the impacts of these investigated optimisations in combination, nor developed strategies to implement them at an industry-wide scale.

This thesis takes a novel approach, examining the potential for a wide array of actors to combine their respective capacities towards the goal of reducing the costs and environmental impacts of the entire American wood packaging industry via the holistic optimisation and widespread adoption of returnable wood pallet systems. This approach can be conceptualised as an attempt to solve a new kind of problem – "The wood packaging industry problem."

Sections 1.1.1 to 1.1.3 provide the necessary background information for understanding the American wood packaging industry, its importance to sustainability issues, and its unique connection to the advancement of a circular economy.

1.1.1 Introduction to wood pallet systems

To understand the importance of wood packaging industry transformation, one must also understand the central role its primary product, the wood shipping pallet, plays in modern supply chains. Pallets are the backbone on which physical supply chains operate, carrying over 80% of all commerce worldwide (Raballand & Aldaz-Carroll, 2005). These ubiquitous products serve several critical functions including product protection, the division of inventory into units, and multiplying the labor efficiency of material handling and logistics processes. Though alternatives to the wood pallet exist, namely the injection-molded plastic pallet, wood pallets comprise over 90% of the American pallet market (Buehlmann et al., 2009) and are consistently found to carry lower costs and environmental burdens than pallets made from alternative materials (Khan et al., 2021; Kočí, 2019).

The American wood packaging industry can be classified into two distinct product-service systems based on the way its core product, the wood pallet, is managed throughout its life cycle:

One-way systems: New pallets are manufactured primarily from low-grade, locally available timber. They are then sold to the consumer. The pallets are laden with goods by the consumer and repositioned until they are finally unladen by the recipient. Informal systems of reuse and repair are facilitated for approximately 16% of pallet users (Michel, 2021), but neither the exact extent of reuse and repair practised in these systems nor the lifespan of a typical one-way pallet is known. Activities in one-way pallet systems are primarily carried out by independent SMEs; over 99% of practicing businesses have fewer than fifty employees (Roy et al., 2016). Comparably little is known to scientific literature about the operations of one-way wood pallet systems as compared to returnable pallet systems. One-way systems, classified as systems in which the pallet user maintains ownership of and responsibility for the product, comprise roughly 88% of the American wood pallet market today (Michel, 2021).

Returnable systems: New pallets are manufactured primarily from structural grade lumber. The pallets are rented to the consumer by a pooler who maintains ownership of a large inventory, or "pool," of pallets. The pooler is responsible for all activities necessary to provide a consistent supply of usable pallets at each consumer site and collect used pallets from recipients, which may be third parties who receive product on returnable pallets and do not participate in the system directly. Pallets in returnable systems are reused and repaired via the pooler many times before reaching the end of their useful lives (end-of-use), when they are recycled in a concentrated and consistent flow. Organised returnable systems comprise roughly 12% of the U.S. wood pallet market (Michel, 2021) and activities are predominantly controlled by a few large, centralised organisations.

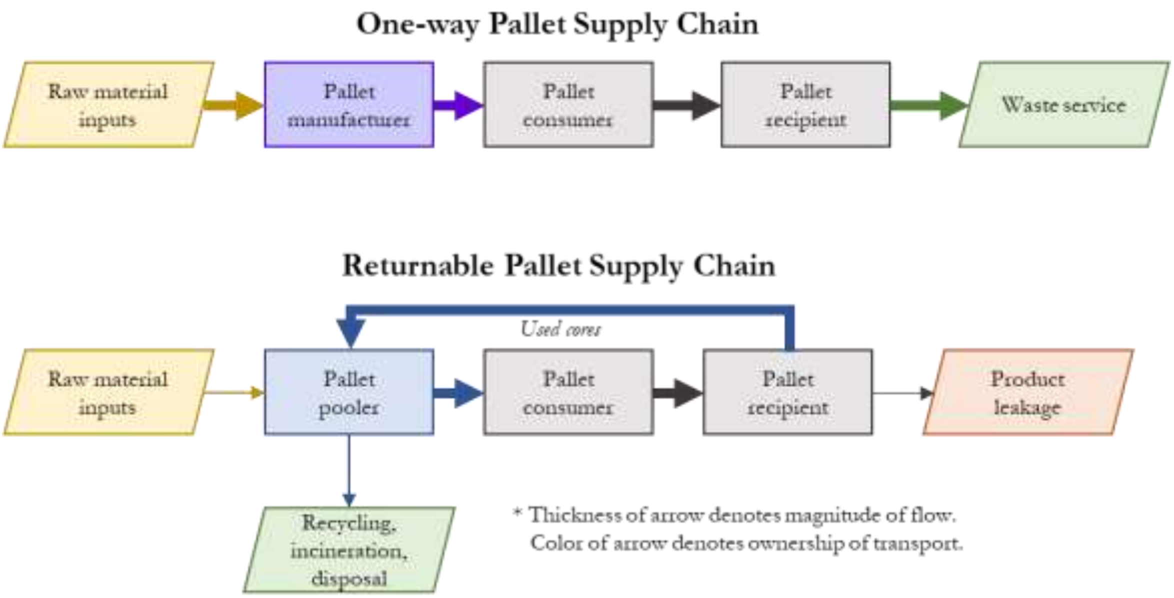


Figure 1-1. Diagrams of typical one-way and returnable pallet supply chain structures in the United States.

Figure 1-1 is an illustration comparing the structure and resource flows of one-way and traditional returnable pallet supply chains. The structure of a returnable pallet supply chain greatly reduces the magnitude of resource inputs and waste outputs related to its function as compared to a one-way pallet supply chain.

1.1.2 Wood packaging as a sustainability problem

Demand for wood pallets places considerable stress on American forest resources. In the United States and the European Union, the wood pallet and container industry is the largest user of new timber outside of the construction industry, consuming more than one fifth of total industrial roundwood harvests (Gerber et al., 2020; *Trends and Perspectives for Pallets and Wooden Packaging*, 2016). Meanwhile, the southeastern United States has recently undergone deforestation at a rate four times that of the Amazon rainforest (*Forests and Biodiversity*, 2015), resulting in a release of sequestered carbon equivalent to 9.2 billion tonnes of CO_2 between 2001 and 2021 (*Global Forest Watch Data Visualizer*, 2022).

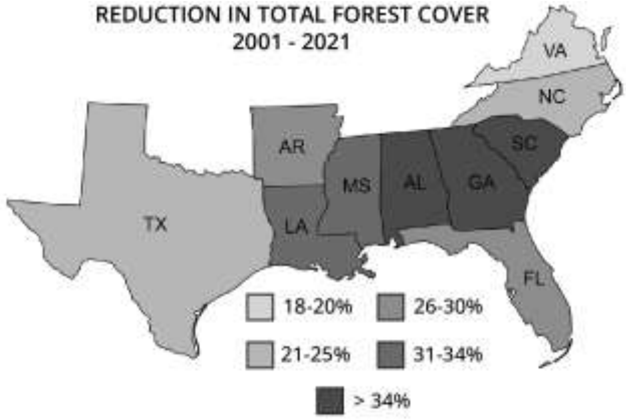


*Figure 1-2. Map of deforestation in the Southern Coastal Plain region of the United States, 2001-2021. Data source: (*Global Forest Watch Data Visualizer*, 2022)*

One purpose-built reusable wood pallet can replace the function of forty one-way pallets (Bengtsson & Logie, 2015), but as of 2021, only twelve percent of pallet users in the United States participate in organised reuse schemes, citing cost and convenience as major barriers to adoption (Michel, 2021). Displacing the demand for one-way pallets with reusable alternatives would significantly reduce the environmental burden placed on American forests by the wood packaging industry.

Beyond the possibility for reduction of virgin timber demand and its consequential deforestation impacts, there is considerable potential for timber diverted from consumption by a circular transformation of the American wood packaging industry to be used in ways which alleviate other environmental pressures, such as substitution of GHG-intensive materials like steel and concrete in mass timber construction applications.

1.1.3 Circular economy and the wood packaging industry

The European Parliament defines a circular economy as "A production and consumption model which involves reusing, repairing, refurbishing and recycling existing materials and products to keep materials within the economy wherever possible" (*Circular Economy [EPRS]*, n.d.). Circular economy development is driven by a confluence of environmental and economic motivations: It is now common knowledge that we must decouple resource consumption from economic output in order to maintain our current level of economic prosperity without exceeding natural resource constraints.

The circular economy approach to waste management is often conceptualised as a hierarchy of strategies used to minimise waste and resource value loss, with source reduction and reuse being prioritised above recycling and final disposal. This "waste management hierarchy" is a central tenet of waste legislation in the jurisdictions with the most ambitious waste management programmes, most notably the European Union Directive on Packaging and Packaging Waste ("Directive 94/62/EC," 1995). This circular approach to waste management has shown a significant and positive correlation with economic development while reducing per-capita waste generation in the European Union (Azwardi et al., 2023).

Figure 1-3 below depicts the R-framework for circular economy, which can be applied to the context of wood packaging systems. Practices with a higher position in the chart retain natural resource value more effectively, while those with a lower position result in greater resource value loss. To achieve maximum circularity, systems of production and consumption so that products and their component materials cascade down this hierarchy in a manner that retains resource value to the greatest degree possible (Russell et al., 2018).

Circular economy ↑ Transformation ↑ **Linear economy**

Prevention	R0	Refuse	Achieve product redundancy
	R1	Rethink	Increase intensity of product use
	R2	Reduce	Increase resource efficiency of production and/or use
Reuse	R3	Reuse	Reuse product directly for original function
	R4	Repair	Restore product to original function
	R5	Refurbish	Restore product to diminished function
	R6	Remanufacture	Use parts of discarded product in new product with original function
Recycling	R7	Repurpose	Use discarded product or its parts in new product with different function
	R8	Recycle	Process materials to retain some or all resource value
Recovery	R9	Recover	Incinerate materials with energy recovery

Figure 1-3. R-framework for circular economy practices.
*Information source: (*Circular Economy*, 2015)*

Figure 1-4 below depicts the flow of wood pallet cores, or empty pallets collected at end of use, recovered in the U.S. in year 2016 to their next destinations.

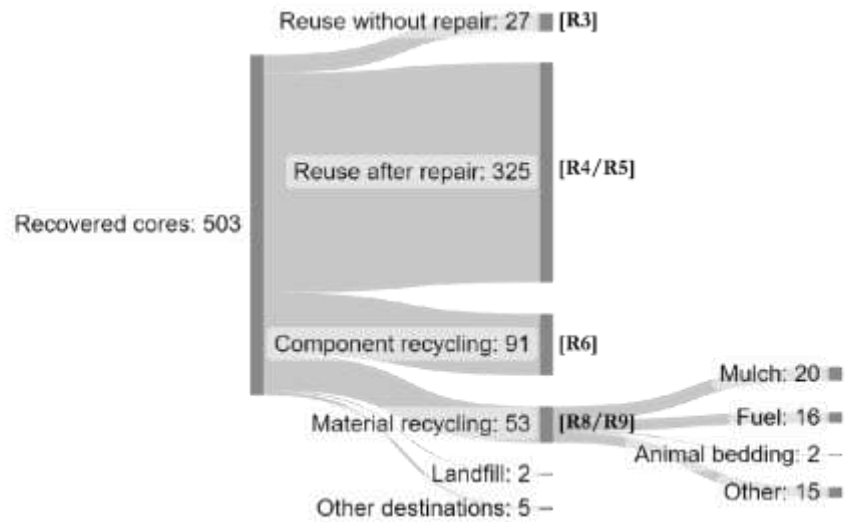


Figure 1-4. Destinations of wood pallet cores recovered in the U.S. in 2016 (millions).
Data source: (Gerber et al., 2020)

Analysing these results under the R-framework, we can see that for the fraction of wood pallet cores which are recovered after use, R4, R5, and R6 practices are dominant. Following this, it is reasonable to assume that the wood packaging industry already exercises a high degree of circularity; indeed, pallet pooling organisations are commonly regarded as some of the most sustainable businesses operating today (Freijo, 2022). However, it is important to note that the mere occurrence of circular practices does not preclude the possibility of improvements to these practices using R1 and R2 interventions. This possibility has not been investigated strategically in any publication to date and is the central exploration of this research.

While existing research in the field of packaging sustainability often lauds the returnable pallet as an exemplary circular product, this thesis instead examines how existing capacities for reuse and product life cycle extension in the wood packaging industry can be leveraged to further improve on a strong foundation for circularity.

1.2 Aim and Research Objectives

The aim of the thesis is to build economic and environmental cases for a circular wood packaging industry in the United States and construct actionable strategic recommendations supporting industry transformation. This is accomplished via a quantitative examination of the current capabilities of the industry and outcomes of a circular transformation, followed by a qualtitative construction of practical transformation strategies under weak and strong ecological modernisation approaches.

The following research objectives (ROs) are addressed:

RO1: Examine the theoretical case for the circular transformation of the American wood packaging industry under an ecological modernisation (EM) framework.

RO2: Assess the degree of circularity of the American wood packaging industry as it operates today through the lens of the seven operational principles of a circular economy.

RO3: Generate practical recommendations and strategies aimed at increasing the circularity of the American wood packaging industry.

1.3 Scope and Delimitations

The scope of this study is the wood packaging industry in the contiguous United States, consisting of returnable and one-way wood pallet systems. All primary data was collected from participants working within this industry and geographic boundary, and secondary data used in quantitative modelling was derived from studies performed in a U.S. context wherever possible. Techniques used in this thesis could be applied to any geographic context, but findings described here can only be used to make inferences about the American context.

As no industry partner is affiliated with this study, primary data relies on convenience sampling and the disclosures of industry stakeholders; as such, direct observations of practices of the American wood packaging industry cannot be made. Secondary data, particularly the parameters used in the expanded relative cost model, was obtained from academic literature where possible. The disparity of geographic and operational contexts among which the various studies providing these parameters were conducted is a factor that limits the accuracy of estimates made using the expanded relative cost model designed for this study. Assumptions about the values of independent variables comprising the expanded relative cost model were tested using a sensitivity analysis technique introduced in Section 3.4.2.

All claims to the economic and environmental performance of wood pallet systems are best estimates, not empirical fact. The small size of most organisations working within the wood pallet industry has made it difficult to access relevant expertise, especially regarding informal recycling operations. This has resulted in a low capture rate for the survey introduced in Section 3.2.1. A low capture rate and a lack of direct pooler participation may influence the representativeness of survey responses relative to the practices of the American wood pallet industry as a whole.

1.4 Ethical Considerations

The research design used in this thesis has been reviewed against the criteria for research requiring an ethics board review at Lund University and has been found to not require a statement from the ethics committee.

The author has made the following disclosures regarding data protection and privacy to all survey respondents:

> This survey is conducted in compliance with the General Data Protection Regulation (GDPR) of the European Union. Results from this assessment will be anonymized and presented in aggregate. No names of organizations nor contact information will be published. Your specific responses may be reported, but not in a capacity that will identify you or your organization. By way of publication, some non-identifying information from responses will be shared internationally.
>
> Contact information for the distribution of this survey was collected from the member directory of the National Wood Pallet and Container Association, a publicly accessible source. If you provide consent to be contacted by answering 'Yes' to Section 9, Question 2, your contact information and responses may be used for Customer Relationship Management by Y.G. Packaging Solutions LLC, an American business organization affiliated with this research.

All interview participants involved in this study have provided permission for their viewpoints to be disclosed anonymously.

The author discloses an interest in the outcomes of the study due to his role as a founder of Y.G. Packaging Solutions LLC, an American business organisation which provides sustainability-oriented engineering services and solutions for the producers and consumers of industrial packaging products. This interest has influenced neither collection nor processing of data for this project.

Portions of the literature review (Chapter 2) and development of the expanded relative cost model (Section 3.1.1) were completed by the author under the supervision of the Department of Sustainable Biomaterials at Virginia Tech on a voluntary basis during Spring and Summer 2022. The Department has provided explicit written permission for these sections to be included in the thesis as the author's own work.

1.5 Audience

This work is aimed at informing professionals within the wood packaging industry, government, and academia. Wood pallet pooling and recycling operations are affected most significantly and directly, so decision-makers in these organisations stand to benefit the most from the outputs of this research. Regulators should also be mindful of their potential role in promoting wood packaging circularity. Finally, academics within the fields of forest resources, waste management, and cleaner production may find insight and/or inspiration from this text.

1.6 Disposition

Chapter 1 (Introduction) defines the problem of achieving a circular transformation of the American wood packaging industry and provides some basic information about how the thesis project contributes to its solution. This chapter also addresses the scope, limitations, ethical considerations, and intended audience of the thesis.

Chapter 2 (Literature review) presents the literature review methodology used for the thesis, justifies the selection of analytical frameworks, and presents the most significant findings from the literature review.

Chapter 3 (Research design, materials and methods) describes the research design employed in the thesis and explains how a variety of data collection and data processing techniques were combined to contribute to the research objectives of the thesis.

Chapter 4 (Results and analysis) presents the results of the research and provides a basic analysis of their significance to the research objectives where applicable.

Chapter 5 (Discussion) provides more detailed analyses of results under selected analytical frameworks and reflections on methodological choices, legitimacy, and generalisability of the work.

Chapter 6 (Conclusion) addresses RO3 by providing a detailed strategic guide for a circular transformation of the American wood packaging industry. This is followed by suggestions for future research.

2 Literature review

As the scope of the thesis concerns the circular transformation of wood packaging industry via the adaptation of its systems (rather than the products themselves), literature review began with a published review of ninety academic publications related to the management and logistics of returnable wood pallets (Tornese et al., 2021). Market research, environmental assessments, and optimisation studies of relevance to the thesis were selected from the references of the review publication and annotated. The references of each of these publications were reviewed to find further supporting information from the wider literature on forest resources, packaging systems, and circular economy used to inform these studies. Forty-eight academic publications were reviewed in full in order to form a complete picture of the current scientific knowledge related to wood packaging systems and their optimisations as described in Section 2.1. Figure 2-1 below is a graphical representation of this literature review approach.

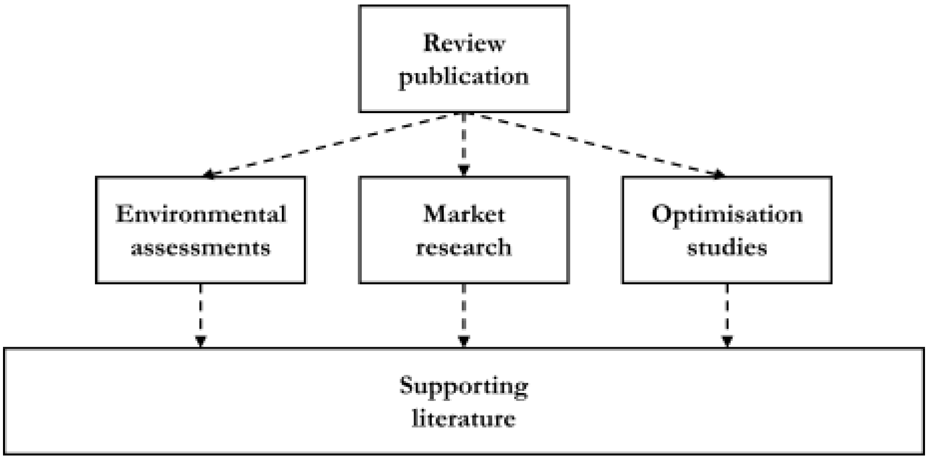


Figure 2-1. Graphical representation of wood packaging system optimisation literature review methodology.

Three conceptual frameworks were chosen for their relevance and utility to the investigation of a circular transformation of the American wood packaging industry:

1. **Ecological modernisation theory** is a change theory that has been used in an academic context investigate industrial and societal responses to packaging waste management challenges at the firm and national levels (Björk, 2021). Due to the economic nature of the problem under investigation in this thesis, EM is a useful framework for assessing the level of government intervention necessary to support industry transformation.

2. **The relative cost approach to container system design** provides a framework for quantitative evaluation of the economic viability of different packaging systems. The formulas provided by the authors can be used in combination with secondary data from literature to create models of existing and proposed one-way and returnable packaging systems and directly compare their economic performance.

3. **Operational principles of a circular economy** can be used to qualitatively assess the circularity of current industry practices and classify strategies to improve them.

2.1 Current knowledge related to optimisation of wood packaging systems

Appendix I contains the full annotated bibliography regarding returnable packaging system design. All information regarding pallet management practices and input parameters for the expanded relative cost model described in Section 3.4.1 has been derived from this bibliography unless otherwise stated.

The practices identified in the scientific literature on container system optimisation resulting in significant cost and impact reductions within returnable wood pallet systems are as follows:

1. **Cross-docking:** The inspection of used pallets at the dispatch point rather than at the pooling facility so that only damaged pallets must be returned reduces the emissions of returnable block pallet systems by 17-73% depending on loading and handling conditions (Tornese et al., 2016).

2. **Pre-emptive remanufacturing:** The practice of replacing multiple components with a short predicted remaining lifespan at the time a single component must be replaced so that the incidence of damages is reduced and fewer return trips must be made reduces the costs and emissions of the remanufacturing phase of the returnable pallet life cycle by 31-44% and 29-39%, respectively (Tornese et al., 2019).

3. **Restructuring reverse logistics activities** to consolidate returns at the highest point in the buyer's supply chain via backhaul trips, thus reducing the distances empty pallets travel in between uses, reduced the total truck-km and emissions required to operate a simulated Italian retail pallet supply chain by 65% and 60%, respectively (Accorsi et al., 2019).

4. **Modifying user behaviour** to improve loading and handling conditions and reduce loss rate. One conservative estimate places the contribution of lost and damaged pallets to system emissions at 38% (Bottani & Casella, 2018). Minimising loss and damage rate through better pallet handling practices among users is critical to maximising the resource efficiency of returnable pallet systems.

2.2 Theories and conceptual frameworks of relevance to the study

This section provides detailed descriptions of the three conceptual frameworks under which results are analysed and explains their respective relationships to the circular transformation of the American wood packaging industry.

2.2.1 Ecological modernisation theory

Ecological modernisation is a discourse within environmental policymaking which rejects the position that radical change to the core social institutions underpinning industrial society (i.e. de-growth) is necessary to prevent ecological collapse; instead, ecological modernisation posits that ecological limits can be respected through incremental reforms which do not break with our existing paradigm of economic development (Hajer, 1997). "Sustainable development" and "Green growth" are popular approaches which have ideological roots in ecological modernisation theory. This incremental reform is said to be accomplished through three central activities (Gouldson & Murphy, 1996):

1. Restructuring of production and consumption towards ecological goals via development and diffusion of clean production technologies and resource decoupling

2. Placing an economic value on nature via tax reforms

3. Incorporating environmental policy goals into non-environmental policy interventions

Ecological modernisation can take either a weak or a strong form; in the weak form, a technocratic elite relies heavily on technological development to address ecological issues and there is little public intervention; in the strong form, there is high public participation and an emphasis on reforming systems (Christoff, 1996). The results of this pre-study will inform the implicit form of ecological modernisation needed to transform the U.S. wood pallet industry: if reusable pallets can be made cost-competitive with one-way pallets, the weak form may be employed; otherwise, the strong form may be necessary.

2.2.2 The relative cost approach to container system design

One study provides a mathematical model for calculating and comparing the total system costs of one-way and returnable packaging systems (Mollenkopf et al., 2005). The formulas comprising this model serve as the basis for the cost component of the model described in Section 3.4.1. A summary of formulas can be found in Appendix II. The authors identify three key factors for the viability of returnable container systems, in order of importance:

1. Ratio of new returnable container purchase price to new one-way container purchase price.

2. Average daily volume of product to be transported. Returnable systems benefit from high user demand because they cause containers to be cycled more frequently.

3. Delivery distance. Returnable systems benefit from short delivery and retrieval distances.

Given that returnable pallets provide the same function as one-way pallets, it can be surmised that wood pallet users will choose the container system which satisfies their needs at the lowest possible cost. The expanded relative cost model investigates whether it is possible to provide a returnable pallet system to a typical user at a lower cost than a one-way pallet system. It will also investigate potential resource efficiency advantages of optimised returnable pallet systems over current returnable and one-way pallet systems.

This approach can be combined with ecological modernisation theory to draw some high-level conclusions about pathways to circular transformation based on the weak and strong approaches to ecological modernisation discussed in Section 2.2.1.

2.2.3 Operational principles of a circular economy

Seven operational principles of a circular economy have been proposed (Suárez-Eiroa et al., 2019), all of which relate to the wood packaging industry. To aid in your understanding, these seven principles and their respective relationships to the topic of wood packaging resource efficiency are described below.

1. **Adjusting inputs to the system to regeneration rates**
   There are finite technical and ecological limits to the volume of wood biomass which can be sustainably harvested for human use. Reducing the timber consumption of the wood packaging industry would make a significant fraction of this maximum sustainable harvest available for alternative purposes.

2. **Adjusting outputs from the system to absorption rates**
   GHG emissions from wood packaging systems should be minimised to reduce the industry's contribution to climate change.

3. **Closing the system**
   Material leakage in the form of lost, damaged, and unviable secondhand product should be minimised.

4. **Maintaining resource value within the system**
   Wood packaging should be kept in service for as long as possible, and material that is no longer usable should be cascaded down the value hierarchy in such that value durability is maximised. Wood material has a variety of technical, biological, and energy applications, and the same material can serve many of these functions in a sequence before it is finally disposed of.

5. **Reducing the system's size**
   Minimising the in-use stock of packaging by increasing its utilisation and minimising the distances over which the packaging must travel are key strategies to reduce the resource consumption of the wood packaging industry.

6. **Designing for circular economy**
   Wood packaging which is designed for value durability and a high intensity of use will carry lower environmental burdens than that which is designed to meet an initial consumer's specification at a minimum purchase price.

7. **Educating for circular economy**
   Wood packaging manufacturers must be aware of best practices for design, procurement, manufacturing, transportation, repair, and EOL management of their products. Users must be aware of best practices for loading, handling, and reverse logistics of these products.

3 Methodology

Building the case for a circular transformation of the American wood packaging industry can be understood as a matter of answering three broad questions in a series:

1. What are the potential economic and environmental benefits of a circular transformation of the American wood packaging industry?
2. Where does the industry currently stand on the path to circularity?
3. What can be done to accelerate the circular transformation of the industry?

The remainder of Chapter 3 describes the research design, data sources and methods used to answer these questions.

3.1 Research design

The thesis employed a mixed methods, multi-stage research design to achieve the three research objectives outlined in Section 1.2. Quantitative data obtained from literature review and survey responses of industry practices was processed using the expanded relative cost model and breakeven, sensitivity, and risk analyses. Qualitative data obtained from survey responses, interviews, and document analysis was used alongside quantitative results to build case studies and inform a barriers and drivers analysis. These methods, combined with the three analytical frameworks introduced in Section 2.2, were employed to fulfill three research objectives: building the economic and environmental case for transformation, assessing the circularity of current industry practices, and generating strategic recommendations for accelerating the industry's transition toward circularity. Figure 3-1 below provides a graphical representation of the research design used for the thesis.

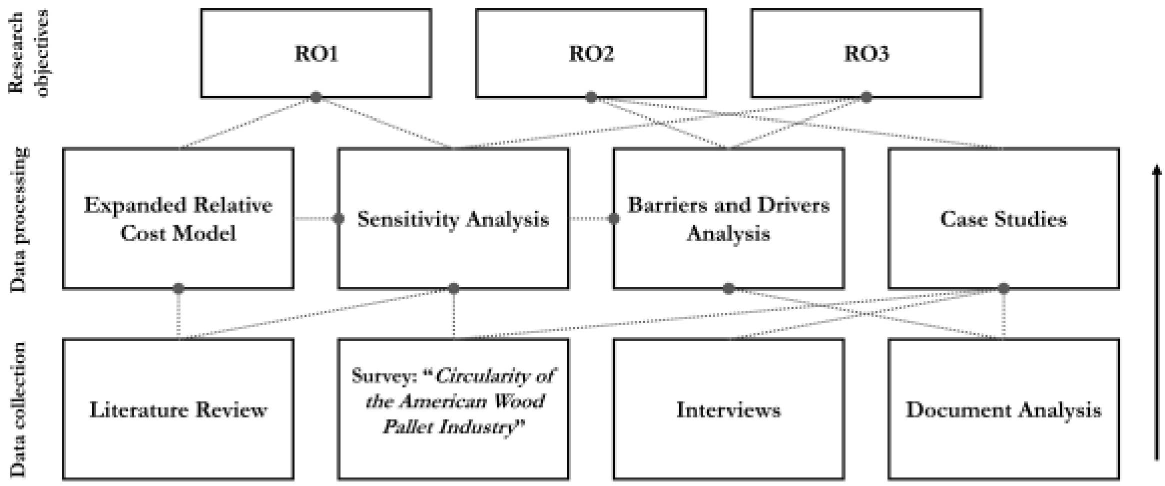


Figure 3-1. Graphical representation of research design and contributions of methods to research objectives.

3.2 Methods used to collect data

This section describes the methods used to collect the data used in the various elements of the research design described in Section 3.1.

3.2.1 Survey: "Circularity of the American Wood Pallet Industry"

A 53-item questionnaire about the current practices of organisations working within each phase of the wood pallet life cycle was created using Google Forms. Organisation of the questionnaire into life cycle phases of design, raw material procurement, new manufacturing, delivery and retrieval, repair, EOL management, and closed loop systems; and inclusion of several specific questions about industry practices were inspired by a recent conference paper providing a conceptual design for a tool to measure circular economy practices in pallet supply chains (M. G. Gnoni et al., 2018). The survey contributes to RO2 by generating the first comprehensive assessment of the circularity of American wood pallet operations across all life cycle phases. A list of questionnaire items can be found in Appendix III.

The survey was distributed to 350 members of the National Wood Pallet & Container Association (NWPCA) via email on 1 March 2023. Follow-up emails were sent on 20 March and 27 March to remind potential respondents about the survey. The survey was also posted to the "Pallet Enterprise" LinkedIn group on 1 March, receiving 602 impressions during the response period. The survey was closed to responses on 31 March 2023.

3.2.2 Document analysis

A narrative review of trade literature, legislation, educational materials, and industry reports was performed to collect relevant information about the wood packaging industry and its wider economic and regulatory context. This information was used alongside other materials collected for the thesis to build case studies and inform a barriers and drivers analysis, both of which place the American wood packaging industry in a wider context to generate more effective and informed strategic recommendations for its circular transformation.

3.2.3 Stakeholder interviews

Ten semi-structured interviews were conducted to obtain supplementary information about various topics of relevance to the thesis. Before the interviews, each participant was sent a list of open-ended questions tailored to their specific role and expertise. Each interview began with a brief introduction of the research project, followed by a discussion of each question from the provided list. Table 3-1 below describes the character and content of each interview conducted for the thesis project and provides a "reference code" used to refer participants' claims to their respective interviews in later sections of this document.

Table 3-1. Information about interviews conducted for the thesis project.

Role	Geographic Scope	Content of Interview	Format	Reference Code
Owner of several independent wood pallet manufacturing and recycling operations	Central United States	Changes in industry landscape, operational challenges	Telephone	[I1]
Executive involved in a prior initiative to establish a decentralised pallet pooling scheme	United States	Technical details about the pool, advantages of decentralised pooling, reasons for failure of the initiative	Telephone	[I2]
Owner of a mass timber construction consulting firm	Europe, particularly Nordic countries	Engineering, business, and environmental aspects of mass timber applications	Video conference	[I3]
Former executive of a major wood pallet pooler	United States, Europe	Prevalence of best practices, barriers and drivers of pooling adoption, industry ESG trends	Video conference	[I4]
Representative of an NGO advancing packaging sustainability	United States	Effective policy and organisational design for packaging waste, adapting municipal waste regulations to B2B context	Video conference	[O1]
Representative of an NGO advancing recycling practices	United States	Effective policy and organisational design for packaging waste, adapting municipal waste regulations to B2B context	Video conference	[O2]
Representative of an NGO advancing mass timber adoption	United States	Barriers and drivers of mass timber adoption in the U.S.	Video conference	[O3]
Packaging engineering researcher, focus in distribution packaging	United States	Common industry practices, barriers to circular pallet systems in the U.S.	Email	[A1]
Forest resources sustainability researcher	United States	EPD for wood pallets, pallet industry trends	Email	[A2]
Forest products researcher, focus in mass timber products	United States	Barriers and drivers of mass timber adoption in the U.S.	Video conference	[A3]

3.3 Materials collected

This section characterises the primary and secondary data collected for use in the thesis.

3.3.1 Model input parameters

Input values for the expanded relative cost model were obtained from scientific literature wherever possible. Otherwise, conservative assumptions were made, predominantly based on values reported in gray literature. A full list of pre-study input variables and their sources is included in Appendix IV.

3.3.2 Survey responses

Responses from eight members of the National Wood Pallet and Container Association were collected, yielding at a minimum the respondent's email, organisation size in number of employees, and a list of life cycle activities relevant to their organisation. All respondents gave more detailed responses pertaining to some or all of their specific practices, which are organised into seven life cycle phases: Product design, raw material procurement, new product manufacturing, product delivery and retrieval, repair, closed loop systems, and end-of-life management.

Some responses yielded numerical values which were later used as points of comparison in the risk analysis introduced in Section 3.4.2. Others were used to assess the effects of organisational size on operational circularity. Several free-response questions prompted respondents to provide more detailed information about their operations and practices. A specific section was dedicated to closed loop (returnable) pallet systems and their optimisations.

3.3.3 Interview notes

Notes regarding key concepts, talking points, relevant statistics, and other pertinent information were recorded manually during each interview using a word processing application and later reorganised for clarity. Relevant information obtained through email correspondence was recorded directly.

3.3.4 Trade literature, reports, and regulations

Eighteen items were selected and annotated for use in the case studies and barriers and drivers analysis described in Sections 3.4.3 and 3.4.4, respectively. Table 3-2 below details the gray literature reviewed as part of the document analysis described in Section 3.2.2.

Table 3-2. Summary of gray literature reviewed for document analysis.

Title	Classification	Topic	Reference
2021 International Building Code	Regulation	Alternative wood destinations	*(Council, 2020)*
9BLOC Organizers Seek Innovation and Diversity in Funding the Next Big U.S. Pallet Pool	Blog	Decentralised pallet reuse	*(Brindley, 2012)*

Title	Classification	Topic	Reference
Australian Packaging Covenant Collective Impact Report	Regulation / Report	Packaging waste management regulation	*(*APCO Collective Impact Report*, 2021)*
Brambles Sustainability Review 2022	Report	Pooler sustainability	*(Freijo, 2022)*
Canadian Pallet Council (CPC) Background and Demise	Blog	Decentralised pallet reuse	*(*Canadian Pallet Council (CPC) Background And Demise*, 2019)*
Council Moves to Widen Use of Cross-Laminated Timber	Blog	Alternative wood destinations	*("Council Moves to Widen Use of Cross-Laminated Timber," 2019)*
CPC Members Vote to Dissolve Canadian Pallet Pool	Blog	Decentralised pallet reuse	*(*CPC Members Vote To Dissolve Canadian Pallet Pool - Reusable Packaging News*, 2015)*
Environmental Product Declaration for Wood Pallets	Report	Industry sustainability trends	*(*Environmental Product Declaration: Wooden Pallets*, 2020)*
EPR Masterclass: Packaging EPR Global Trends, Presented by EXPRA	Webinar	Packaging waste management regulation	*(Cassel et al., 2023)*
European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste	Regulation	Packaging waste management regulation	*("Directive 94/62/EC," 1995)*
Getting Credit for Sound Green Practices: Carbon Credits Could Develop into Viable Environmental Benefit for Pallet Recyclers	Blog	Industry sustainability trends	*(Meeks, 2022)*
Guidance for Reusable Packaging	Report	Packaging waste management	*(McNamara et al., 2022)*
Pallets Make the World Go 'Round: Circular Versus Linear Economies and Their Effects on the Pallet Industry	Blog	Industry sustainability trends	*(Horvath, 2022)*

Title	Classification	Topic	Reference
Principles for Reuse/Refill in EPR and DRS	Blog	Packaging waste management regulation	*("Principles for Reuse/Refill in EPR and DRS," 2023)*
Shared Elements of EPR Legislation for Packaging & Paper Products	Report	Packaging waste management regulation	*(Cassel & Keane, 2020)*
The True Cost of Pallet Logistics: Recyclers Are Likely Losing Money Returning Proprietary Pallets	Blog	Industry operations	*(Brindley, 2016)*
Wood Innovation: Sustainability Becomes More Important, Companies Seek to Develop Wood-Based, Eco-Friendly Products	Blog	Alternative wood destinations	*(Lively, 2022)*
Wooden Pallets and Circular Economy	Blog	Industry sustainability trends	*(Quesada, 2021)*

3.4 Methods used to process information

This section describes the methods used to process the information listed in Section 3.3 in pursuit of the research objectives of the thesis. These methods were chosen because they provide quantitative measures of the economic and environmental performance of the wood packaging industry under a range of potential scenarios and provide an overview of how factors internal and external to the industry may be exploited to create the conditions for an effective circular transformation. The chosen methods constitute the minimum which is necessary to inform practical, evidence-based recommendations to relevant actors to drive this transformation.

3.4.1 Expanded relative cost model for container systems

A scenario analysis model was built in Excel that incorporates and expands upon Mollenkopf et al.'s relative cost approach for assessing the viability of one-way and returnable container systems, discussed in detail in Section 2.2. The model contributes to RO1 by assessing the economic and environmental benefits of the optimisation and adoption of returnable wood pallet systems.

This model was used to calculate the per-hire costs, timber consumption, steel consumption, and GHG emissions of five one-way and reusable wood pallet system alternatives at the scale of the individual packaging user using values derived from existing academic and trade literature on transport packaging systems as inputs. The functional unit is the "pallet hire;" which represents either the purchase of one single-use pallet or the rental of one returnable pallet for one use cycle. The system boundary for emissions, timber consumption, and steel consumption begins with raw materials at the new pallet manufacturer's gate and ends at collection for EOL management.

The five pallet systems modelled in this analysis are based on a hypothetical "typical user" with a demand for 100 48x40" pallets per day, 5 days per week, 50 weeks per year:

System **[E]FTL:** A one-way pallet system in which a user purchases one-way 48x40" stringer class pallets in weekly full truckload lots (500 pallets per order) delivered by 53' diesel tractor trailer. The empty pallets reach end-of-life and exit the boundaries of the analysis after one use.

System **[E]LTL:** A one-way pallet system in which a user purchases one-way 48x40" stringer class pallets in daily less-than-truckload lots (100 pallets per order) delivered by 53' diesel tractor trailer. The empty pallets reach end-of-life and exit the boundaries of the analysis after one use.

System **[R] FTL:** Reflective of the current pooled pallet system without optimisation. The user rents FTL lots of returnable 48x40" Grocery Manufacturer's Association standard block class pallets, the design which is most commonly used in pooling operations in the U.S. All transports are made by 53' diesel tractor trailer. Handling conditions and loss rate reflect baselines from literature. The pallets are returned to the pooling facility after each use for inspection, remanufacturing, and re-issue. Damaged components are sold to a recycler at a rate of $0.02 per pound and exit the boundaries of the analysis.

System **[R+]FTL:** Existing pooling practices are optimised using the four best practices identified in Section 2.1. The user rents FTL lots delivered weekly by 53' diesel tractor trailer. Handling conditions are optimal and loss rate is reduced to 1%. Reverse logistics is also carried out by 53' diesel tractor trailer in FTL lots. The system boundary remains at sale for recycling.

System **[R+]LTL:** Existing pooling practices are optimised using the four best practices identified in Section 2.1. The user rents LTL lots delivered daily by 26' diesel medium duty truck. Handling conditions are optimal and loss rate is reduced to 1%. Reverse logistics is also carried out by 26' diesel medium duty truck in LTL lots. The system boundary remains at sale for recycling.

These results were then aggregated to the scale of the entire U.S. wood pallet market according to the following three portfolios of pallet systems to generate estimates of the total economic and social value of the optimisation and increased adoption of returnable wood pallet systems throughout the United States:

Baseline: System [R]FTL comprises 25% of total U.S. annual hires, system [E]FTL comprises 22% of hires, and system [E]LTL comprises 53% of hires. This portfolio approximates the composition of the U.S. wood pallet market as of 2022.

Existing reuse improved: [R+]FTL comprises 25% of hires, [E]FTL comprises 22% of hires, and [E]LTL comprises 53% of hires. This portfolio represents a scenario in which the practices of returnable pallet systems are optimised for cost- and resource efficiency according to findings from academic literature, but returnable systems do not gain market share nor displace demand for one-way pallet systems.

Universal improved reuse: [R+]FTL comprises 47% of hires and [R+]LTL comprises 53% of hires. This portfolio represents a scenario in which the practices of returnable pallet systems are optimised for cost- and resource efficiency according to findings from academic literature, and returnable systems are universally adopted in place of one-way pallet systems.

"Social costs" in this case represent the indirect economic costs of resource consumption, and are calculated as a sum of the social costs of GHG emissions and the opportunity costs of timber and steel consumption. Figures for timber and steel consumption of different wood pallet systems were derived from a life cycle assessment of different reuse intensities of industrial wooden containers conducted in Spain (Gasol et al., 2008).

Appendix IV describes the variables used in the model and the sources from which their baseline values have been derived. Appendix II provides a list of formulas used to calculate container system costs. Table 3-3 below outlines the parameters of the U.S. wood pallet market used in the aggregation of costs and impacts.

Table 3-3. Baseline parameters of the wood pallet market in the United States used in the aggregation of costs and impacts in the expanded relative cost model.

Parameter	**Value**	**Source / Assumption**
Number in Circulation	2.00×10^9	*(Leblanc, 2020)* (Buehlmann et al., 2009)
Fraction High-reuse	12%	*(Michel, 2021)*
Fraction Low-reuse	14%	*(Michel, 2021)*
Fraction Single-Use	74%	*(Michel, 2021)*
High-reuse hires/year	2.9	*(Bengtsson & Logie, 2015)*
Low-reuse hires/year	2.2	*(Gasol et al., 2008)*
Single-use hires	1	Single-use pallet assumed to be used once.
Social cost of carbon (S/t)	56	*(Backman, 2021)*
Market value of sawn timber ($/t)	334	(Lumber Commodity Price History*, 2023)* Lumber valued at $668 per thousand board feet (mbf) as of 2022/05/31. Density of lumber assumed to be 2 t/mbf.
Market value of steel ($/t)	1472	(Steel Prices (USA)*, 2023)*
Producer Price Index, Wood Container and Pallet Manufacturing, April 2022	245.6	*(U.S. Bureau of Labor Statistics, 2022a)*

3.4.2 Breakeven, sensitivity, and risk analyses

The per-hire cost calculations of the expanded relative cost model rely on 22 independent variable inputs, which are listed in Table 3-4 below alongside their baseline values. Assumptions about these variables are tested using breakeven and sensitivity analyses to evaluate the reliability of the expanded relative cost model's calculations and identify the greatest threats to the economic viability of returnable wood packaging systems. The analyses contribute to RO1 by assessing the situational validity of the results of the expanded relative cost model, and to RO3 by identifying key opportunities and threats related to achieving and maintaining economic viability within returnable wood pallet systems.

Variable
TOTAL
UCE
UCR
CL
CT
CRR
RF
LRR
CW
DR
(e/r)RR
d
eDD
rDD
RFT
RLT
SR
LR
TR
OHE
DF
PVF
MARR

Table 3-4. Baseline values of independent variables used to calculate per-hire system costs.

Variable	Description	Unit	Baseline Value				
			[E] FTL	[E] LTL	[R] FTL	[R+] FTL	[R+] LTL
TOTAL	**Total system costs**	**$/part**	**11.90**	**14.29**	**19.97**	**10.65**	**12.18**
UCE	Unit cost for expendable container	$/container	9.20	9.20	-	-	-
UCR	Unit cost for returnable container	$/container	-	-	40.46	40.46	40.46
CL	Container life	years	-	-	10.00	1.23	1.23
CT	Cycle time	days	-	-	86.21	10.00	10.00
CRR	Container return rate	-	-	-	1.06	1.01	1.01
RF	Refurbished fraction	-	-	-	0.73	0.47	0.47
LRR	Per-trip loss rate	-	-	-	0.06	0.01	0.01
CW	Container weight	lbs	30.40	30.40	69.60	69.60	69.60
DR	Disposal cost rate	$/lb	0.00	0.03	-	-	-
(e/r)RR	Recycling revenue rate	$/lb	0.00	0.00	0.02	0.02	0.02
d	Round-trip discount rate	-	-	-	0.22	0.22	0.22
eDD	One-way delivery distance for expendable systems	miles	21.00	31.00	-	-	-
rDD	One-way delivery / retrieval distance for returnable systems	miles	-	-	420.00	147.00	147.00
RFT	FTL transportation rate	$/mile	2.79	-	2.79	2.79	-
RLT	LTL transportation rate	$/100lbs-mile	-	0.02	-	-	0.02
SR	Stop-off rate	$/stop	-	43.22	-	-	43.22
LR	Labor rate	$/hr	16.80	16.80	16.80	16.80	16.80
TR	Handling time	hours	-	-	0.05	0.10	0.10
OHE	Operational holding expense	$/container position-year	11.12	11.12	11.12	11.12	11.12
DF	Dwell fee	$/container-day	-	-	0.06	0.06	0.06
PVF	Peak volume factor	-	1.50	1.50	1.50	1.50	1.50
MARR	Minimum attractive rate of return	-	0.25	0.25	0.25	0.25	0.25

Breakeven analysis

The goal seek function in Excel was used to identify the value of each variable within each system where, when all other variables across all systems except the individual variable in the individual system undergoing breakeven analysis, the total system costs of a returnable system and its equivalent one-way system are equal. This value is referred to in Table 4-3 as the "breakeven value." FTL and LTL systems were evaluated separately using this technique, as each delivery mode serves a different type of consumer who would not necessarily be able to choose freely between the two modes. A limitation of this approach is that it does not consider the effects of variables affecting multiple systems at once, such as transportation costs, instead considering the effects of variable change on each system in isolation from the others.

Sensitivity analysis

For each variable tested under breakeven analysis, the difference in system cost vs. baseline was divided by the difference in variable value vs. baseline to yield a decimal sensitivity value from 0 to 1. A higher sensitivity value indicates that a change in the associated variable has a greater relative effect on total system costs.

Risk analysis

A likelihood of breakeven, "all else held equal," was assigned to each variable in each system and the risk analysis matrix seen in Figure 3-2 below was populated based on the sensitivity values and likelihood values obtained for each variable to assess the relative threat of each variable to the cost-competitiveness of optimised [R+] returnable systems over one way systems, as well as the relative opportunity of each variable to improve the cost-effectiveness of baseline [R] returnable systems.

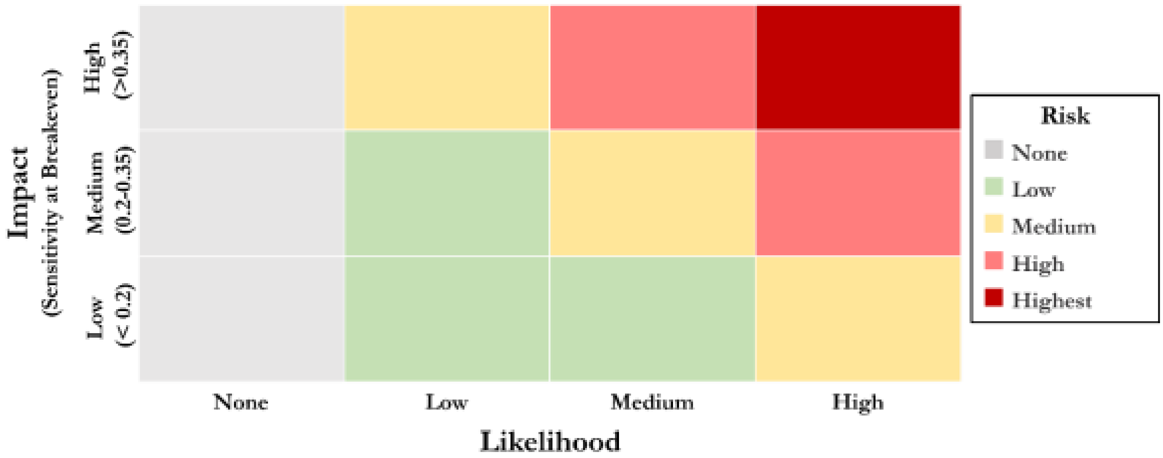


Figure 3-2. Risk analysis matrix used to identify opportunities and threats to the economic viability of returnable wood pallet systems in the U.S.

3.4.3 Construction of case studies

Information from interviews and document analysis was compiled into four brief case studies concerning different aspects of the industry and their role in driving a circular transformation, addressing RO2. These are:

1. Sustainability strategy of a major pallet pooler: The latest sustainability report from Brambles Ltd., who operate the multinational CHEP pallet pool, was reviewed to identify goals that could be pursued by smaller organisations within the wood packaging industry. An interview with a former pallet pooling executive provided information on the degree to which his organisation practised the four best practices identified in Section 2.1.

2. Policy for wood packaging reuse and recycling: International policies governing packaging waste in the European Union and Australia and recent domestic packaging EPR programmes implemented at the state level were reviewed for their potential to improve the circularity of the wood packaging industry.

3. Decentralised pallet reuse schemes: Document analysis and interviews were combined to illustrate the strengths of the EPAL decentralised pallet pool in Europe and investigate why similar programmes in North America have failed.

4. Mass timber: The potential to use timber displaced by a circular transformation as an alternative to concrete and steel in the construction industry was investigated.

3.4.4 Identification of barriers and drivers

Information from literature review, document analysis, and interviews was combined to identify a set of internal and external barriers and drivers of circular transformation of the American wood packaging industry. Understanding these barriers and drivers helps different actors understand how they can intervene to drive the transformation by exploiting drivers and mitigating barriers, contributing to RO3.

4 Results and analysis

Sections 4.1 to 4.5 present the results of the expanded relative cost model; breakeven, sensitivity, and risk analyses; survey responses; case studies; and barriers and drivers analysis. An examination of these results through the lenses of ecological modernisation and the seven operational principles of circular economy can be found in Section 5.1.

4.1 Expanded relative cost model

This section presents results and analysis of calculations made using the expanded relative cost model introduced in Section 3.4.1 at per-hire and national scales. The model demonstrates that optimisation of returnable wood pallet systems according to best practices identified in academic literature has the potential to reduce both costs and resource consumption of the American wood packaging industry.

4.1.1 Costs and impacts of selected pallet systems on a per-hire basis

This section presents a direct comparison of packaging user costs; GHG emissions from manufacturing, repair, and transportation activities; timber consumption; and steel consumption on a per-hire basis. Table 4-1 provides a summary of the figures presented in this section.

Table 4-1. Summary of costs and impacts of selected wood pallet systems on a per-hire basis.

Scenario	[E] FTL	[E] LTL	[R] FTL	[R+] FTL	[R+] LTL
Cost per hire ($)	$ 11.90	$ 14.29	$ 19.97	$ 10.65	$ 12.18
Emissions per hire (kg CO2-eq.)	2.9	2.8	41.2	14.5	14.6
Materials & Manufacturing	2.17	2.17	0.25	0.18	0.18
Transport	0.74	0.67	40.98	14.34	14.46
Fraction from Transport	25%	23%	99%	99%	99%
Timber per hire (kg)	13.1	13.1	2.0	1.3	1.3
Steel per hire (kg)	0.697	0.697	0.027	0.017	0.017

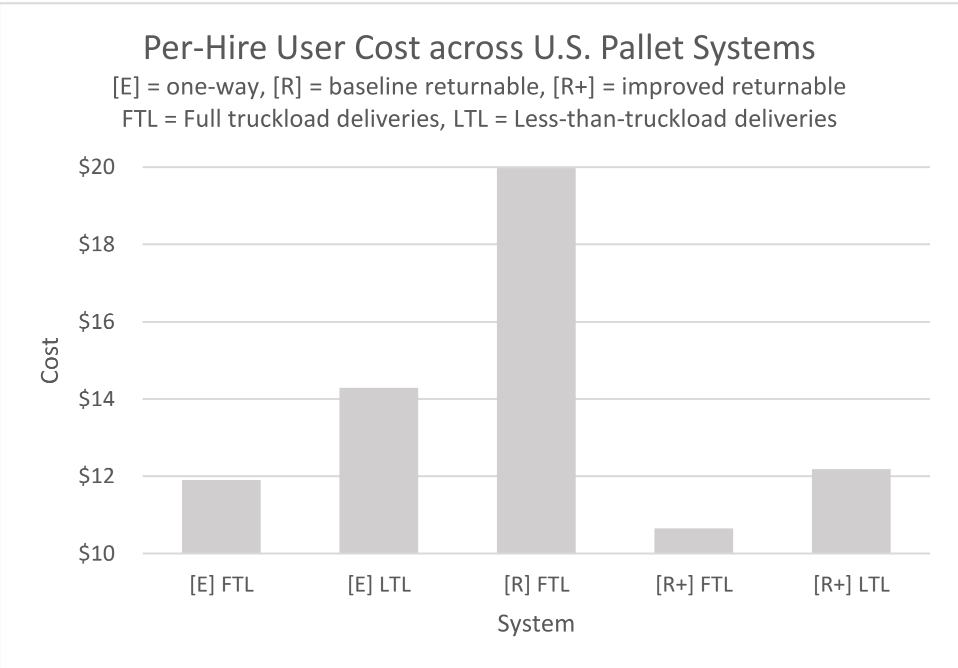


Figure 4-1. Comparison of per-hire user costs across selected wood pallet systems.

Optimisation of returnable pallet systems reduces user costs substantially. User costs of optimised returnable systems are universally lower than those of equivalent one-way pallet systems. The cost of participation in pooling systems for FTL users is reduced by 47% and the possibility for LTL users to participate in cost-effective returnable pallet systems is realised. Under baseline conditions, participation a pooling system costs 68% more for the typical FTL customer than a one-way pallet system. However, an optimised returnable pallet system costs 11% less than a one-way pallet system for the same customer.

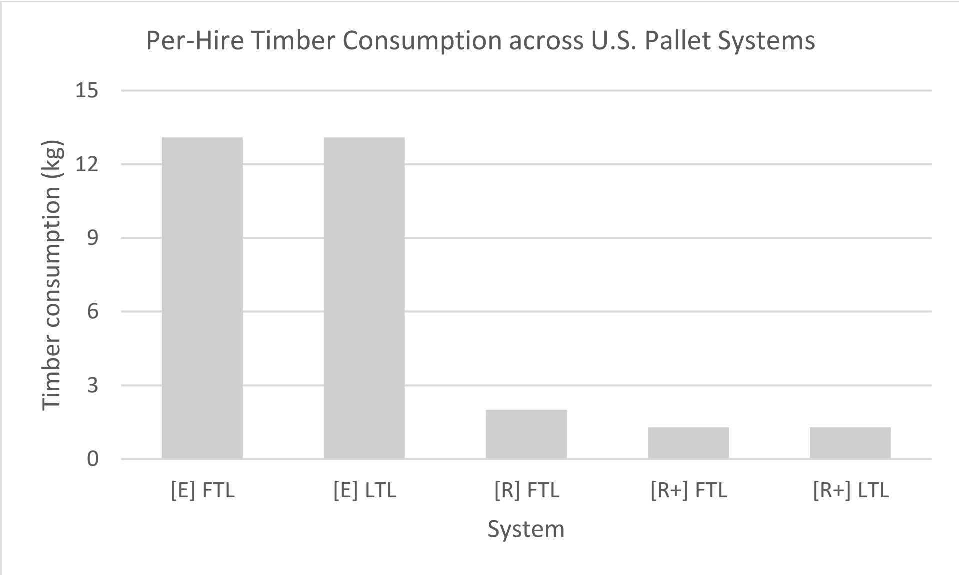


Figure 4-2. Comparison of per-hire timber consumption across selected wood pallet systems.

The most significant resource efficiency advantage of existing returnable pallet systems is their low timber consumption compared to one-way pallet systems. Optimisation compounds this advantage, reducing the timber consumption of existing returnable pallet systems by 35%. An optimised returnable pallet system consumes 90% less timber than a one-way pallet system.

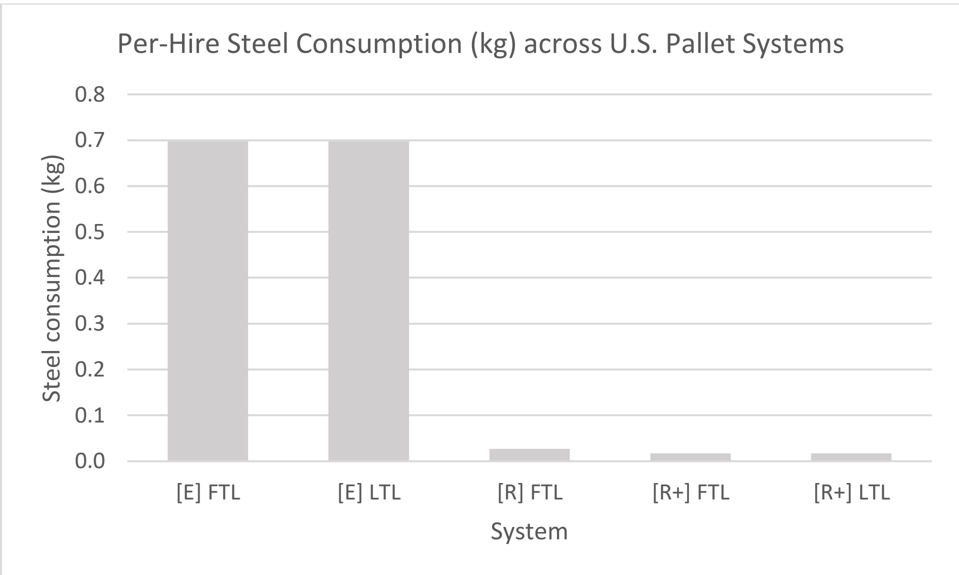


Figure 4-3. Comparison of per-hire steel consumption across selected wood pallet systems.

Optimisation of returnable pallet systems reduces their steel consumption by 37%. An optimised returnable pallet system consumes 98% less steel than a one-way pallet system.

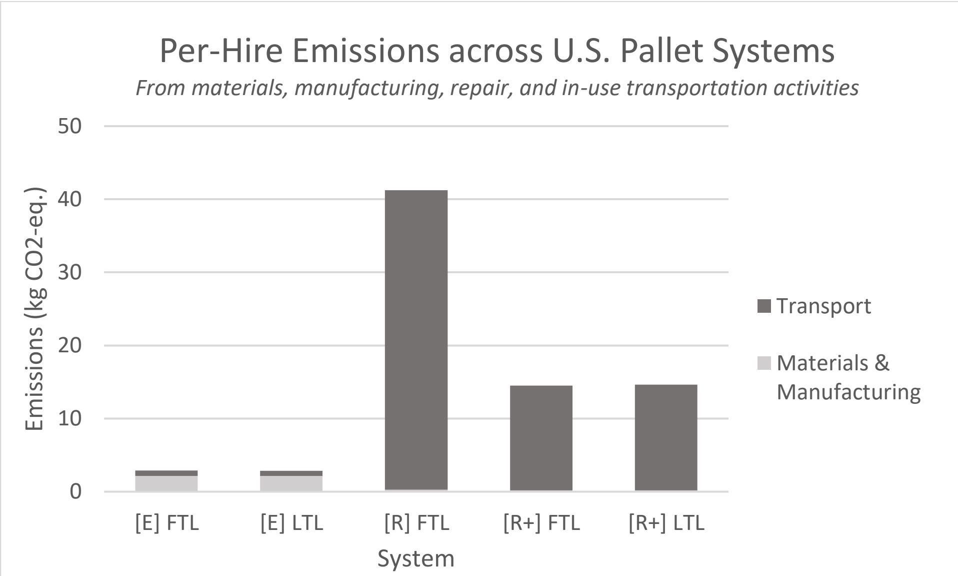


Figure 4-4. Comparison of per-hire GHG emissions across selected wood pallet systems.

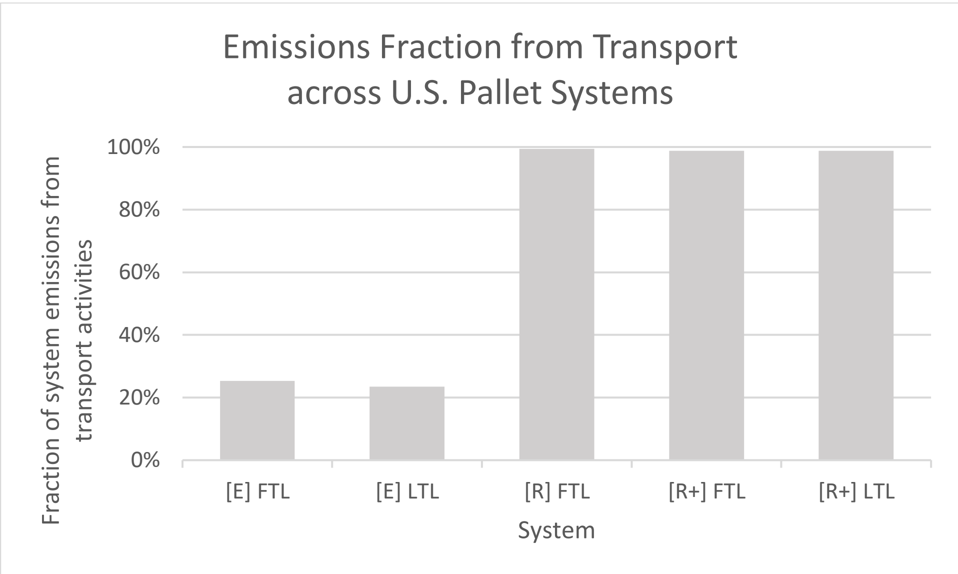


Figure 4-5. Comparison of the share of total system GHG emissions generated from transportation activities across selected wood pallet systems.

All forms of returnable pallet systems generate greater GHG emissions than one-way pallet systems due to the much greater transport distances involved in their operation. 99% of the emissions of returnable pallet systems come from transport. However, it is possible to reduce per-hire emissions of returnable pallet systems by roughly 65% through optimisation. This is mainly due to a reduction in the distances empty pallets travel under an optimised reuse system.

4.1.2 Aggregation of costs and impacts to national scale

This section presents a direct comparison of packaging user costs; social costs of GHG emissions, timber consumption, and steel consumption; GHG emissions from manufacturing, repair, and transportation activities; timber consumption; and steel consumption aggregated to the scale of the entire U.S. wood pallet market under the three pallet management scenarios described in Section 3.4.1. Table 4-2 provides a summary of the figures presented in this section.

Table 4-2. Summary of costs and impacts of selected pallet management strategies aggregated to the scale of the U.S. wood pallet market.

Scenario	Baseline	Existing reuse improved	Universal improved reuse
User cost	$42 385 000 000	$35 898 000 000	$32 004 000 000
Social cost	$14 194 000 000	$12 475 000 000	$4 198 000 000
Total costs	$56 579 000 000	$48 373 000 000	$36 202 000 000
Total emissions (t CO2-eq.)	34 700 000	16 100 000	40 700 000
Total timber (t)	31 500 000	29 500 000	5 500 000
Total steel (t)	1 200 000	1 200 000	50 000

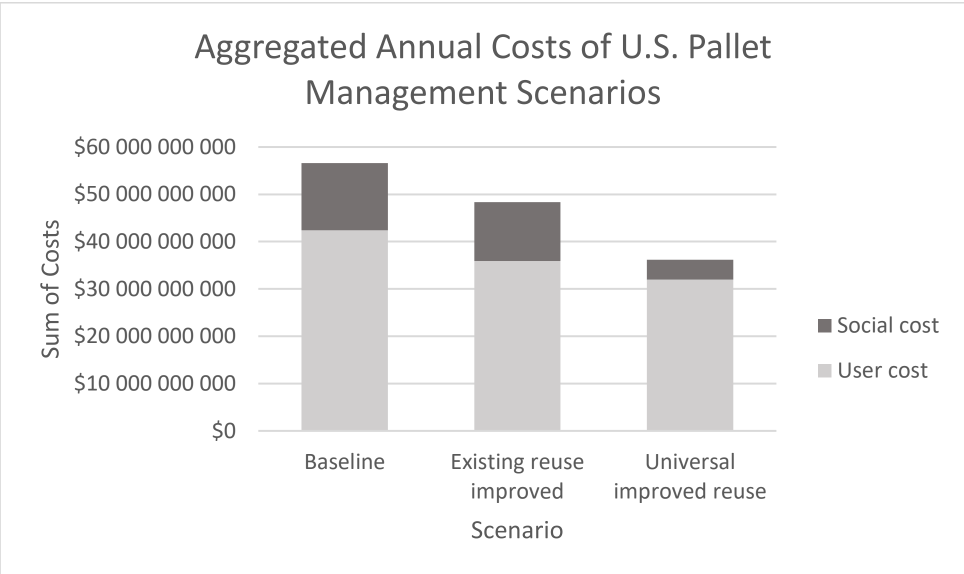


Figure 4-6. Comparison of aggregated annual user and social costs across selected wood pallet management scenarios.

There is a demonstrable cost benefit to the adoption of optimised returnable pallet systems in the United States. Optimising existing returnable systems carries an annual cost savings of roughly $8.2 billion. Replacing one-way pallet systems with optimised returnable pallet systems generates an additional $12.1 billion in annual cost savings. User costs may be reduced by up to 25% and the social costs of resource churn and emissions may be reduced by up to 70% compared to the baseline scenario.

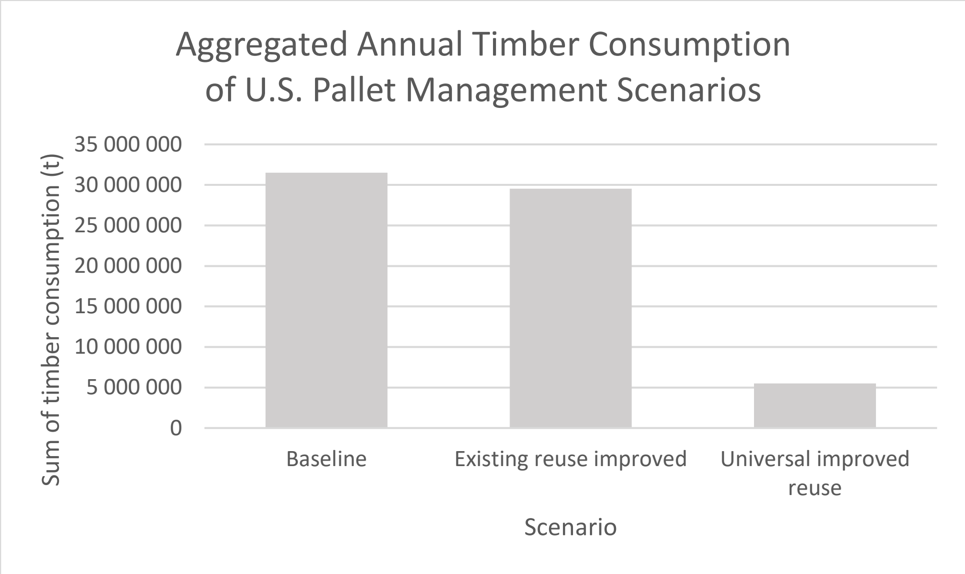


Figure 4-7. Comparison of aggregated annual timber consumption across selected wood pallet management scenarios.

Under conditions of universal improved reuse, it is possible to reduce the timber consumption of the American wood pallet industry by roughly 25 million tonnes per year, a reduction equivalent to roughly 10% of current industrial roundwood consumption in the United States from all sources (*Forest Products Annual Market Review 2020-2021*, 2022).

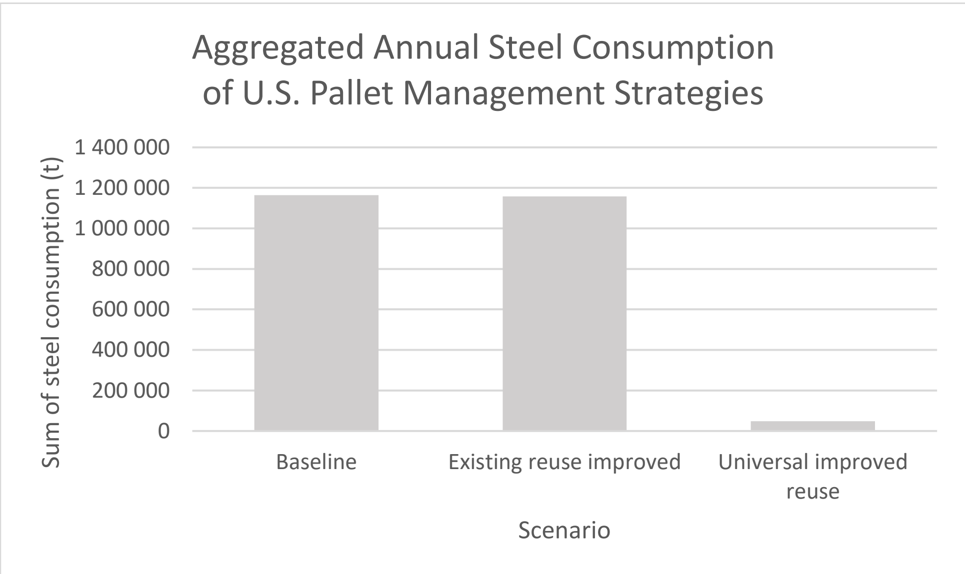


Figure 4-8. Comparison of aggregated annual steel consumption across selected wood pallet management scenarios.

Under conditions of universal improved reuse, it is possible to reduce the steel consumption of the U.S. wood pallet industry by roughly 1.1 million tonnes per year, a reduction equivalent to roughly 1% of current steel consumption in the United States from all sources (*Mineral Commodity Summary - Iron and Steel*, 2022).

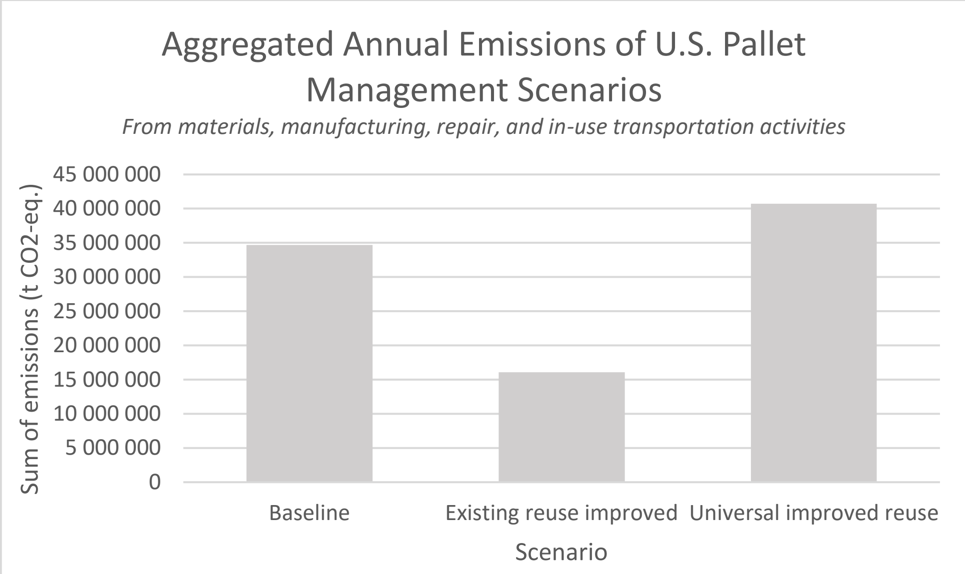


Figure 4-9. Comparison of aggregated annual GHG emissions across selected wood pallet management scenarios.

Emissions reductions of roughly 20 million tonnes CO_2-eq. per year are possible via the optimisation of existing pooling systems. This is a reduction equivalent to roughly 0.4% of current total anthropogenic GHG emissions from all sources in the U.S. (US EPA, 2017). However, the high transport emissions associated with returnable pallet systems lead to an overall increase in emissions of roughly 6 million tonnes per year over baseline in the universal improved reuse scenario. There is a tradeoff between the reduction of costs, timber consumption, and steel consumption and the reduction of GHG emissions in American wood pallet management scenarios.

4.2 Breakeven, sensitivity, and risk analyses

This section presents the results of the breakeven, sensitivity, and risk analyses. Factors which present the highest threats to the cost-effectiveness of optimised returnable systems and the greatest opportunities to improve the cost-effectiveness of existing returnable systems are identified.

Table 4-3. Results of breakeven analysis.

Variable	Breakeven Value					Difference from Baseline				
	[E] FTL	[E] LTL	[R] FTL	[R+] FTL	[R+] LTL	[E] FTL	[E] LTL	[R] FTL	[R+] FTL	[R+] LTL
TOTAL	**10.65**	**12.18**	**11.90**	**11.90**	**14.29**	**-10.5%**	**-14.8%**	**-40.4%**	**11.7%**	**17.3%**
UCE	8.19	7.51	-	-	-	-10.9%	-18.4%	-	-	-
UCR	-	-	18.77	47.42	52.97	-	-	-53.6%	17.2%	30.9%
CL	-	-	N/A	0.82	0.66	-	-	-	-33.9%	-46.3%
CT	-	-	-168.34	15.12	18.64	-	-	-295.3%	51.2%	86.4%
CRR	-	-	-2.02	1.52	1.87	-	-	-290.1%	50.3%	84.8%
RF	-	-	0.13	0.60	0.71	-	-	-82.2%	28.6%	51.1%
LRR	-	-	-0.14	0.04	0.06	-	-	-333.3%	309.0%	521.5%
CW	-	-	11546.49	-1823.34	38.12	-	-	16489.8%	-2719.7%	-45.2%
DR	-0.04	-0.04	-	-	-	-	-258.4%	-	-	-
(e/r)RR	-	-	3.38	-0.53	-0.91	-	-	16491.5%	-2719.7%	-4586.6%
d	-	-	1.94	-0.54	-0.42	-	-	781.8%	-346.6%	-292.9%
eDD	-203.18	-316.08	-	-	-	-1067.5%	-1119.6%	-	-	-
rDD	-	-	-507.01	290.72	268.45	-	-	-220.7%	97.8%	82.6%
RFT	-	-	-3.37	5.52	-	-	-	-220.7%	97.8%	-
RLT	-	-	-	-	0.01	-	-	-	-	-45.4%
SR	-	-	-	-	128.64	-	-	-	-	197.6%
LR	-	-	-144.59	29.31	37.90	-	-	-960.7%	74.5%	125.6%
TR	-	-	-0.43	0.17	0.23	-	-	-960.6%	74.5%	125.6%
OHE	-	-	-299.47	59.23	362.75	-	-	-2794.1%	432.9%	3163.4%
DF	-	-	-2.43	0.44	2.15	-	-	-4500.5%	697.8%	3799.2%
PVF	-	-	-2.85	2.25	2.77	-	-	-290.1%	50.3%	84.8%
MARR	-	-	-3.38	0.88	1.31	-	-	-1452.0%	252.0%	424.0%

Six variables generate a breakeven outcome within ±50% of their baseline values: Unit cost of an expendable container, unit cost of a reusable container, container lifespan, fraction requiring refurbishment per cycle (FTL), container weight (LTL), and LTL transportation rate. Of these, container unit cost and fraction requiring refurbishment have the greatest marginal impacts.

Table 4-4. Sensitivity of per-hire cost to selected variables and likelihood of breakeven occurrence.

Variable	Sensitivity at Breakeven					Likelihood of Breakeven "All else equal"				
	[E] FTL	[E] LTL	[R] FTL	[R+] FTL	[R+] LTL	[E] FTL "Threat"	[E] LTL "Threat"	"Opportunity	[R+] FTL "Threat"	[R+] LTL "Threat"
TOTAL	-	-	-	-	-	-	-	-	-	-
UCE	0.961	0.804	-	-	-	High	High			
UCR	-	-	0.754	0.682	0.560			Medium	High	High
CL	-	-	-	0.347	0.374				Medium	Medium
CT	-	-	0.137	0.229	0.201			None	High	High
CRR	-	-	0.139	0.234	0.204			None	Low	Low
RF	-	-	0.492	0.410	0.339			Low	High	High
LRR	-	-	0.121	0.038	0.033			None	High	High
CW	-	-	0.002	0.004	0.383			None	None	Low
DR	-	0.057	-	-	-	High	High			
(e/r)RR	-	-	0.002	0.004	0.004			Low	Low	Low
d	-	-	0.052	0.034	0.059			None	None	None
eDD	0.010	0.013	-	-	-	None	None			
rDD	-	-	0.183	0.120	0.210			None	High	High
RFT	-	-	0.183	0.120	-			None	Medium	
RLT	-	-	-	-	0.381					High
SR	-	-	-	-	0.088					Medium
LR	-	-	0.042	0.158	0.138			None	Medium	Medium
TR	-	-	0.042	0.158	0.138			None	High	High
OHE	-	-	0.014	0.027	0.005			None	Medium	Low
DF	-	-	0.009	0.017	0.005			None	Low	Low
PVF	-	-	0.139	0.234	0.204			None	Low*	Low*
MARR	-	-	0.028	0.047	0.041				Low**	Low**

Variables with a high sensitivity at the breakeven point (>0.35) are UCE, UCR, CL (LTL), RF (FTL), and RLT. Variables with a high likelihood of independently causing a breakeven scenario (all else held equal) are UCE, UCR (optimised systems only), CT, RF (R+), LRR (R+), DR, rDD (R+), RLT, and TR (R+). *PVF and **MARR vary significantly between firms and will occasionally result in breakeven scenarios for individual packaging users, but are unlikely to threaten the cost-effectiveness of returnable systems for a large fraction of total users, so these variables were assigned a low likelihood.

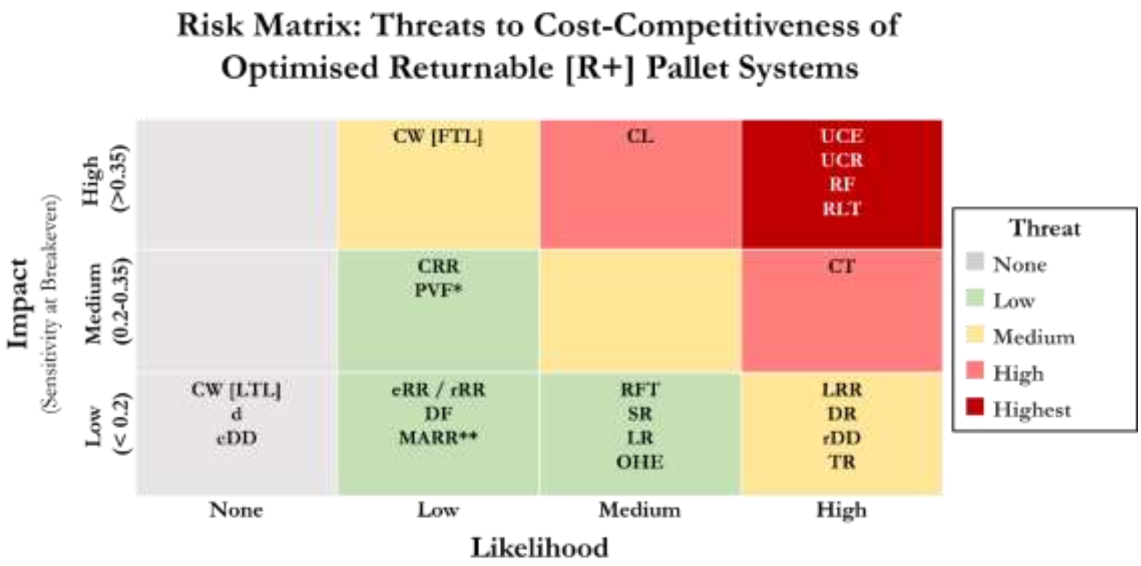


Figure 4-10. Risk matrix classifying threat of independent variables to reduce cost-competitiveness of optimised returnable wood pallet systems compared to one-way wood pallet systems.

Though results of the expanded relative cost model show a modest cost advantage for optimised returnable systems over one-way systems under baseline conditions, risk analysis shows that this advantage is fragile. Unit costs of new one-way and returnable wood pallets have a dramatic effect on the costs of these systems, favoring one-way systems when new manufacturing costs are lower. Costs of producing wood pallets in the United States have been highly volatile in recent years (U.S. Bureau of Labor Statistics, 2022a), owing largely to raw material price instability, so this factor poses a very high risk to the market-driven proliferation of circular wood packaging systems in the United States. An increase in the fraction of returnable pallets requiring refurbishment per cycle, a product of users' loading and handling behavior (Tornese et al., 2018), would also threaten R+ systems. LTL systems are susceptible to increases in freight costs. Finally, a low cycle time (less than 15 days) and long container life (at least 1 year) are both critical to the market viability of R+ systems.

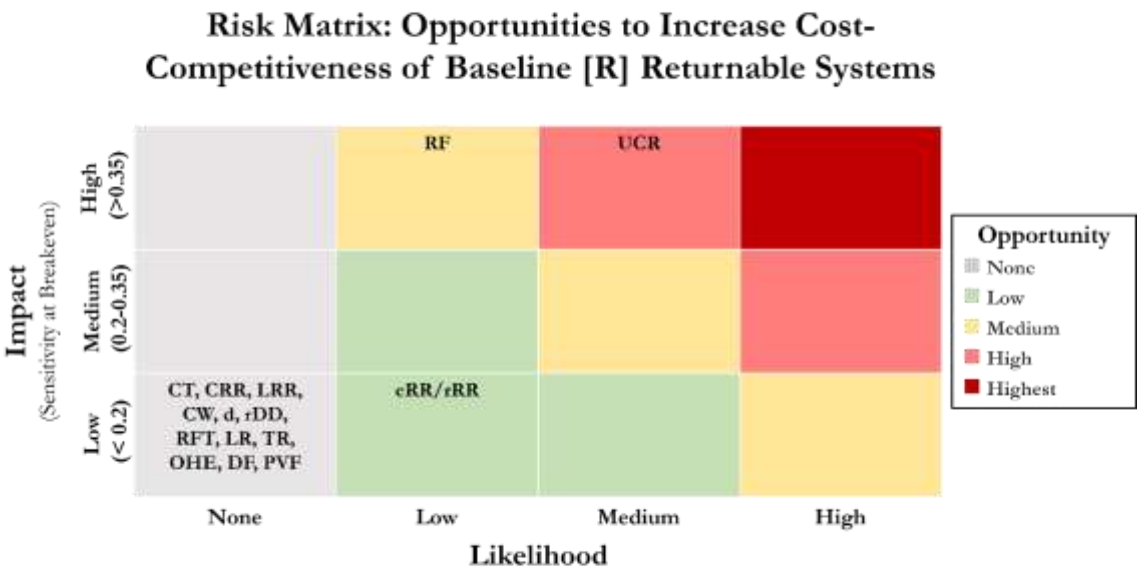


Figure 4-11. Risk matrix classifying opportunity of independent variables to increase cost-competitiveness of baseline returnable wood pallet systems compared to one-way wood pallet systems.

Conversely, very little can be done to make returnable pallet systems cost-competitive with one-way systems without implementing the best practices identified in Section 2.1. Only reduction in the unit cost of a new returnable pallet presents a high opportunity to make R systems competitive in the U.S. market on its own. Results from the risk analysis show that reductions of new pallet manufacturing costs and the incidence of in-use damages are the most important factors for decisionmakers in returnable pallet systems to focus on if they wish to gain market share away from one-way pallet systems.

4.3 Survey: "Circularity of the American Wood Pallet Industry"

Eight individuals in leadership positions within wood pallet businesses responded to the survey out of a total of 952 impressions, resulting in a capture rate of 0.82%. All eight respondents represented independent manufacturers and recyclers, while no poolers were represented.

Five respondents declared a role of "President," one respondent declared a role of "Operations Manager," one respondent declared a role of "General Manager of Accounting," and one respondent did not declare a role.

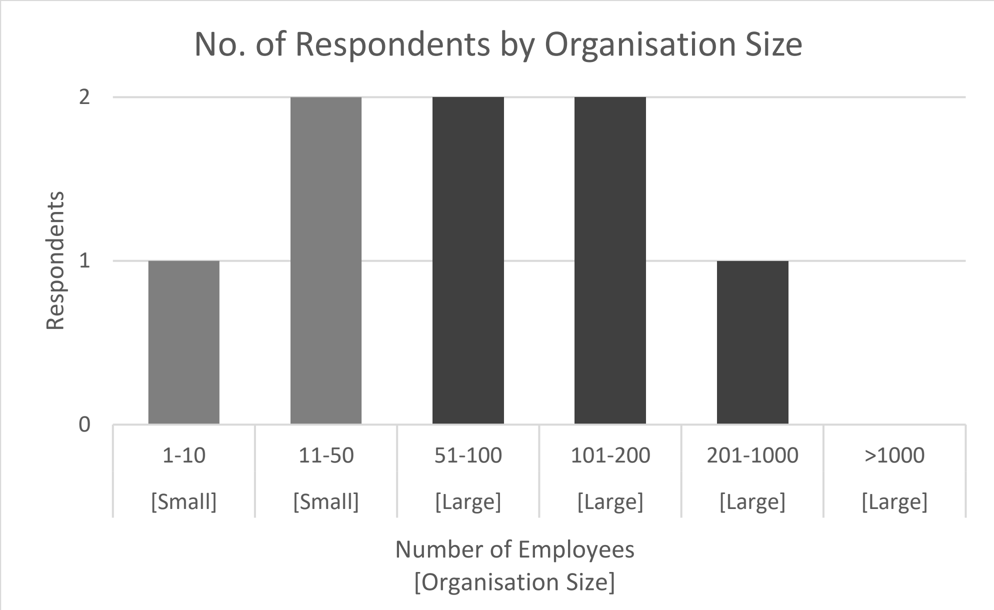


Figure 4-12. Survey respondents by organisation size.

Three respondents (38%) represented small organisations having fewer than 50 employees, which comprise more than 99% of organisations in the American wood pallet industry (Roy et al., 2016). The remainder (62%) represented large organisations having 51 or more employees. No respondent represented an organisation with more than 1000 employees.

Throughout the rest of Section 4.3, distinctions between small and large organisations are made where relevant to illustrate the effects of organisation size on various life cycle practices.

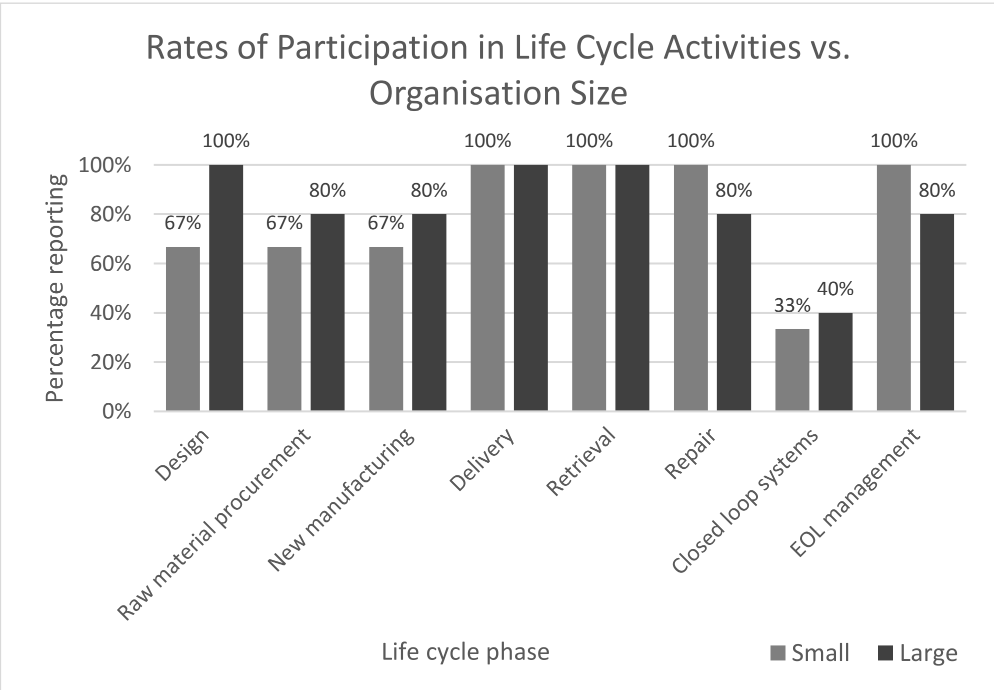


Figure 4-13. Respondents' rates of participation in life cycle activities by organisation size.

There is a relative difference between the participation of small and large organisations at different stages of the wood pallet life cycle. Rates of participation among large organisations are relatively higher in earlier phases (design, raw material procurement, and new manufacturing), while small organisations have higher rates of participation in later phases (repair and EOL management). All organisations are shown to participate in the delivery and retrieval of pallets equally (100%), while participation in closed loop systems is low across all organisations (38%). These findings indicate a possible transference of responsibility over value-added activities from large, centralised operations early in the product life cycle to smaller operations late in the product life cycle. In other words, large organisations tend to create the products whose continued use tends to become the responsibility of smaller organisations as the products near end-of-life.

4.3.1 Design

Seven out of eight respondents (two small and five large) reported participation in the design phase and provided the following information about their product design practices:

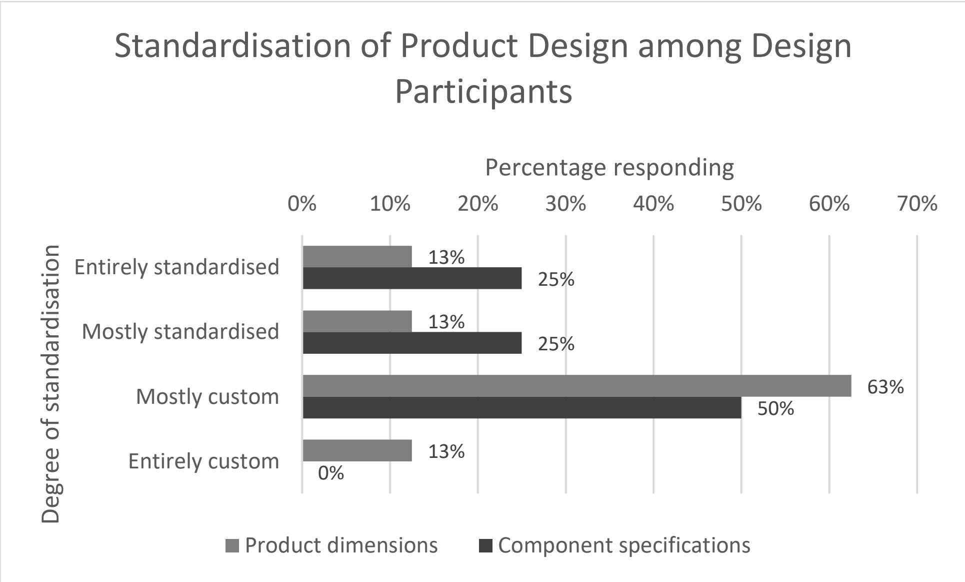


Figure 4-14. Levels of product design standardisation among design phase participants.

Standardisation of wood pallet designs supports life cycle extension and material value retention in both one-way and returnable pallet systems. Product dimension standardisation enables a greater degree of direct reuse between distinct users, whose packaging and material handling operations are likely only compatible with a narrow range of product designs. Component standardisation increases the possibility that components salvaged from decommissioned pallets can be utilised directly in repair activities with minimal material loss.

Component specifications show a higher degree of standardisation (50% mostly or entirely standardised) than product dimensions (25% mostly or entirely standardised). The most common response for product dimensions (63%) and component specifications (50%) is "Mostly custom." A fraction of participants works with entirely standardised product (13%) and component (25%) designs, indicating that a highly standardised product offering is practically achievable for wood pallet designers.

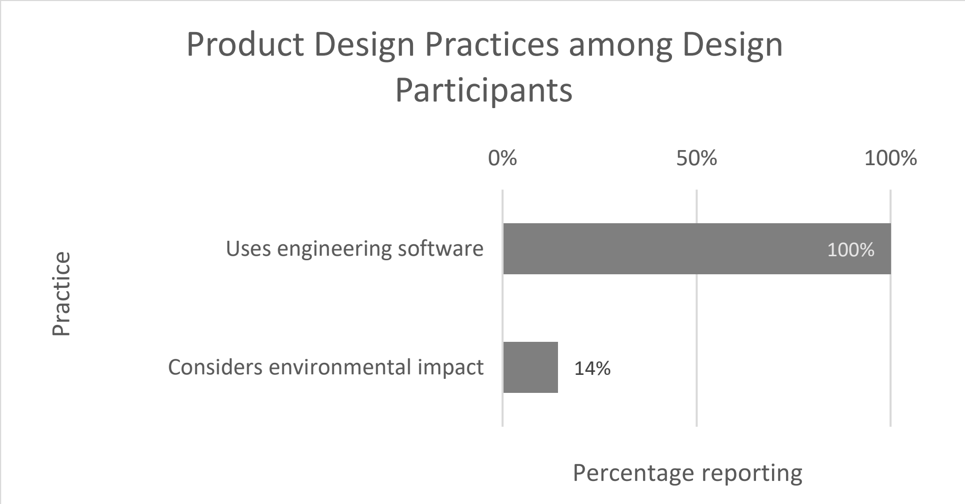


Figure 4-15. Prevalence of selected product design practices among design phase participants.

Commercially available unit load engineering software can be used to improve performance, extend service life, and reduce material consumption of wood pallet designs. 100% of design phase participants use such software to create their designs, but only 14% consider environmental impact reduction as an important factor in their design process. Informing wood packaging designers and consumers about existing capabilities for, and potential benefits of, environmentally conscious design practices could contribute to a circular transformation of the American wood packaging industry.

4.3.2 Raw material procurement

Seven out of eight respondents (two small and five large) reported participation in the raw material procurement phase and provided the following information about their new wood raw material procurement practices:

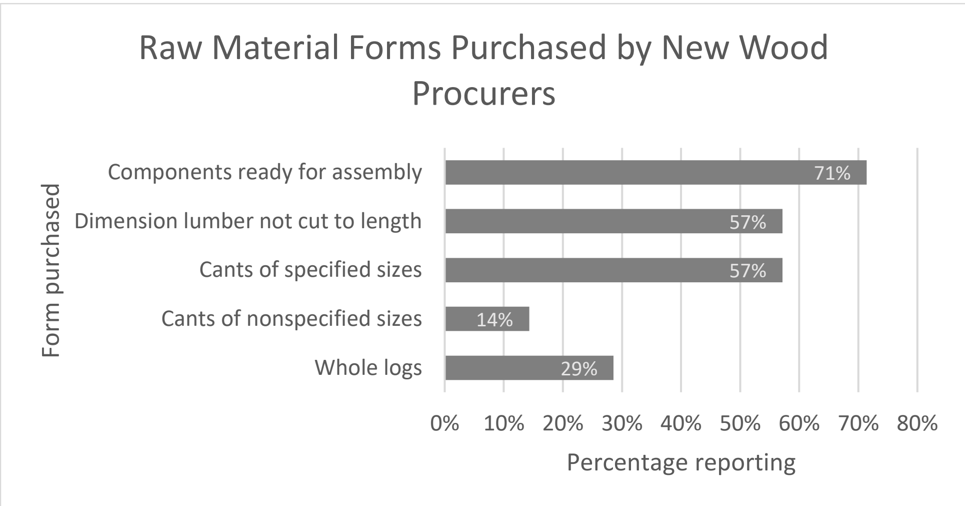


Figure 4-16. Prevalence of selected new wood raw material forms among procurement phase participants.

When manufacturers purchase wood raw material in a more processed form from the sawmill, the scrap produced from processing the wood into a usable form is generated in a more concentrated stream and unnecessary transportation of scrap material from the sawmill to the manufacturers is avoided. Therefore, it could often be most resource efficient for wood pallet manufacturers to purchase new wood raw material in a form that is as close as possible to its assemblable form without sacrificing volume utilisation in shipping, though this hypothesis is inferential.

The most commonly purchased form of new wood raw material among procurement phase participants is the most processed form, components ready for assembly (71% of participants report purchasing). Dimension lumber not cut to length, which only requires the manufacturer to make a single cut to process the raw material into a usable component, is almost as commonly purchased (57%). Whole logs, the least processed form of new wood material, are purchased by 29% of participants.

Cants, which are larger rectangular lengths of timber cut from the lower grade wood from the centers of logs and large branches, are also commonly purchased (57% specified sizes, 14% nonspecified sizes). Cants require more processing to form into usable components than does dimension lumber but have the distinct resource efficiency advantage over other forms of wood raw material of utilising a byproduct of high-grade timber processed for other industries such as construction and furniture manufacturing. For this reason, the cant is arguably the most resource efficient form of new wood used in wood pallet manufacturing.

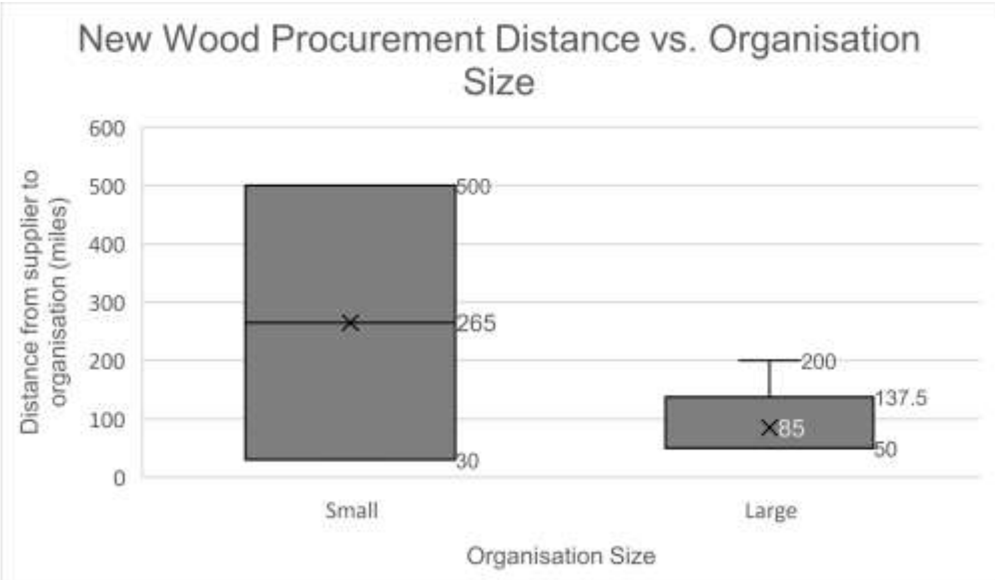


Figure 4-17. New wood raw material procurement distances by organisation size among procurement phase participants.

Raw material transportation impacts were not accounted for in the expanded relative cost model, but they are an Important consideration. Small organisations had a much greater variance in new wood procurement distances (range: 30–500 miles) and a higher mean procurement distance (265 miles) than large organisations (range: 50-200 miles, mean 85 miles). This indicates that the marginal costs and impacts of new wood raw material transportation are lower for large organisations than for small organisations.

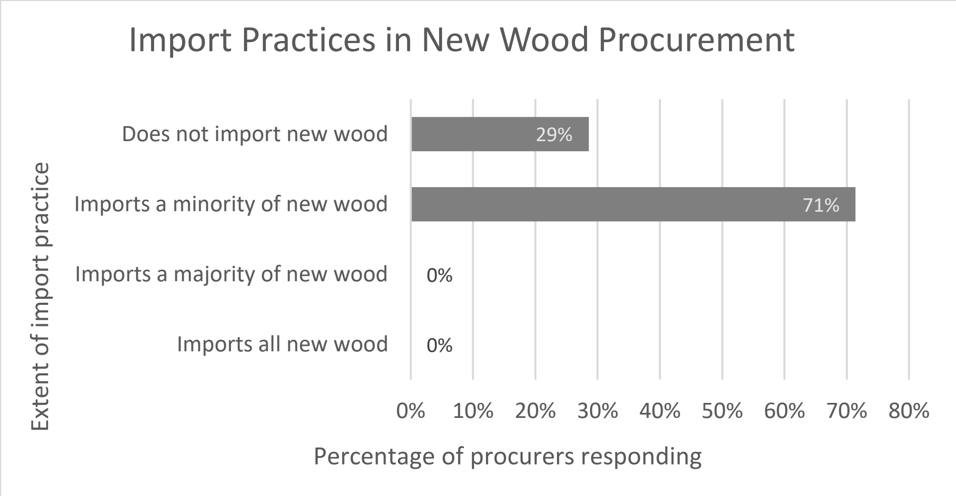


Figure 4-18. New wood import practices among procurement phase participants.

The International Standard on Phytosanitary Measures No. 15 requires all wood packaging material which crosses national borders to undergo heat treatment or chemical fumigation to prevent the spread of diseases and invasive species (*ISPM 15. Regulation of Wood Packaging Material in International Trade*, 2018). Heat treatment is an energy-intensive process and fumigation carries environmental and human toxicity risks. Imported wood has likely been transported over much longer distances than has domestically available wood. Therefore, it is environmentally advantageous to avoid the importation of new wood for wood pallet manufacturing. No procurement phase participant reported importing more than half of their new wood, but most participants (71%) reported importing a minority fraction of their new wood. The remainder (29%) reported that they did not import any new wood.

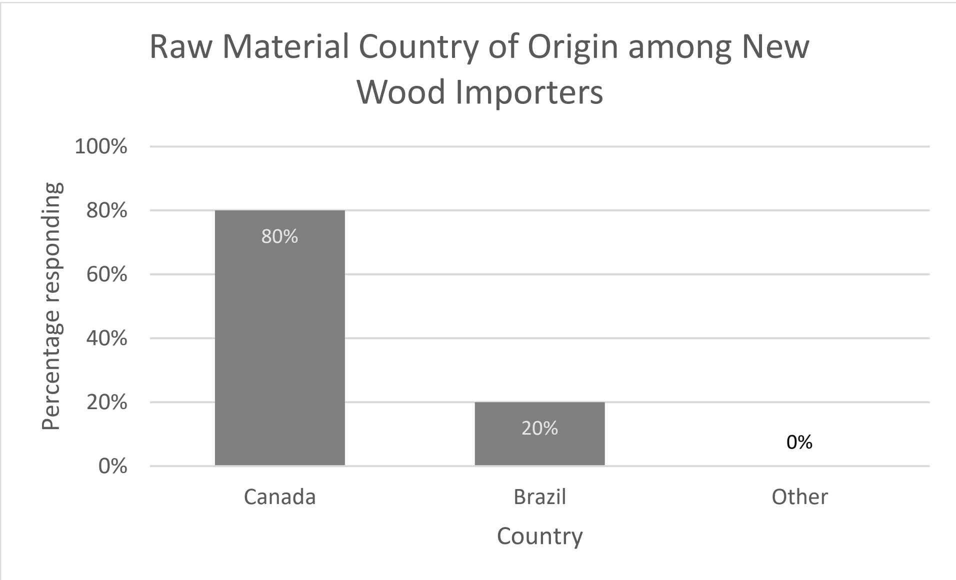


Figure 4-19. Countries of origin of imported new wood among procurement phase participants.

Of the five participants who import new wood, four (80%) import from Canada and one (20%) imports from Brazil. No other countries were represented among new wood exporters in this sample.

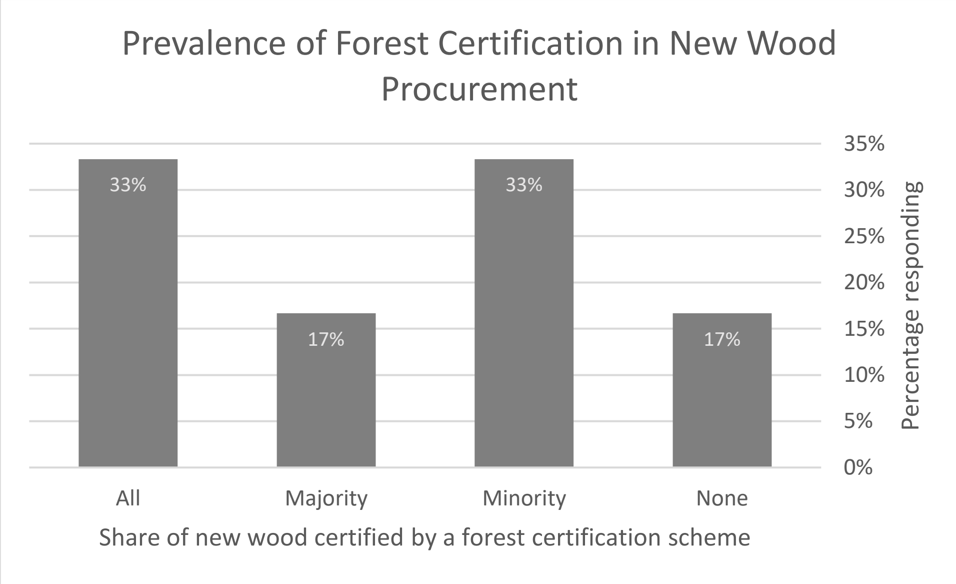


Figure 4-20. Prevalence of forest certification of new wood among procurement phase participants.

Forest certification is a voluntary practice among timber producers which seeks to promote ecologically and socially sustainable forest management practices. It has been shown to have generally positive effects on deforestation, forest degradation, and the economic viability of forest industries across a variety of geographic contexts (Wolff & Schweinle, 2022). There has been a considerable increase in certified wood procurement among American wood pallet manufacturers between 2011 and 2016 (Gerber et al., 2020).

Participants demonstrated varying degrees of certified wood procurement practices; 50% reported purchasing most or all new wood from certified sources, while 50% reported purchasing a minority or none of their new wood from certified sources.

4.3.3 New manufacturing

Six out of eight respondents (two small and four large) reported participation in the manufacturing phase and provided the following information about their new wood pallet manufacturing practices:

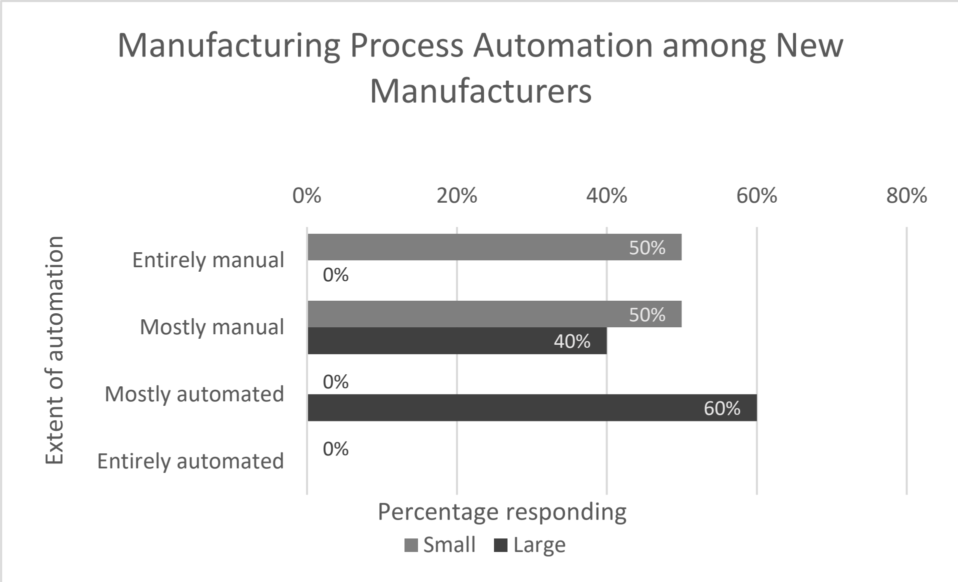


Figure 4-21. Levels of manufacturing process automation among new manufacturing phase participants.

Standardisation of wood pallet manufacturing and repair processes contributes to an increased level of mechanical performance (Clarke & Araman, 2005). Automation of manufacturing processes could enable a greater degree of standardisation, which can lead to more material-efficient designs and reduce the incidence of damages, prolonging product lifespans.

Large organisations reported a greater degree of automation in their manufacturing processes (60% mostly automated, 40% mostly manual) than did small organisations (50% entirely manual, 50% mostly manual), indicating that consolidation could drive manufacturing process automation and standardisation in the wood packaging industry. Most particpants in new manufacturing also reported maintaining some form of quality control scheme in their facilities to maximise product consistency and minimise material losses.

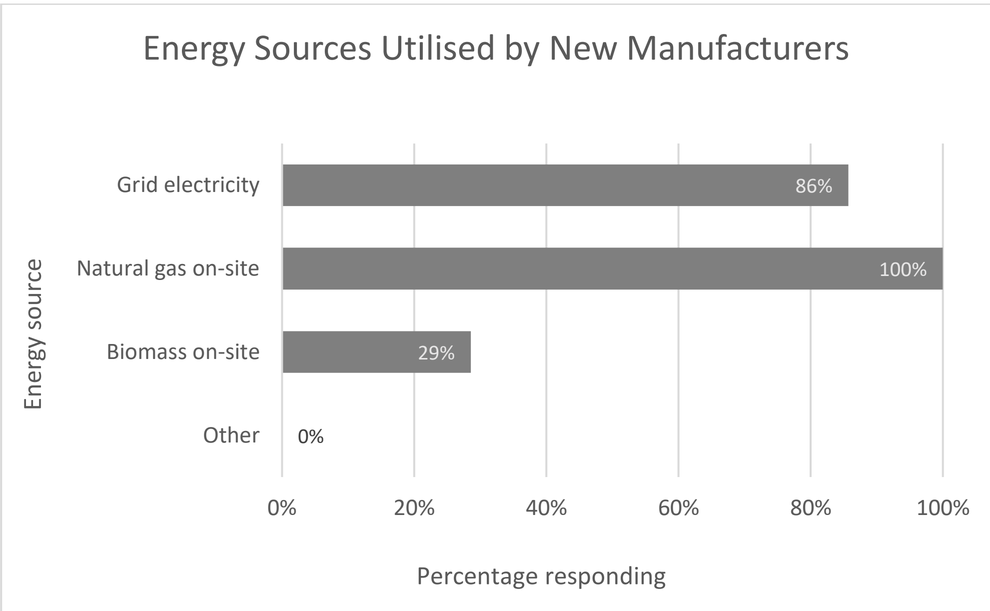


Figure 4-22. Energy sources utilised in manufacturing by new manufacturing phase participants.

For use phase transportation distances under 950 km (590 miles), the manufacturing phase has the highest contribution to the global warming potential of American wood pallet systems out of any life cycle phase (Alanya-Rosenbaum et al., 2021). It is important to consider the GHG intensity of energy consumed by wood pallet manufacturing processes.

100% of new manufacturing participants reported using natural gas for energy production, while 86% reported using grid electricity, a majority of which is generated from fossil fuel sources in the U.S. Despite the availability of wood biomass at pallet manufacturing facilities, only 29% of participants reported generating energy (heat or electricity) from biomass on-site, which is higher than the prevalence of 11% reported in one recent publication on wood pallet repair processes in the U.S. (Park et al., 2016). No participant reported the use of any alternative energy source, such as on-site solar or wind electricity generation.

These results point to an opportunity to reduce the GHG intensity of wood pallet manufacturing in the United States, particularly via the adoption of on-site biomass energy generation practices, but adoption is likely limited by the relatively low value of fuel as a destination for wood waste compared to alternative applications, such as its use as a feedstock for engineered wood products (America, 2002).

4.3.4 Delivery and retrieval

All eight respondents reported participation in the delivery and retrieval phases and provided the following information about their delivery and retrieval practices:

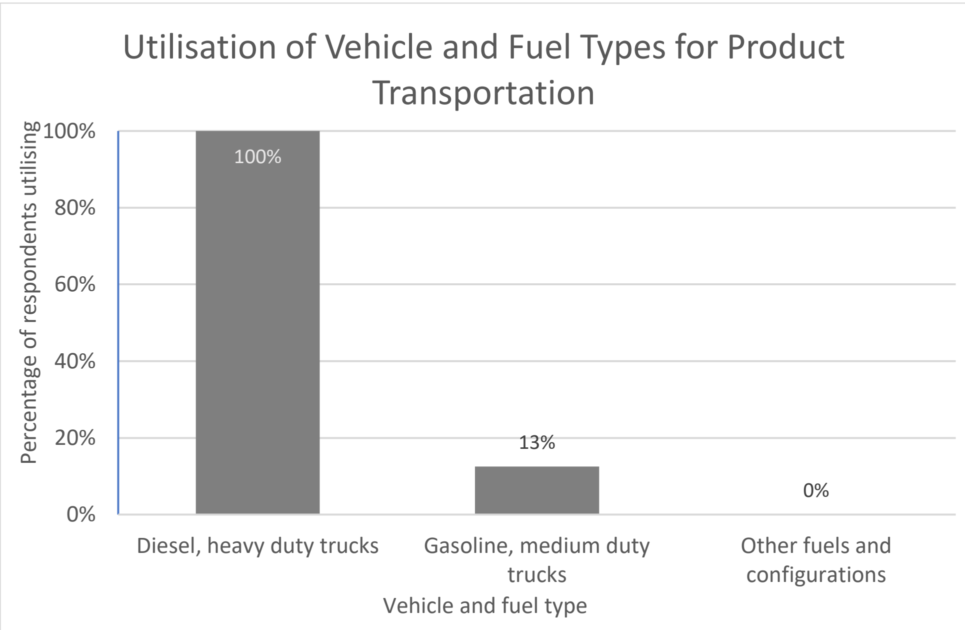


Figure 4-23. Vehicle and fuel types used by respondents.

For use phase transportation distances over 950 km (590 miles), the use phase has the highest contribution to the global warming potential of American wood pallet systems of any life cycle phase (Alanya-Rosenbaum et al., 2021). It is important to consider the GHG intensity of fuels and vehicles used in wood pallet delivery and retrieval activities.

100% of respondents reported use of diesel fuels in heavy-duty trucks (e.g. tractor trailers), while 13% of respondents also reported use of gasoline fuels and medium duty trucks. No respondent reported use of other fuels, such as biofuel or electricity, nor vehicle types, including non-road vehicles such as trains and barges. It is predicted that alternative fuels and road vehicle configurations will not reach significant levels of use by year 2050 without the market influences of additional climate-oriented policy interventions (Kluschke et al., 2019).

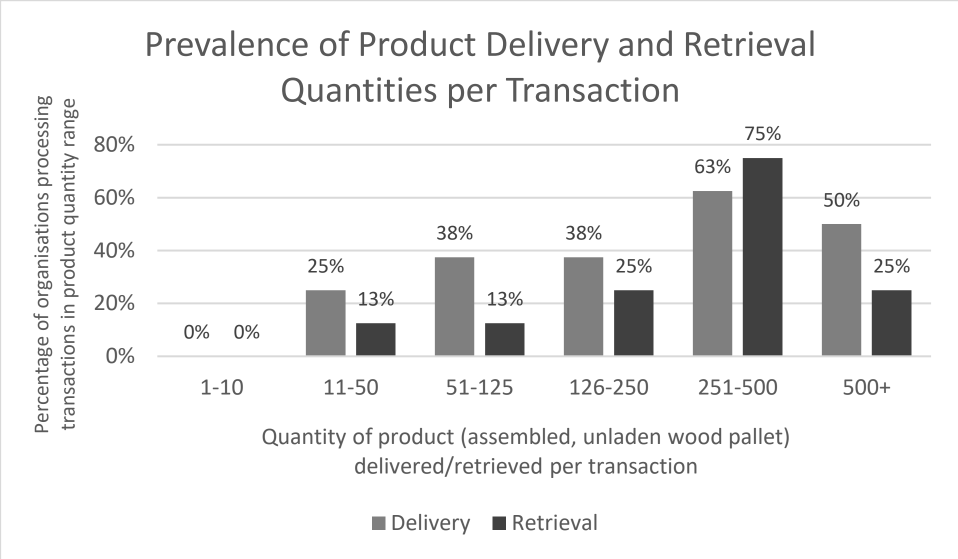


Figure 4-24. Prevalence of product quantities delivered and retrieved by respondents.

Respondents most commonly reported delivering (63%) and retrieving (75%) quantities of 251-500 pallets per transaction, a quantity roughly equivalent to one full heavy-duty truckload. Retrieval of quantities between 11 and 250 pallets was less commonly practiced (13-25%) than delivery of the same quantities (25-38%). 50% of respondents reported delivering and 25% reported receiving quantities of greater than 500 pallets in a single transaction. These results indicate that the delivery and retrieval of quantities as low as 11-50 pallets per transaction can be practically viable, demonstrating the possibility of organised pallet reuse for small-scale (LTL) pallet consumers.

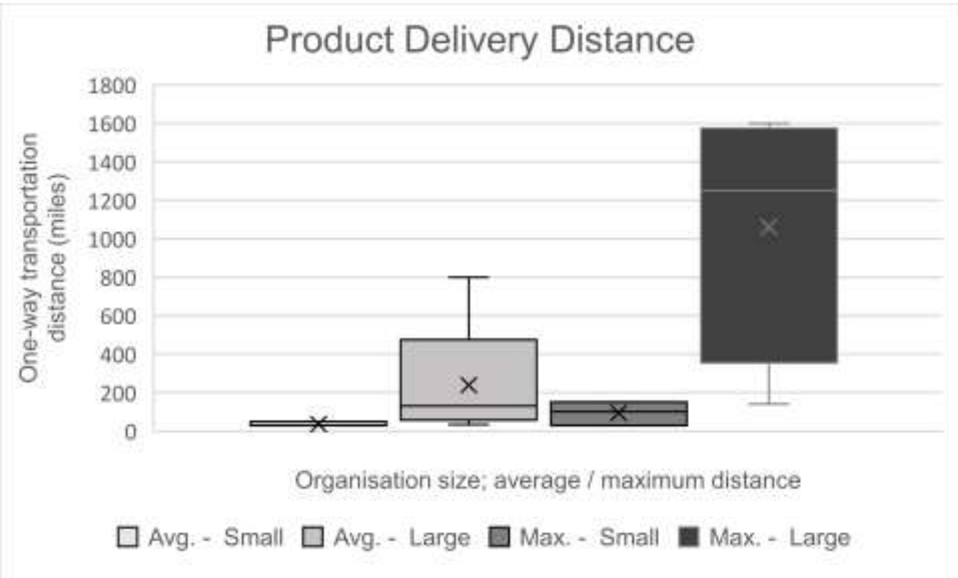


Figure 4-25. Average and maximum product delivery distances by organisation size among respondents.

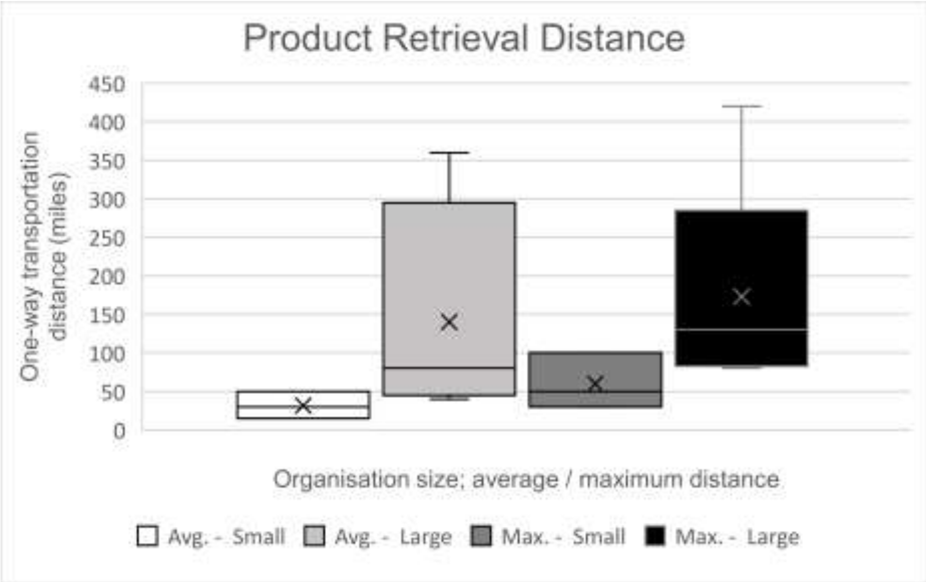


Figure 4-26. Average and maximum product retrieval distances by organisation size among respondents.

Table 4-5. Summary of mean and maximum reported delivery and retrieval distances by organisation size.

Legend: Mean of set [Range], miles	**Organisation size**			
	Small (1-50 employees)		**Large (>50 employees)**	
	Reported mean	Reported max.	Reported mean	Reported max.
Delivery	37 [30-50]	93 [30-150]	239 [35-800]	1060 [140-1600]
Retrieval	32 [15-50]	60 [30-100]	140 [45-360]	173 [80-420]

The global warming potential of American wood pallet systems has been shown to be highly sensitive to use phase transportation distance (Alanya-Rosenbaum et al., 2021). It is important to consider the distances over which wood pallets are transported while unladen with goods.

Mean reported delivery distances were on average much greater than mean reported retrieval (mean response: 163 vs. 94 miles), as well as maximum reported distances for delivery and retrieval (mean response: 646 vs. 131 miles), indicating that wood pallet delivery is practically viable over a much larger geographic service area than is retrieval. Small organisations reported much lower delivery and retrieval distances than did large organisations, as seen in Table 4-5 above.

These findings indicate that a decentralisation of delivery and retrieval activities across a great number of small organisations, each serving a relatively small geographic area, as opposed to a centralised organisation of these activities amongst fewer service points serving larger areas at greater scale, could be effective at decreasing use phase transportation distances, and in turn, reduce the GHG emissions of American wood pallet systems.

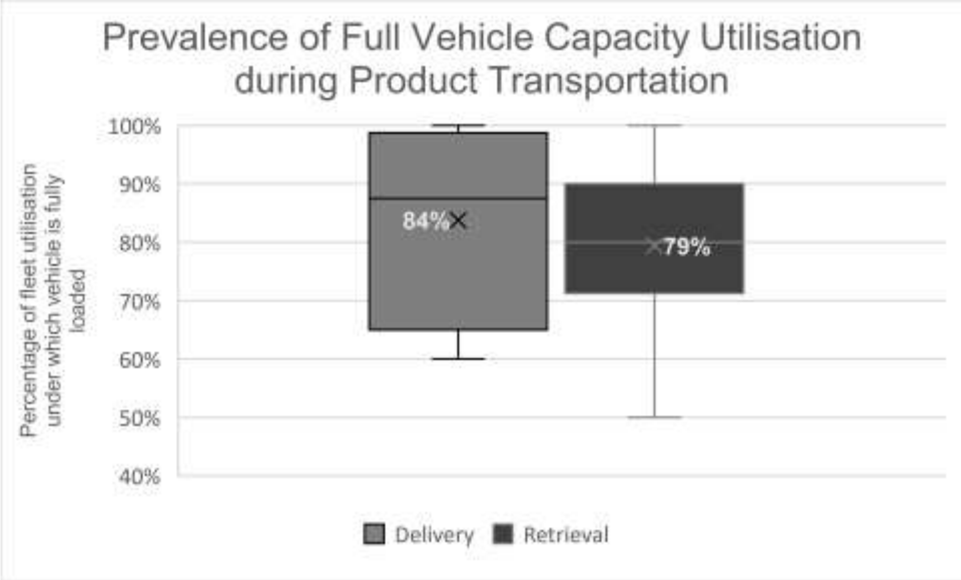


Figure 4-27. Rates of full vehicle capacity utilsation among delivery and retrieval phase participants.

Figure 4-28. Prevalence of "empty mileage" among delivery and retrieval phase participants.

Increasing the utilisation of vehicle capacity during delivery and retrieval reduces the GHG intensity of delivery and retrieval activities, as emissions from fuel consumption are distributed amongst a greater number of products in transit. Delivery activities show a slightly higher prevalence of full capacity utilisation (84% for delivery vs. 79% for retrieval), as seen in Figure 4-27. There is a high variance in the prevalence of "empty mileage," vehicle transport mileage under which no product is moved, among respondents (range: 0-50% of total fleet mileage, mean: 20%). One respondent could not determine a prevalence of empty mileage.

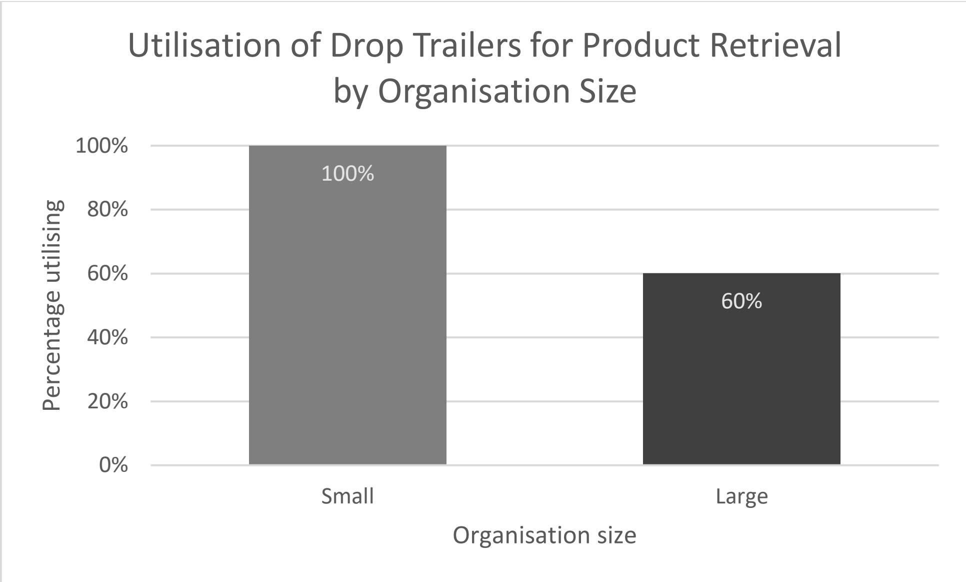


Figure 4-29. Prevalence of drop trailer utilisation by organisation size among retrieval phase participants.

One strategy commonly used by wood pallet recyclers during product retrieval is the use of "drop trailers," which are empty trailers left at a customer location and gradually filled with empty pallets as the customer generates them. The pallet recycler retrieves the trailer once it is full. This practice can reduce the demand for retrievals of LTL quantities of pallets at customer locations, leading to higher vehicle capacity utilisation. 100% of respondents in small organisations and 60% of respondents in large organisations reported the use of drop trailers for pallet retrieval.

Other strategies reported by respondents to optimise delivery and retrieval practices include the tracking of vehicles using GPS and enterprise resource planning systems, consolidation of several LTL delivery orders into a single vehicle, and staging delivery and retrieval activities sequentially without intermediate return trips to the service point (a practice colloquially known as "milk run deliveries").

The fraction of wood pallets in the U.S. economy which are unrecovered after each use cycle is unknown [A1], but not all wood pallets are recovered for reuse, repair, or EOL management. Reasons given by respondents for the refusal to retrieve pallets include insufficient quantity, poor condition, non-standard dimensions, unsafe loading conditions, and presence of contaminants in the forms of chemicals and metal shavings. It is currently unknown what happens to these lost pallets at EOL, but it is likely that a majority are allowed to decompose, incinerated without energy recovery, or repurposed.

4.3.5 Repair

Repair of damaged wood pallet components is practised to extend the useful life of wood pallets and maintain their resource value. Wood pallet repair and remanufacturing activities in the United States conserve roughly 90% of dry wood mass per repair cycle, with the remainder being ground for recycling or incinerated (Alanya-Rosenbaum et al., 2022). Seven out of eight respondents (three small and four large) reported participation in the repair phase and provided the following information about their wood pallet repair practices:

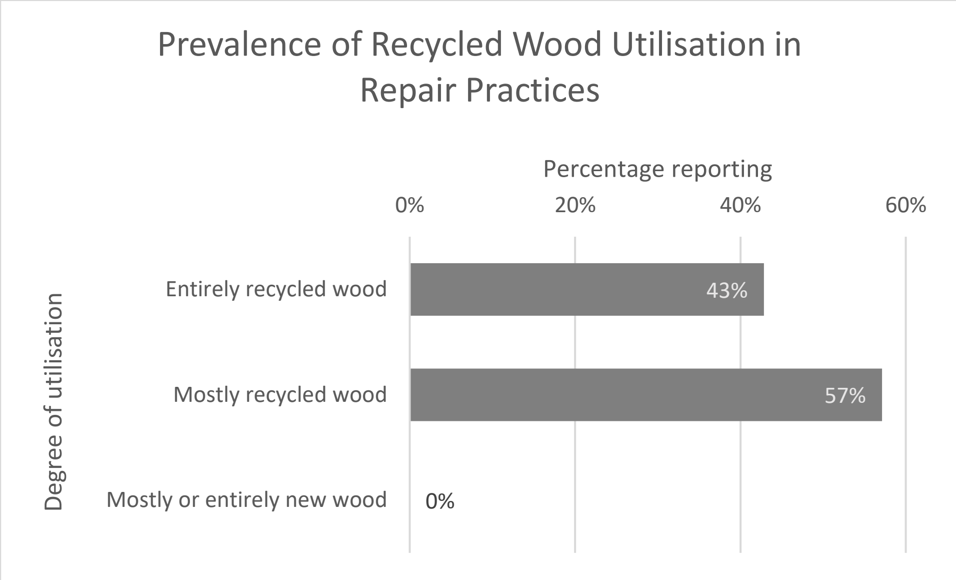


Figure 4-30. Degree of recycled wood utilisation in repair activities among repair phase participants.

All repair phase participants reported a high degree of utilisation of recycled wood, commonly obtained from dismantled cores reaching EOL, in repair activities. All firms used more recycled wood than new wood in repair activities. A large fraction (43%) reported using entirely recycled wood in repair, suggesting that new wood inputs are not strictly necessary for viable wood pallet repair operations.

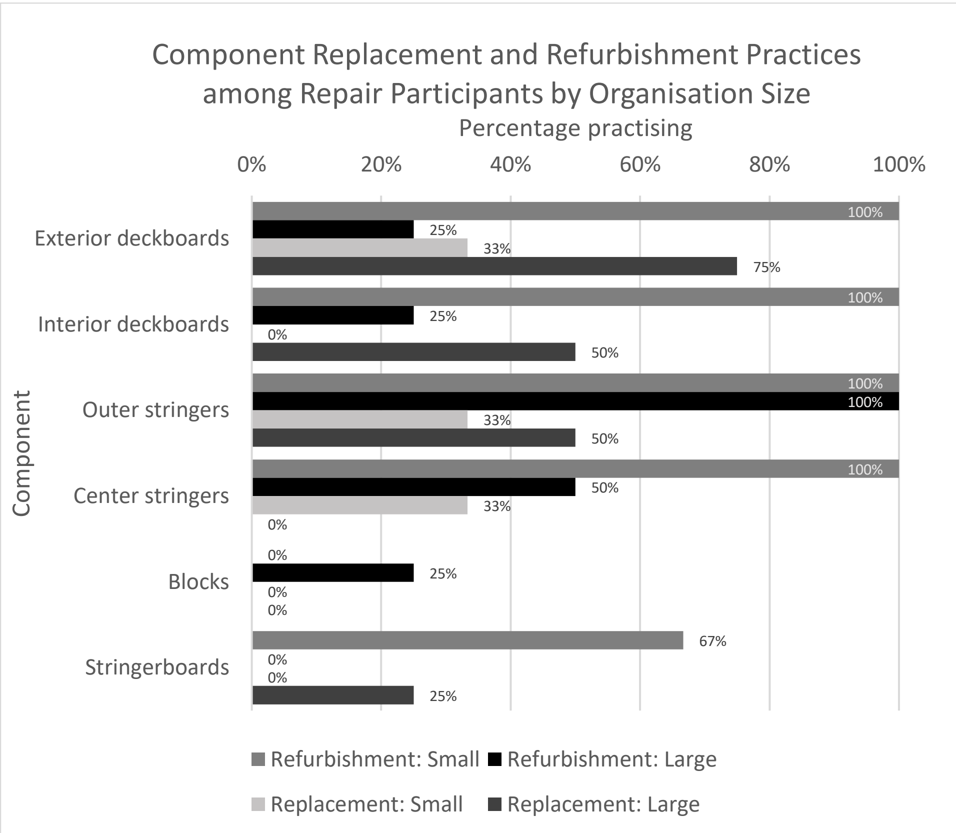


Figure 4-31. Prevalence of selected component refurbishment and replacement practices by organisation size among repair phase participants.

Repair practices can be classified into refurbishment; which involves the fastening of additional material such as lumber, metal plates, or staples to damaged wood components to maintain their integrity; and replacement of damaged wood components with full intact wood components of equivalent dimensions.

Participants reported a higher prevalence of refurbishment practices than replacement practices. Stringers and deckboards were repaired more commonly than blocks and stringerboards, but at least one participant reported refurbishment or replacement of each component type. All participants reported using a grading scheme to classify repaired pallets by quality for resale, but the grading systems were not consistent across participants.

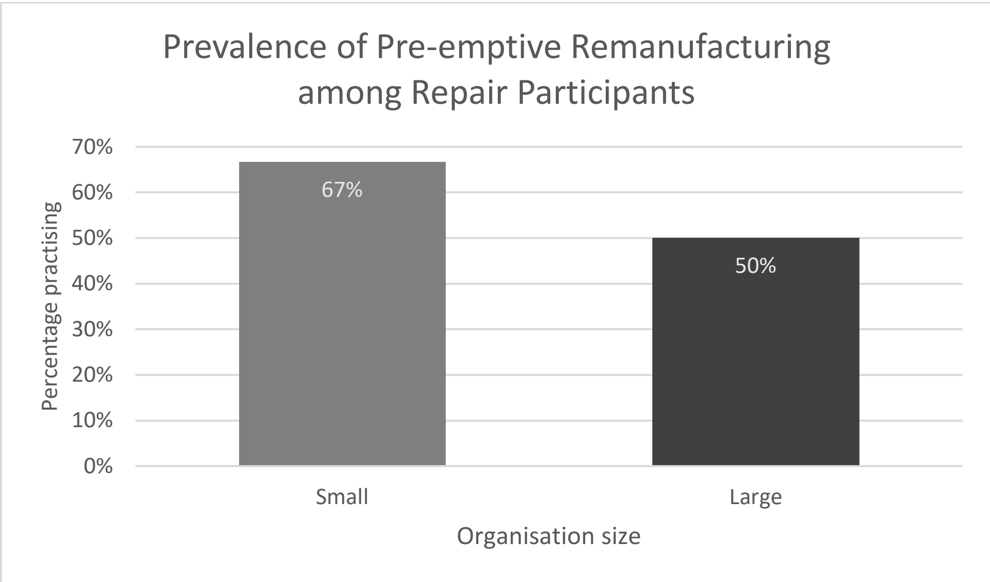


Figure 4-32. Prevalence of pre-emptive remanufacturing practices by organisation size among repair phase participants.

Pre-emptive remanufacturing refers to the practice of repairing undamaged components with a low remaining service life at the same time as damaged components in order to reduce the incidence of component damage and frequency of repairs. When optimised against opportunity loss from prematurely replaced components, pre-emptive remanufacturing reduces the GHG emissions of wood pallet repair activities by 11-41% (Tornese et al., 2016). 67% of small organisations and 50% of large organisations participating in repair reported practising pre-emptive remanufacturing.

4.3.6 Closed loop systems

Three respondents (one small and two large) reported participating in closed loop (returnable) wood pallet systems and provided the following information about their best practises:

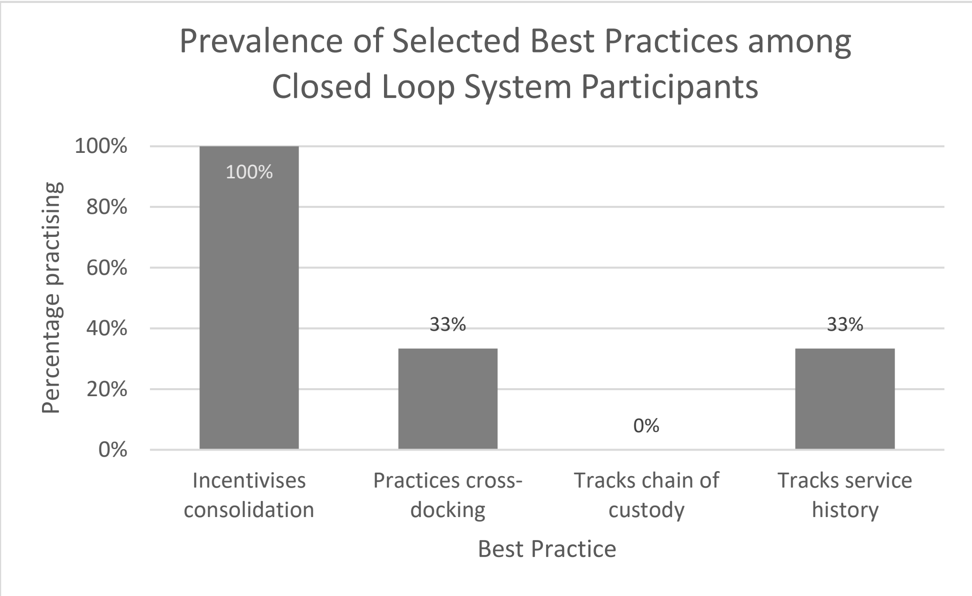


Figure 4-33. Prevalence of selected best practices among closed loop system participants.

Consolidation of empty pallets into FTL quantities within pallet users' supply chains before pooler retrieval has been shown to reduce total system emissions in a simulated Italian retail supply chain by up to 60% compared to a system with only endpoint pooler retrievals (Accorsi et al., 2019). All survey participants report a high degree of consolidation in their closed loop supply chains, in one case incentivising the practice by refusing to retrieve LTL quantities of empty pallets from their customers.

Cross-docking, the practice of inspecting returnable pallets at the collection point and routing undamaged pallets directly to the next user, has been shown to reduce the emissions of returnable wood block pallet systems by 17-73% (Tornese et al., 2016). Only one survey respondent reported this practice, wherein customers perform inspection and sorting of damaged pallets on the recycler's behalf before retrieval.

Detailed information about the locations and service histories of returnable containers has great potential to improve the efficiency of logistics, minimise the incidence of lost and damaged containers, and influence the behaviour of packaging users (Gnimpieba et al., 2015; Kroon & Vrijens, 1995; Wu et al., 2021). These factors are critical for minimisation of the GHG emissions of returnable container systems (Bottani & Casella, 2018). Despite this, the capabilities of surveyed participants to collect this information are limited: No participant can track the chain of custody (or location) of individual pallets, and only one participant maintains service histories of individual pallets within their closed loop systems. This participant reported that tracking service history helped them reduce the incidence of lost and damaged pallets within their system.

4.3.7 End-of-life management

Seven out of eight respondents (three small and four large) reported participation in the end-of-life management phase and provided the following information about their management of wood pallets at EOL:

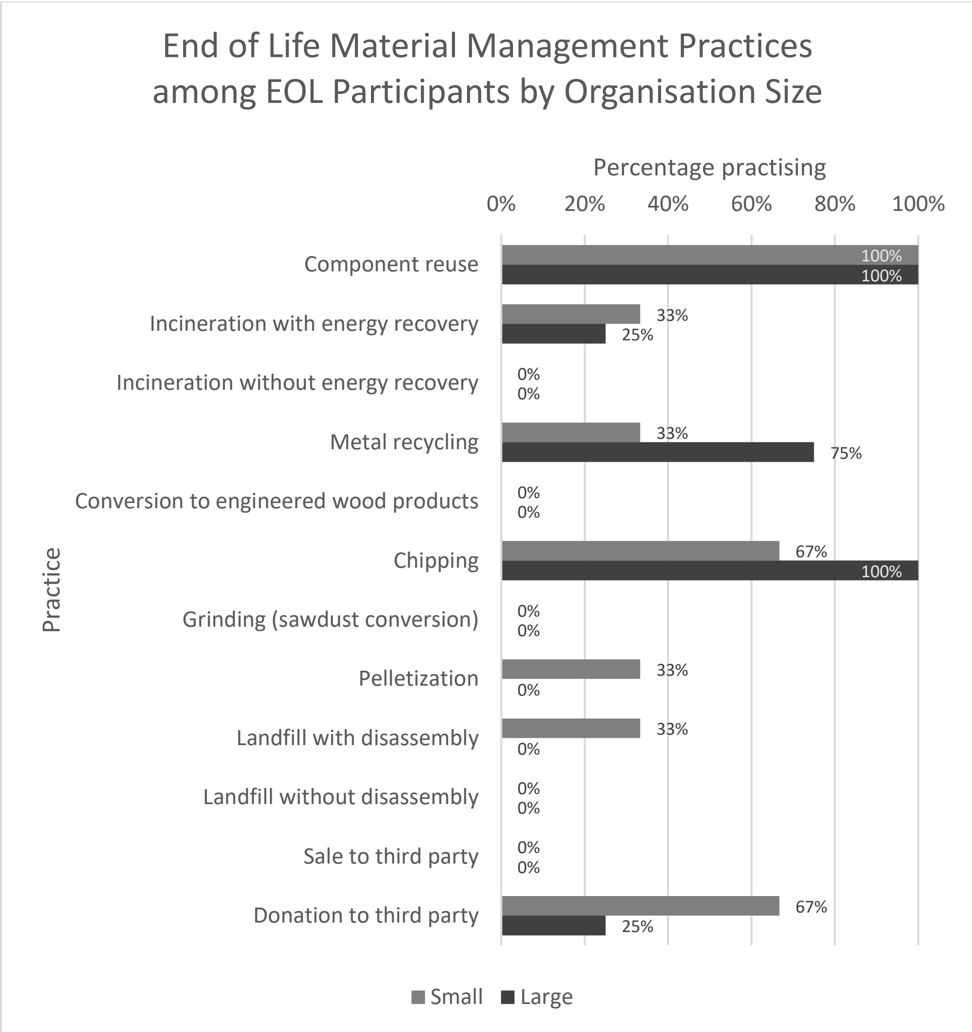


Figure 4-34. Prevalence of selected EOL material management practices by organisation size among EOL phase participants.

The EOL practice which retains the greatest resource value of wood waste, direct reuse of components in repair activities, was also the most widely practised: 100% of participants reported component reuse. Incineration with energy recovery, the EOL practice with the greatest potential for global warming mitigation (Alanya-Rosenbaum et al., 2021; Carrano et al., 2015), was practised by relatively few participants (33% small, 25% large). No participant reported conversion of wood waste into engineered wood products despite its relatively high value compared to other wood waste destinations (America, 2002).

Larger organisations show a higher prevalence of chipping and metal recycling (100% and 75%) than do small organisations (67% and 33%). Small organisations show a higher prevalence of landfilling (33% vs. 0%) and donation to third parties (67% vs. 25%), which are both undesirable EOL practices in regard to maintaining resource value. Participants reported that contamination from oil, chemicals, metal shavings, and mold can cause wood pallets to reach EOL prematurely in their operations.

4.4 Case studies

Interviews and document analysis resulted in four case studies, each serving as a model for the steps a unique actor can take to improve the circularity of the American wood packaging industry. Section 4.4.1 examines the practices of a major pallet pooler, Section 4.4.2 looks to international packaging waste policy as a possible inspiration for domestic policy interventions, Section 4.4.3 illustrates the success of decentralised pallet reuse schemes in Europe and examines the reasons similar schemes have failed in North America, and Section 4.4.4 investigates mass timber construction as a destination for wood material diverted by a circular transformation.

4.4.1 Circular practices of major pallet poolers

The latest sustainability report from Brambles Limited (Freijo, 2022), who operate the world's largest centralised pallet pool, describes the following sustainability targets for 2025:

1. **Forest positive:** Enable sustainable growth of two trees for every tree consumed through afforestation initiatives, maintain 100% procurement of SFC certified wood, and grow the fraction of chain-of-custody certified wood from 72%.
2. **Climate positive:** 100% renewable electricity in operations by 2025, carbon neutral operations by 2025, and net-zero GHG emissions by 2040.
3. **Waste positive:** Zero waste to landfill at all locations including subcontracted service centres, with a current diversion rate of 58%.

It is unclear whether these targets will be achieved, but they can serve as a model for the ambition of smaller organisations in the wood packaging industry without the resources to develop their own detailed sustainability strategies.

Additionally, the best practices for resource efficient returnable wood pallet systems identified in Section 2.1 are practised by one centralised pooler to varying degrees [I4]:

1. **Cross-docking:** The pooler's largest retail customer practises inspection and sorting in their distribution centres, but this represents a minority of their business. Customers do not typically hold inventories of empty pallets large enough to generate FTL quantities of undamaged pallets for direct reuse, owing partially to the high damage rates these products experience.

2. **Pre-emptive remanufacturing:** None is practised. Damaged pallets are repaired to the least extent possible before re-issue.

3. **Consolidation:** It is unclear to what extent consolidation is practised in reverse logistics. Forward logistics is highly optimised, as over 99% of the pooler's business is FTL.

4. **Modifying user behaviour:** The pooler administrates an outreach programme which helps their customers structure their logistics activities to minimise packaging waste, including waste generated from pallet damages during handling.

4.4.2 Policy for wood packaging reuse and recycling

Domestic adoption of policy governing packaging waste has been accelerating, particularly in the form of extended producer responsibility (EPR) programmes; 33 EPR bills covering packaging waste have been introduced in U.S. state legislatures in the year 2022 alone (Cassel et al., 2023). A definition of EPR by its inventor is provided here:

> "[EPR] is a policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially to the take-back, recycling and final disposal of the product. [EPR] is implemented through administrative, economic and informative policy instruments." (Lindhqvist, 2000)

Four states currently have laws introducing EPR for packaging: California, Colorado, Maine, and Oregon. Each state has a different implementation and there is a lack of national harmonisation of state packaging EPR programmes, which may cause difficulty for packaging producers as more states adopt programmes of their own (Cassel et al., 2023). The applicability of each of these four enacted state programmes to the wood packaging industry is investigated below:

1. California Senate Bill 54 (CA SB-54, 2022):
   A producer responsibility organisation (PRO) is established and recycling targets are set for plastic packaging materials only. Wood packaging is not covered by this act.

2. Colorado House Bill 22-1355 (CO HB 22-1355, 2022):
   The bill excludes "packaging material used exclusively in industrial or manufacturing processes," "packaging materials used solely in business-to-business transactions where a covered material is not intended to be distributed to the end consumer," and "packaging materials used solely in transportation or distribution to nonconsumers." As wood packaging is predominantly used in B2B contexts and rarely distributed to the end consumers of goods, the vast majority of wood packaging would not be covered by this EPR programme.

3. Maine Statute 2146 (Stewardship Program for Packaging, 2022):
   Packaging producers generating less than $2 million in annual revenue are exempted from participation in the stewardship programme. Collection and recycling activities are funded and administrated through municipal waste authorities, who do not typically interact with significant volumes of wood packaging (Shiner et al., 2021). Provisions for target-setting are made only for glass, metal, paper, and plastic materials. Given these facts, it is unclear whether wood packaging producers generating over $5 million in annual revenue would be affected by Maine Statute 2146.

4. Oregon Senate Bill 582 (OR SB-582, 2021):
   A PRO is established for packaging, food serviceware, and paper products. However, pallets and specialty packaging used exclusively in industrial operations (e.g. spools and film roll cores) are exempted products. Therefore, SB-582 does not apply to wood packaging producers.

Internationally, regulatory measures such as target-setting for collection, recycling, and the inclusion of recycled material in new products are commonplace. Two examples are provided below where there is relevance to the wood packaging industry:

1. E.U. Directive on Packaging and Packaging Waste ("Directive 94/62/EC," 1995): Recycling is defined as strategies R3-R8 from the R-framework seen in Figure 1-3. Incineration is a notable exclusion, a change to the definition of recycling introduced to the Directive in 2018 (Björk, 2021) E.U. member states are required to recycle 25% of wood packaging waste by weight by the end of calendar year 2025, and 30% by the end of year 2030. Applying these targets to the context of the U.S. wood pallet industry, we see that in year 2016, 95.4% of recovered cores were recycled (Gerber et al., 2020). This suggests that E.U. targets could be met by the American wood packaging industry with collection rates as low as 30%. Though goal attainment would be impossible to evaluate in this case as actual collection rates are unknown [A1], it is likely that much more ambitious recycling targets would be necessary to make target-setting an effective tool to advance circular material management in the American wood packaging industry.

2. Australia National Packaging Targets (*Australia National Waste Policy Action Plan*, 2019) The Australian Packaging Covenant Organisation (APCO), Australia's PRO for packaging, mandates that all packaging used in Australia is reusable, recyclable, or compostable by 2025. APCO also mandates a 50% average recycled content across all packaging by 2025. Wood packaging meets these criteria by its nature, but is excluded from the totals due to a lack of data. A high degree of decentralisation of the wood packaging industry (Roy et al., 2016) very likely inhibits effective target-setting for wood packaging policy across geographic contexts.

No policy reviewed here, domestic or international, has the necessary provisions to promote the resource efficient life cycle management of wood packaging products. It is unlikely target-setting would even be effective under current conditions due to the highly decentralised nature of the American wood packaging industry and a resulting lack of information on the flow of its products and materials. Due to the nature of wood packaging flows differing from that of other types of packaging waste streams (Wood packaging cores are managed by the producers directly throughout their life cycles, while other types of packaging typically become the responsibility of municipal waste services after use), effective EPR programmes for wood packaging must be organised differently than conventional EPR programmes targeting packaging waste. Section 6.1.1 describes these organisational differences in detail.

4.4.3 Decentralised pallet reuse schemes

EPAL is a non-profit organisation which maintains a pool of over 650 million standardised returnable wood pallets in Europe (*About EPAL*, n.d.). Their responsibilities include producing design standards for returnable pallets, licensing and inspecting third party service providers to produce and maintain these designs, and operating an exchange system under which vouchers are used to facilitate the direct exchange of undamaged pallets between users. EPAL do not handle any physical product themselves, instead relying on a network of over 1,550 service providers to manufacture, distribute, and manage the life cycle of EPAL platforms. This structure allows for existing, competing firms within the wood packaging industry to jointly operate a single, unified system at scale.

This decentralised pooling approach carries several distinct benefits over the centralised returnable pallet systems seen in the U.S. such as CHEP [I2]. First, a vast network of independent manufacturers and recyclers can be leveraged to reduce delivery and retrieval distances. This is due to the fact that for any given wood packaging user, it is likely that an independent service centre is located closer to them than a particular pooler's nearest depot. Lower transportation distances drastically reduce the costs and GHG emissions of returnable pallet systems (Accorsi et al., 2019). These shorter transportation distances also increase the viability of LTL deliveries, allowing a larger portion of the wood packaging market to be served by a returnable system. Second, centralised pooling operations like CHEP have inventory control limitations that restrict the range of designs that can be offered [I2]. The vast majority of American returnable pallet market is comprised of the 48"x40" pallet [I1,I2], a size which comprises only 35% of the total American pallet market including one-way products (Gerber et al., 2020). This is a limitation which leaves the majority of the American wood pallet market without a viable returnable option, but systems like EPAL offer a wider range of designs which are compatible with a greater number of users' operations. An offering of the five most common pallet form factors in the U.S. would provide an option to 52% of the American wood pallet market as of 2016 (Gerber et al., 2020) – a figure that is likely even higher today owing to increasing consolidation and standardisation within the industry.

Finally, and most notably, decentralised pooling has the potential to advance the adoption of returnables without significant alterations to the structures and business models of the industry as it exists today; only the product and some minor practices would have to change. Neither existing poolers nor independent recyclers are threatened by the adoption of returnable systems that they participate in directly; in fact, the optimisations introduced by such a system may even lead to greater profit margins for these groups. As a result, these actors are much less likely to resist the adoption of a new returnable system than under an approach where a new centralised pool must gain market share away from established industry players.

Despite the advantages of decentralised pooling systems, attempts to establish an equivalent to the EPAL system in North America have failed. The Canadian Pallet Council (CPC), a decentralised pool serving the grocery and consumer goods sectors in Canada, dissolved in 2015 after 38 years of operation (*CPC Members Vote To Dissolve Canadian Pallet Pool - Reusable Packaging News*, 2015). Reasons cited for its dissolution include declining demand for CPC pallets among Canadian wood packaging users due to the poor quality and higher weight of its stringer pallet design compared to the lighter, more durable block designs of centralised poolers such as CHEP, who entered the North American market in the 1990s (*Canadian Pallet Council (CPC) Background And Demise*, 2019).

In the United States, efforts to establish 9BLOC, a nationwide decentralised block pallet pool, a decade ago were stalled because of a failure to secure initial funding. In 2012, the estimated minimum cost to establish the 9BLOC pool at a sufficient scale was $160 million [I2], but private investors feared that a lack of direct control over the products in circulation would lead to high loss rates and low financial returns [I2]. In the case of EPAL, initial funding to establish the pool was provided by the German railway authority, which circumvented the barrier of securing private investment [I2]. Another factor that led to the failure of 9BLOC to launch was a high administrative barrier to participation; 9BLOC pallets would have initially comprised a small fraction of participating manufacturers' and recyclers' business, so the relative administrative burden of participation in the 9BLOC system was a deterrent to support of the system's launch within the American wood packaging industry [I2].

The success of EPAL and the failure of CPC and 9BLOC suggest that the maintenance of durable, lightweight designs, a high degree of market penetration, and availability of initial public financing are key success factors for a decentralised pallet pool.

4.4.4 Mass timber construction: A promising destination for diverted wood

Mass timber construction (MTC) refers to the use of engineered wood products in large structures such as apartment and office buildings. Whereas unprocessed dimension lumber beams lack the structural properties necessary for use in large constructions, MTC is a recent development allowing biological materials to replace technical materials such as concrete and steel in these applications for the first time.

Decarbonisation of the construction sector, which accounted for 39% of global energy- and process-related CO_2 emissions in 2018, is critical to fulfilment of the GHG emissions targets of the Paris Agreement and United Nations Sustainable Development Goals (*Global Status Report for Buildings and Construction*, 2019). Substitution of emissions-intensive materials including steel and concrete with MTC has significant potential to contribute to the construction sector's decarbonisation; one comparative LCA shows a 22-50% reduction in embodied carbon emissions of MTC structures vs. conventional structures across a wide range of building types and geographic regions in an American context (Puettmann et al., 2021). MTC also carries operational advantages over conventional large constructions, such as reduced on-site labor demands and faster turnarounds, which can offset the marginally higher costs of MTC materials compared to conventional materials (Abed et al., 2022).

Regulatory barriers once prevented the adoption of MTC in the United States [O3,A3], but the most recent national building codes allow for MTC of residential and commercial structures up to 18 stories in height (Council, 2020). Mass timber components can be readily reused across many deconstruction and construction cycles and have a theoretically indefinite lifespan if kept dry, meaning growth of MTC in the building stock over time would have a "carbon battery" effect [I3], owing to the fact that wood sequesters atmospheric carbon. This phenomenon further contributes to decarbonisation of the construction sector. Both high- and low-grade timber typically used by the American wood packaging industry can be used in MTC applications [I3,O3,A3], but mass production of MTC is currently limited to structural grade lumber and a limited range of species in the U.S. [I3,A3].

Increased adoption of MTC is projected to increase global cumulative softwood lumber consumption by between 8 and 58 million m^3 (3 and 24 bbf) between years 2015 and 2060 (Nepal et al., 2021). By contrast, the American wood pallet industry consumed an estimated 11.9 million m^3 (5.03 bbf) of softwood lumber in year 2016 alone (Gerber et al., 2020). These figures suggest that reduction of the timber consumption of wood packaging systems in the U.S. via circular transformation is sufficient to satisfy the global increase in demand for softwood lumber induced by MTC adoption without increasing forest removals.

4.5 Barriers and drivers of circular transformation

This section describes internal and external barriers and drivers to the optimisation and widespread adoption of returnable wood packaging systems identified from the literature review and methods used in the thesis. Table 4-6 summarises the information presented in this section.

Table 4-6. Summary of barriers and drivers of circular transformation of the American wood packaging industry.

Barriers		**Drivers**	
Internal	**External**	**Internal**	**External**
Inconsistent product quality High cost of independent recycler participation in pooling activities EPD for wooden pallets Monopolisation and centralisation of pooling activities Perception of high "status quo" sustainability High, rising user costs Low degree of market standardisation Lack of product data visibility Lack of LTL service providers Lack of eco-design practices Large orgs: High transportation distances Small orgs: Low degree of process automation, lack of EOL material management capacity, lack of coherent sustainability strategy	Rising freight costs Lack of finance for decentralised pooling Lack of reporting standards for collection Fragmentation of waste management strategy & policy Lack of competing demand for low-grade timber raw material	Rise of forest certification Rise of automation Consolidation of industry	Raw material price volatility Deforestation in Southeastern U.S. Carbon pricing in certain jurisdictions Packaging EPR legislation in certain jurisdictions Decreasing costs of product tracking systems

4.5.1 Barriers

Internal

A former executive for a major pallet pooler cites inconsistent product quality and rapidly rising costs as the most significant barriers to the adoption of pooled pallet systems [I4]. The returnable wood pallet market in the U.S. is also highly centralised and undergoing consolidation [A2], leading to a lack of competitive influence. This has resulted in unfavorable terms for independent recyclers' participation in reverse logistics and repair activities (Brindley, 2016), contributing to a lack of capacity to carry out these activities at a local geographic scale. Perceptions of sustainability within the wood pallet industry also contribute to a lack of progress. Major poolers are frequently regarded by environmental certification schemes as the front runners in packaging sustainability (Freijo, 2022) for their BAU performance, while opportunities to improve on the sustainability of their practices are not commonly brought to the public's attention. An environmental product declaration for wood pallets has been issued to certify the wood pallet as a more sustainable alternative to load carriers made from alternative materials such as plastic and paper (*Environmental Product Declaration: Wooden Pallets*, 2020), but the study supporting this declaration makes no distinction between one-way and returnable pallets in its methodology (Alanya-Rosenbaum et al., 2021). As a result, the declaration likely entrenches existing practices rather than advocating for circular transformation.

Several operational barriers within the industry also exist: First, there is a low degree of product standardisation compared to the European market, where returnable pallet systems are somewhat more prevalent (Gerber et al., 2020). This makes inventory control more difficult [I1,I2] and limits the range of customers that can be served by a centralised pooling model. Second, as seen in Figure 4-15, prevalence of eco-design practices is low despite the capacity of commonly used software to support these practices. Third, as major poolers deal almost exclusively in FTL orders [I4], wood packaging users who require LTL service are left without a viable returnable option, despite the economic viability of LTL pooling activities (Bottani & Casella, 2018). Finally, as seen in Figure 4-33, there is a lack of information on chain of custody and service histories of products within returnable wood pallet systems necessary to support resource efficient life cycle management of these products.

Large organisations within the American wood packaging industry are hindered by greater delivery and retrieval distances due to their more geographically centralised operations, as seen in Table 4-5. Small organisations face infrastructural barriers related to a relative lack of process automation and EOL material management capacity relative to large organisations. These disparities suggest an opportunity for small and large organisations to use their relative advantages collaboratively to operate wood packaging systems in more resource efficient ways.

External

A lack of public information about the practices of organisations within the American wood packaging industry, particularly pallet poolers [A1], makes quantifying the benefits of returnable wood packaging systems and measuring goal-attainment related to waste management regulations difficult. As seen in Section 4.4.2, American policy interventions aiming to promote the circular management of packaging and packaging waste are fragmented and largely inapplicable to wood packaging products and producers. A lack of demand for the low-grade timber commonly utilised by the American wood packaging industry is a barrier to efforts to reduce consumption of this material within the industry [A1], though MTC is a promising alternative destination for this material, as seen in Section 4.4.4. As seen in Section 4.4.3, unavailability of private finance is a barrier to the establishment of a decentralised pooling scheme in the U.S. Fnally, rising freight costs make pooling operations more costly relative to less transport-intensive one-way systems; between May 2020 and May 2022, road freight costs in the U.S. increased by approximately 43% (U.S. Bureau of Labor Statistics, 2022c).

4.5.2 Drivers

Internal

The American wood packaging industry has seen precipitous increases in the prevalence of forest certification and process automation in recent years (Park et al., 2016), two trends which drive the sustainability of the industry forward. Consolidation of industry firms is another trend [A2] which may also increase the efficiency of supply chain activities through increased inter-facility collaboration if the geographic distribution of these facilities is not also consolidated.

External

Environmental pressures are external drivers of circular transformation: Deforestation in the U.S. is a considerable pressure (*Forests and Biodiversity*, 2015) which a transformation may relieve, though the degree to which a transformation would reduce deforestation is currently unknown. Carbon pricing schemes implemented in certain jurisdictions have been cited by the American wood packaging industry as another potential driver (Meeks, 2022). If packaging EPR legislation is amended to include wood packaging, it could also support a circular transformation.

The volatility of wood raw material prices is a notable economic driver of circular transformation as it increases new manufacturing costs; between May 2020 and May 2022, commodity prices for lumber fluctuated by over 110% (U.S. Bureau of Labor Statistics, 2022b). Periods of high lumber prices present windows of opportunity to establish cost-effective returnable wood packaging systems, as these costs are shown to affect one-way systems to a greater degree than returnable systems. Falling costs of product tracking systems such as RFID (M. Gnoni & Rollo, 2010) may also support cost and impact reductions within returnable wood packaging systems.

5 Discussion

5.1 Examination of results under relevant frameworks

This section examines the results presented in Chapter 4 under the frameworks introduced in Section 2.2.1 and 2.2.3. Section 5.1.1 considers the results of the expanded relative cost model and risk analysis under ecological modernisation theory to predict the modes of government intervention necessary to support a circular transformation of the American wood packaging industry. Section 5.1.2 examines findings from the survey and case studies using the seven operational principles of a circular economy to discuss the current circularity of the industry and what can be done by relevant actors to advance it.

5.1.1 Ecological modernisation theory

Under the framework of ecological modernisation theory, a weak ecological modernisation approach is sufficient if market incentives can drive the change necessary to achieve an ecological objective via the actions of industry. Otherwise, a strong approach involving the intervention of society beyond market incentives (i.e. policy intervention) is necessary to achieve the objective. Having introduced the ecological imperative of a circular transformation of the American wood packaging industry in Chapter 1 and quantified its potential in Chapter 4, the ecological objective in this case is the optimisation and widespread adoption of returnable wood pallet systems.

The results from the expanded relative cost model (Section 4.1) suggest that it is possible to achieve this objective via market competition subject to the assumptions inherent to the model and scenarios used. However, the risk analysis (Section 4.2) demonstrates that the achievement of the ecological objective under weak EM is highly situational, being particularly sensitive to new pallet manufacturing costs and in-use loss and damage rates.

These findings support the notion that regulatory instruments such as single-use packaging bans and recycling targets are not necessary for circular transformation; however, economic instruments that incentivise the adoption of optimised returnable systems over one-way systems may help to preserve the integrity of these systems all possible market conditions while maintaining an ecosystem for wood packaging reuse which is supported by existing private actors. This solution constitutes a "middle ground" between weak and strong EM approaches. Section 6.1 describes how American regulators can achieve this objective via taxation of one-way wood packaging production and the establishment of a producer responsibility organisation (PRO) for wood packaging.

5.1.2 Operational principles of circular economy

The operations of wood packaging producers and recyclers can be improved to align with the operational principles of circular economy described in Section 2.2.3 across all wood packaging life cycle phases. In design, it is important to inform producers about eco-design capabilities and encourage them to use eco-design practices, including standardisation and interchangeability, value durability, and utilisation of locally available raw materials. In procurement, forest certification requirements and selection of durable materials which can extend product life are important considerations. Manufacturing of one-way packaging should be discouraged, process automation and standardisation should be adopted to the greatest extent possible, and returnables should be circulated quickly to reduce the size of the in-use stock of packaging. Circular transportation practices include reducing fuel GHG intensity, minimising transportation distances, and using product tracking systems to address sources of unnecessary losses and damages. New lumber should be eliminated from repair activities, pre-emptive remanufacturing should be universally practised, and a standardised grading system for repaired packaging should be adopted industry-wide. All producers should have infrastructure to practise material cascading at EOL, including energy recovery from wood biomass where economically viable, and avoid landfilling and leakage of material to undocumented destinations. Efforts should be made to ensure producers and wood packaging users collaborate to return all cores to a service centre, no matter their condition.

A summary of these improvements across each operational principle and wood packaging life cycle phase is provided in Table 5-1 below:

Table 5-1. Suggested industry contributions to the seven operational principles of circular economy across wood packaging life cycle phases.

	Design	Procurement	Manufacturing	Transportation	Repair	EOL
1. Adjust system inputs to regeneration rates		Ensure wood raw material is sourced sustainably through forest certification.		Discourage the use of fossil fuels. Maximise fleet utilisation and minimise empty mileage.	Eliminate the use of new lumber in repair processes where possible.	
2. Adjust system outputs to absorption rates				Encourage the use of low-emission fuels.		Avoid landfilling, incineration without energy recovery, and disorganised EOL management of products.
3. Close system			Disincentivise one-way packaging via economic policy measures. Utilise all process scrap.	Provide a returnable system to LTL users. Use chain of custody tracking to identify and eliminate sources of product leakage.		
4. Reduce system size	Create designs that make use of locally available raw material.		Circulate returnables as quickly as possible to reduce size of in-use stock.	Utilise capacity of small facilities serving local markets to reduce transportation distances.		Utilise wood scrap for energy on-site where economically viable.

	Design	Procurement	Manufacturing	Transportation	Repair	EOL
5. Maintain resource value within system		Procure high grades of timber and high-quality fasteners to extend product useful life.		Ensure retrieval of every product by recycler or pooler after use.	Practice pre-emptive remanufacturing, optimised against resource value loss.	
6. Design for CE	Design products with a high degree of standardisation and value durability.		Automate and standardise manufacturing processes to the greatest degree possible.	Design reverse logistics processes and networks for minimal distance, including cross-docking and consolidation.	Standardise grading system for repaired products.	Incorporate material recycling infrastructure into all facilities.
7. Educate for CE	Inform designers about eco-design capabilities and benefits. Inform packaging users about the benefits of eco-designed products.			Inform packaging users about best practices for handling and loading which minimise in-use damages.		Inform packaging users of the importance of returning all products, including damaged and contaminated products, to a service centre.

5.2 Reflection

This section provides a reflection on the quality of research achieved during the thesis project and proposes guidance for expansions on the project work and its findings in other contexts.

5.2.1 Methodological choices

This thesis used economic and operational frameworks to investigate the potential of a circular transformation of the American wood packaging industry. The initial line of thinking was to build a strategy for centralised poolers such as CHEP to overtake the industry through market competition via increased operating efficiencies. As a result, its findings mainly concern the economic feasibility of practical, internal adaptations to existing pooling practices. Unexpectedly, the most important breakthrough during the project was not the discovery of a new competitive strategy for CHEP, but rather a conseptualisation of a circular wood packaging system with a decentralised structure, governed by a producer responsibility organisation, and sustained by policy interventions and collaboration between industry competitors.

This change of frame from an internal, competitive focus to a bureaucratic, collaborative focus has evolved the vision for solving the wood packaging industry problem. Moving forward, political feasibility is the central question; this change will ultimately reduce the size of the American wood packaging industry by value, so efforts must be taken to either frame the transformation in a way that is palatable to both poolers and independent recyclers or circumvent the industry's political influence in preventing such a transformation from succeeding. The findings of this research indicate that the circular transformation of the American wood packaging industry is a rare example of a "win-win" ecological cause: there is a clear environmental benefit *alongside* an economic benefit, at least from the perspective of wood packaging users. Therefore, continuations of this research should focus on developing strategies to garner political support for a PRO for wood packaging and economic incentives for the American wood packaging industry to participate in the PRO to the greatest degree possible. Resistance to these political interventions from the wood packaging industry and forest industry should be anticipated.

5.2.2 Legitimacy

The legitimacy of, and degree to which each of the three research objectives presented in the thesis have been answered, is addressed below:

1. Examine the theoretical case for the circular transformation of the American wood packaging industry under an ecological modernisation (EM) framework.

   Using Mollenkopf et al.'s relative cost approach to container system design to model the costs of different wood packaging systems, then aggregate the costs of system portfolios to a national scale, was a novel and effective approach to assessing the viability of returnable wood packaging systems considering the information available in the scientific literature. Delineating between weak and strong ecological modernisation on the basis of system costs was an effective means of suggesting the appropriate degree and type of public support necessary to drive a circular transformation. The expanded cost model's findings are limited by a lack of information about the structure and performance of pallet pooling operations in the U.S. and the assumption that one-way packaging is only used once. More transparency from the American wood packaging industry is necessary to address these limitations.

2. Assess the degree of circularity of the American wood packaging industry as it operates today through the lens of the seven operational principles of a circular economy.

   The questionnaire distributed to American wood pallet enterprises thoroughly investigated the practices of the American wood packaging industry across all product life cycle phases. However, a low capture rate which did not include perspectives from pooling businesses limits the legitimacy of its findings. As a result, the questionnaire has only demonstrative value, meaning it cannot be used to make precise or definitive claims about the level of circularity of the industry as it operates today. Still, the findings from the questionnaire highlighted many opportunities for operational improvements which were conceptualised through the lens of Suárez-Eiroa et al.'s operational principles for a circular economy.

3. Generate practical recommendations and strategies aimed at increasing the circularity of the American wood packaging industry.

   Results from the expanded relative cost model, risk analysis, questionnaire, interviews, and document analysis all contributed to a strategy for circular transformation centered around decentralised pooling, producer responsibility, and economic incentives, as seen in Section 6.1. This RO resulted in a clear assignment of responsibilities for packaging users, producers, recyclers, and regulators across all packaging life cycle phases. Pathways to implementation of this strategy and many specific aspects of the functioning of the proposed decentralised pooling system are yet to be investigated in detail.

These research objectives and the approaches taken to address them in the thesis have proven to be legitimate and instrumental in starting to solve the research problem. They have also generated new questions: How should a PRO for wood packaging be organised? What is the optimal combination of product designs and repair schedules that will serve the greatest number of users with the lowest costs and environmental impacts? How should a system which tracks product life cycle information be implemented? Is there a possibility to expand the scope of PRO activities to additional products and/or geographies? The thesis has not fully solved the "Wood packaging industry problem" outlined in Section 1.1, but it has effectively completed the first two steps: Making the case that this is a worthwhile problem to solve and providing a direction for decision-makers to start moving in.

5.2.3 Generalisability

The same research design used in the thesis could be applied to other geographic contexts, though availability of information used here in the expanded relative cost model will present a challenge, as most existing academic literature about wood packaging systems has been carried out in an American context.

On the other hand, this research design is not necessarily generalisable to wood packaging products other than pallets, as the life cycles of these products vary greatly. There is no widespread organisation of reuse for wood packaging products other than pallets, leaving no basis for comparison to draw from. Additionally, literature on the performance, environmental impacts, and markets for other wood packaging products is sparse. For these reasons, and for the fact that wood pallets are by far the most widely used wood packaging product, the scope of the thesis was focused on wood pallets.

6 Conclusions

The findings of the thesis suggest that a circular transformation of the American wood packaging industry is possible via the optimisation and widespread adoption of returnable wood pallet systems. This transformation can be supported via the establishment of a non-profit producer responsibility organisation for wood packaging that oversees a nationwide decentralised pool of returnable wood pallets and economic policy instruments that ensure the economic competitiveness of returnable wood pallet systems regardless of market conditions. It is maintained via the existing capacities and modes of operation of the American wood packaging industry, allowing for a rapid and low-friction transformation pathway. This change is predicted to result in substantial economic and environmental benefits, most notably the reduction of U.S. industrial roundwood consumption by up to 10%.

Section 6.1 provides a strategic guide for the implementation of policy instruments, structure and functions of a PRO for wood packaging, and response from wood packaging industry participants in support of this transformation. Section 6.2 provides suggestions for future research in support of an effective circular transformation of the American wood packaging industry.

6.1 A producer responsibility model for the American wood packaging industry

The findings of this research indicate that the establishment of a decentralised wood packaging reuse programme similar to the EPAL programme in Europe, structured as a producer responsibility organisation for wood packaging and supported by economic policy incentives, is the most effective approach to a circular transformation of the American wood packaging industry. Recommendations for each of three key actors (Producer responsibility organisation, producers, and regulators) in the subsections below. Table 6-1 summarises these responsibilities according to the life cycle phases of wood packaging.

Table 6-1. Organisation of responsibilities within a circular wood packaging system organised by actor and life cycle phase.

Life Cycle Phase	**Actor**			
	Decentralised Reuse Organisation (PRO)	**Poolers (Producers)**	**Independent Recyclers (Producers)**	**Regulators**
Design	Issue design specifications with a high degree of standardisation and value durability, tailored to properties of regionally available timber.	Alter designs to comply with PRO standards, possibly including a wider range of dimensions.	Use PRO designs. Work with customers to make their operations compatible with PRO designs wherever possible.	
Raw Material Procurement	Require participants to procure certified wood.	Procure certified wood under market conditions.	Procure certified wood under market conditions.	Impose a tariff on imports of wood packaging raw materials.
New Manufacturing	Require new cores to be serialised in a centralised life cycle tracking database.	Manufacture initial stock of PRO packaging. Maintain stock of cores under market conditions. Continue to operate under rental model and/or adopt buy-sell model.	Manufacture initial stock of PRO packaging. Maintain stock of cores under market conditions. Operate under buy-sell model.	Impose a tax on the sale of new wood packaging manufactured outside the PRO system unless the packaging will be used to export product.
Delivery & Retrieval	Manage interregional balance of inventories. Provide inventory routing optimisation tools to participants to help them minimise transports. Operate transfer stations in regions with a low geographic density of activity.	Incentivise very large customers to practise cross-docking wherever economically viable. Scan outbound deliveries and inbound retrievals into database.	Utilise smaller capacity vehicles to serve LTL markets. Scan outbound deliveries and inbound retrievals into database.	Finance PRO to reimburse participants for unprofitable retrievals. (Very remote, contaminated, poor condition). Incentivise the adoption of alternative fuels and drivetrains for road freight.

Repair	Require participants to maintain service histories of individual cores and practice pre-emptive remanufacturing according to schedules optimised against resource value loss. Set standards for how repairs are performed. Establish a standardised grading system for resale based on service history.	Perform repairs according to PRO schedules. Maintain service histories in database.	Perform repairs according to PRO schedules. Maintain service histories in database.	Target-setting should not be necessary to maintain a high level of reuse and repair, as these practices are already commonplace for secondhand cores collected in the U.S. without such targets.
EOL Management	Require participants to practise component reuse, install equipment for material recycling, and deregister cores from database at EOL.	Deregister cores at EOL, route to destination per market conditions, and report destinations of material in aggregate.	Deregister cores at EOL, route to destination per market conditions, and report destinations of material in aggregate.	Mandate reporting of EOL destinations of PRO cores on de-registration. Ban landfilling, incineration without energy recovery, and donation of PRO cores. If non-PRO activity remains significant, consider sponsoring studies on collection rates.
Other	Inspect participants regularly for compliance. Distribute information to packaging users about supply chain best practices. Use database to identify and target sources of core leakage. Issue penalties for violations.	Possibly, use database as an actuarial tool to characterise users' "risk" (prevalence of losses and damages), assigning higher rates to those with a high risk. This incentivises better supply chain practices among users.	Possibly, use database as an actuarial tool to characterise users' "risk" (prevalence of losses and damages), assigning higher rates to those with a high risk. This incentivises better supply chain practices among users.	Finance the establishment of a PRO, production of an initial stock of returnable packaging, and installation of tracking equipment (RFID or barcode reader and database management tools) at participant locations. Allow for the use of low-grade timber in mass timber applications.

6.1.1 Producer responsibility organisation

The proposed role of a producer responsibility organisation for wood packaging combines the functions of existing decentralised pools – setting standards for products and producer activities and maintenance of producers' compliance with these standards – with some of the functions of existing PROs for other types of packaging – ensuring product stewardship and penalising producers for harmful activities. This PRO operates differently from existing PROs in that targets for best practices such as reuse and recycling are not set, and producers are not universally penalised for their activities; instead, participation in the PRO is seen as the "gold standard" of operation, and only activities that deviate from those required by the PRO standards are penalised. For example, a paper packaging producer may be required to pay a tax based on every unit of packaging they produce to cover the marginal costs of municipal waste management activities induced by that unit of packaging's production, but in the proposed PRO for wood packaging, participation in the PRO-managed reuse scheme is free, and only activities which devate from the standards and requirements set by the PRO are penalised. The potential to participate in a PRO without mandatory administrative costs and penalties may make the concept of a PRO more palatable to wood packaging producers.

The responsibilities proposed for the PRO for wood packaging are as follows: In the design phase, the PRO issues an array of standard product designs which have been created with maximum value durability as a primary design characteristic, intended to serve the largest number of wood packaging users while maintaining a feasible degree of reusability. These designs may vary between geographic regions subject to the mechanical properties of locally available timber to ensure designs can be manufactured without prohibitive costs and impacts of raw material transportation. In the procurement phase, producers should be required to purchase only wood which has been certified by a forest certification scheme. All newly manufactured cores should be required to be serialised within a nationwide product life cycle tracking database. The PRO should provide inventory routing optimisation tools to producers to help them minimise transportation distances. As there is an imbalance between supply and demand between regions of the U.S., it may be necessary for the PRO to commission deliveries between producer facilities to rebalance inventories. Producers should be required to retrieve all PRO cores, even when they are damaged or contaminated. In remote areas, it may be advantageous for the PRO to operate transfer stations that act as a hub between distant users and producers, making retrievals in these areas economically viable for producers. All producers' deliveries and retrivals should be required to be logged in the life cycle tracking database to establish a chain of custody for these products. Similarly, producers should be required to maintain service histories of these products and perform repairs according to a set pre-emptive remanufacturing schedule optimised against resource value loss from prematurely replaced components. A standard for repair practices and grading of repaired products should also be set. All producers should be required to remanufacture intact components from dismantled cores and practice material recycling of damaged components. Cores must be deregistered from the database at EOL, and landfilling, donation and incineration of cores without energy recovery should be prohibited. The PRO is also responsible for inspecting producers regularly for compliance, distributing information to packaging users about best practices for loading and handling of products to minimise damages, identifying and targeting sources of product leakage and unusually high product damages, and issue penalties to producers for violations.

6.1.2 Producers

Unlike the EPAL system, which requires participants to use an exchange business model, producers under the proposed PRO are free to monetise their activities in whichever fashion suits them. Independent manufacturers and recyclers may freely purchase and sell cores at prices governed by market competition, and poolers may continue to work with a rental business model or transition to a buy/sell model. This approach results in the least disruption to the business activities of producers, which may reduce the industry's resistance to the establishment of a PRO for wood packaging.

Producers are responsible for altering their existing portfolios of product designs to align with the standards set by the PRO and procure only certified wood for manufacturing. Producers will be responsible for manufacturing the initial stock of cores and maintaining appropriate inventory levels according to market pressures. Producers must scan all deliveries and retrivals into the life cycle tracking database. Poolers, whose capacities are tailored to very large customers, should work to incentivise cross-docking practices among their customers where it is feasible to do so. Independent recyclers should consider utilising lower capacity vehicles to serve the needs of LTL customers in addition to their FTL orders. All producers must perform product repairs according to PRO standards and pre-emptive remanufacturing schedules and log these services into the database to maintain service histories for these products. They must also deregister cores at EOL and report the mass of material they send to each EOL destination in aggregate. If producers are given access to certain information within the life cycle tracking database, they may use it as a tool to assess the product loss and damage risk of their customers and factor it into their pricing, similar to the way insurance companies and lenders use actuarial methods to price their products according to customers' relative levels of risk. This practice could incentivise wood packaging users to minimise losses and damages in their operations without the need for PRO intervention.

6.1.3 Regulators

The role of regulators is to provide initial financing for the establishment of a decentralised pallet pool, set producer responsibility obligations related to reporting and life cycle practices, and encourage the widespread use of the pool through economic incentives. They provide the "teeth" to the rules set by the PRO. Most importantly, regulators should impose a tax on all wood packaging products produced outside of the PRO programme sufficient to incentivise participation in the programme. Exceptions could be made for products which are not compatible with the programme, such as those which will be exported outside the jurisdiction of the PRO and not returned. Regulators should also consider imposing a tax on imported wood raw material to encourage local procurement.

The estimated cost to establish the 9BLOC pallet pool in 2012 was between $160 million and $250 million [I2]; indexed to April 2023 using the U.S. PPI for wood pallets and container manufacturing, this figure is now between $300 million and $460 million (U.S. Bureau of Labor Statistics, 2022a). Initial costs include the production of an initial stock of PRO cores large enough to ensure an adequate degree of market penetration, developing a life cycle tracking infrastructure and database, and administrative costs related to the creation of the PRO and its standards of practice. The PRO will require recurring public funding to cover costs related to administration of the system and incentivising producers to perform important activities which are not economically viable (e.g. retrieval of contaminated and extremely distant cores), though these costs cannot be accurately estimated at present.

Regulators can also take actions in adjacent areas to improve the resource efficiency of the American wood packaging industry and provide environmentally beneficial destinations for diverted material. These actions include incentivising the adoption of alternative fuels and drivetrains for road freight and incentivising the adoption of mass timber construction.

6.2 Recommendations for future research

The research presented in this thesis has demonstrated the value of a circular transformation of the American wood packaging industry and provided a model for achieving it. However, many questions remain which must be answered in future research in order to ensure this transformation is carried out effectively. These questions are broadly characterised below:

1. How are wood packaging cores actually managed in the U.S. today?

   Research could investigate the life cycle of a typical one way pallet, gather detailed information about the operations of poolers, and determine collection rates for wood packaging.

2. What is the best structure for a PRO for wood packaging and decentralised wood packaging reuse?

   Research could look to existing PROs for products whose EOL management is carried out internally by producers for inspiration, carry out a detailed investigation of the operations of the EPAL system, and create a design for a life cycle tracking system for returnable wood packaging products.

3. How can a PRO for wood packaging be achieved politically in the U.S.?

   Research could investigate how other EPR programmes came to be established at state and federal levels, and how initiatives to establish them overcame political resistance from affected industries. It is important to consider which actors will benefit the most from the PRO programme and which have the power to establish it.

4. How do changes in resource consumption translate to changes in environmental impacts?

   Once the proposed PRO programme is operational, ISO 14040 compliant LCAs should be conducted to quantify the environmental impacts of PRO wood packaging systems as compared to other types of wood packaging systems. Results can help wood packaging producers and users track improvements in their sustainability performance.

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Appendix

Appendix I. Annotated bibliography regarding returnable packaging system design and optimisation.

Title	Reference	Notes
A Blockchain-IoT Platform for the Smart Pallet Pooling Management	(Wu et al., 2021)	Outlines a theoretical model for using a Blockchain-Internet of Things (BIoT) platform distributed to end users to track and manage reusable pallets in a pool, outcomes focus on inventory-routing optimization but could have other applications e.g. pre-emptive remanufacturing and statistical control of user behavior. See paper for specifics on comp sci details and best practices
A measurement tool for circular economy practices: a case study in pallet supply chains	(M. G. Gnoni et al., 2018)	Useful tool for qualitatively assessing the sustainability performance of pallet management firms
A scenario analysis for evaluating RFID investments in pallet management	(M. Gnoni & Rollo, 2010)	
An investigation of wood pallets landfilled and recovered at U.S. municipal solid waste facilities	(Shiner et al., 2021)	• Value of 1 U.S. ton of wood chips sold by MSW facilities: $14.81 (June 2017) • 22% of MSW facilities use wood waste as alternate daily cover for landfills • 14.6% of MSW surveyed operate waste-to-energy facilities, of which 53% of feedstock is wood waste • 3.5% of new wood pallet production is ultimately sent to MSW, of which 1.6% [46%] is landfilled and 1.9% [54%] is diverted
Assessing the life-cycle environmental impacts of the wood pallet sector in the United States	(Alanya-Rosenbaum et al., 2021)	• ""Generic multi-use pallet"" • 1.8 x 10^9 pallets in service in USA (reference: ADEQ/UNECE, 2016) • Environmental impacts are sensitive to pallet service life and load capacity. • FU = 45.4t delivered product • Wood pallets 92% of pallets (Freedonia Group, 2020)

		• Study does not consider transport impacts from hired distances • Assumes only 1 reuse for all types of pallets investigated • ""Industry average"" wood pallet weighs 18.57kg 12%MC or 16.58kg OD • When is a core is dismantled, 37.3% of boards recovered, 40.4% mulched, 17.3% incinerated, 5% landfilled • Use phase (loaded transport) becomes highest source of GHG for d> 950km • Fuel substitution is the most desirable EOL for pallet timber considering GHG impact • 21% of total production is heat treated Questions for authors: • Is there a delineation between pooled pallets and resale pallets in your data? • Are % destinations for boards from dismantled cores accounted for on a mass basis?"
Assessing the viability of reusable packaging: a relative cost approach	(Mollenkopf et al., 2005)	Formulaic framework for comparing system costs to the user between single-use and reusable packaging systems. ALL Formulas on p.184 Assumes 2-year project life, case studies based on US automotive transport packaging systems SUCCESS FACTORS IN ORDER OF SIGNIFICANCE (BASELINE): 1. Ratio of reusable:single-use container purchase price. Reusables benefit from high pack quantity. 2. Average daily volume of product to be transported. Reusables benefit from high volumes. 3. Delivery distance. Reusables benefit from shorter distances.

		4. Cycle time for pkg item and peak volume factor are relatively insignificant to this decision. UNDER VERY FREQUENT SERVICE AND HIGH VOLUMES: 1. Average daily volume 2. Delivery distance
Carbon footprint analysis of pallet remanufacturing	(Tornese et al., 2016)	Scope: use & remanufacturing activities on GMA block and stringer pallets Materials account for 95-99% (transport not included) Stringer pallets carry lower emissions from reman due mainly to the fact that repair items are salvaged from other used pallets, while block pallets use new boards for repair. Transportation (return) distance a critical factor for emissions in all scenarios - netrwork design is key for carbon efficiency Exterior components (3 component types per design) repair/replacement comprise 50-66% and 90-100% of reman emissions of block and stringer pallets respectively For block pallets, a cross-docking strategy increased the total cycles before breakeven with the emissions of manufacturing a new pallet by 17-73% compared to a take-back strategy from reduced transport. Pre-emptive remanufacturing, optimized to balance against opportunity loss from prematurely replaced components, reduces emissions from the remanufacturing phase by 11-41% (avg. case 23%) % of cycles requiring reman activity [worst/avg/best]: block [89/73/47], stringer [100/33/23]."
Cost-effective pallet management strategies	(Roy et al., 2016)	>99% of pallet industry establishments are small businesses (US Census Bureau 2012) Includes 2016 data on pallet systems' user-facing costs

		In purchase-based systems, users typically source from facilities within 25 miles Discusses issue of ""Non-participant distributors"" causing leakage in leasing systems • Suggests >10% attrition to NPDs and other sources makes the leasing system unfeasible ""Pull strategy"" where inventory is moved only on request instead of according to a fixed supplier schedule reduces user costs 11-20% in all scenarios
Designing a closed-loop supply chain for reusable packaging materials: A risk-averse two-stage stochastic programming model using CVaR	(Das et al., 2022)	
Designing an effective closed loop system for pallet management	(Elia & Gnoni, 2015)	
Environmental and economic impacts of preemptive remanufacturing policies for block and stringer pallets	(Tornese et al., 2019)	RQ: Does pre-emptive remanufacturing of block & stringer pallets reduce costs and/or emissions of the remanufacturing phase? A: Yes, costs of remanufacturing phase reduced by 31%/44% and emissions reduced by 29-39% (block/stringer) Costs & emissions correlate strongly (~95%) for pallet remanufacturing Benefit of pre-emptive reman diminishes at lower transportation distances (<50-300 km), changing the optimal reman schedule
Environmental Impacts of Reusable Transport Items: A case study of pallet pooling in a retailer supply chain	(Accorsi et al., 2019)	Scope: Use phase of an isolated Italian retailer-pooler supply chain for forward flows of unitized goods and reverse flows of empty pallets Baseline: empty pallets move from each retailer depot (last step before the retailer) back to the vendors who are palletizing product Pooling 4 (Optimal solution): Pooler and retailer share hubs upstream of the retailer depots and downstream of the vendors; empties travel from retailer depots back to

		closest hub or pooler facility. Pooler holds inventory of empties at both its own facilities and the integrated hubs. The key benefit is that the forward shipments of goods and RTIs to retailer depots can be consolidated at the hubs for much more efficient middle-stage forward transport. The forward efficiency Result: pooling 4 reduced truck-km by 65% and emissions by 60%. Similar results can be achieved with buy-sell systems that utilize retailer hubs that consolidate empties from the depots.
Investigating the environmental and economic impact of loading conditions and repositioning strategies for pallet pooling providers	(Tornese et al., 2018)	RQ1: What is the maximum service radius at which a pooling system is economically & environmentally preferable to a single-use system? RQ2: What are the impacts of user handling/loading conditions, network distances, and alternative repositioning strategies on economic & environmental performance of a pooling system? Excludes end-of-life scenarios, assumes full TL shipments % Reusable without repair after a cycle [good/avg/rough handling] = [50/30/10] Maximum round-trip repositioning distance (i.e. divide by 2 to get effective pooling radius): 191-515km for 16t light truck, 194-821km for 32t semi truck Improving handling and loading environments has a major effect on performance and can increase the effective radius of a pooling facility Cost of repairing a pallet is 1/3 that of manufacturing a new one Crossdocking has no significant performance benefit over take-back through the entire life cycle, but results in a 5% faster reissue time and reduces total pool inventory required by 28% Short repositioning distance (30-50km) reduces total system costs by ~22% and emissions by ~26% compared to long repositioning distance (200-250km)
Investigation of New and Recovered Wood Shipping	(Gerber et al., 2020)	• NAICS 321920: stats about wood pallet industry

Platforms in the United States		• Fig. 2 New & used wood pallet production over time • 2016: 513 million new pallets, 503 million recovered pallet cores (98.1%), of which 326 million (63.5%) reused as pallets and the remaining 177 million (34.5%) converted to co-products • 10 million pallets (1.9%) landfilled w/o recovery • 2016: 9.16 bbf new lumber consumed (21.8% of US total) • 4.13 bbf hardwood (43% of total), of which 4.07 [98.5%] to new pallets and 0.06 [1.5%] to used pallets • 5.03 bf softwood (15% of total), of which 4.48 [89.1%] to new pallets and 0.55 [10.9%] to used pallets • Fig. 3 Regional variations in timber consumption - northeast predominantly hardwood, west pred. softwood • 6% imported, of which >99% from Canada • Certified wood: increase from 3.8% in 2011 to 32% in 2016 (low sample size) • 76% stringer, 21% block, 3% other • 48x40 defacto standard size with 35% • 48x40 comprises 69% of recovered pallets (double the share of production), indicating other sizes are less likely to be recovered • Utilization of recovered pallets (503m): - 5.5% resold without repair - 64.7% repaired - 18.1% disassembled for other uses - 10.6% ground or chipped - 0.3% landfilled - 0.9% other uses

		• Utilization of ground & chipped pallets (3.9 Mt) - Landscape mulch 37.5% - Non-compressed wood fuel 30.0% - Animal bedding 4.2% - Other uses 28.3% • Pooled and one-way pallets are all lumped together
Life cycle assessment comparison among different reuse intensities for industrial wooden containers	(Gasol et al., 2008)	Scope: pallets and spools of different reuse intensities in Spain Over 95% of GWP for high-reuse (HR) pallet systems (30 uses over 10 years, 23% reman rate) comes from transport, and over 65% from transport for low-reuse (LR) systems (4.4 uses over 2 years, 8% reman rate) 33 HR Pallets provide the function of 227 LR pallets Compared to LR pallets, HR pallets impacts: • Energy consumption -64% • Forest exploitation -81% • Abiotic (technical) resources depletion -38% • Ozone depletion -34% • Human toxicity -54% • Acidification -40% • Eutrophication -50% • GWP +7%* *Over 95% of GWP for high-reuse (HR) pallet systems (30 uses over 10 years, 23% reman rate) comes from transport, and over 65% from transport for low-reuse (LR) systems (4.4 uses over 2 years, 8% reman rate)
Life Cycle Assessment of One-way and Pooled Pallet Alternatives	(Bengtsson & Logie, 2015)	Scope: Several pallet products 1165x1165(?) in Australia & China managed by the CML company the average pallet is hired 2.9 times per year over an average life span of 10 years. Edge estimates that each

		pallet makes 3 customer trips per hire, for a total average of 87 customer trips. (8.7 customer trips per year, plus 2.9 are relocations. total 11.6 trips per year) "we have not had access to any information on the afterhire distances over which pallets are used." The average relocation distance for a CML wooden pallet (AU) is 246km per de-hire, of which 159km is by rail, 79km by road and 8km by ship. One pooled softwood pallet serves the function of 41.67 one-way softwood pallets. Transportation is the most impactful activity in the life cycle of pooled pallets. One-way pallets must be reused 4-6 times to breakeven on impact with pooled pallets under the given scenario.
Life cycle assessment of the wood pallet repair and remanufacturing sector in the United States	(Alanya-Rosenbaum et al., 2022)	• The repair/reman. process is on average 90.1% mass-conserving (9.9% of mass converted to wood fuel [47%], mulch [52%], and animal bedding [1%]) • Steel scrap ~99% recycled • Lumber consumption of repair/reman facilities: softwood 72%, hardwood 28%. About 90% of the lumber received was pre-cut (ready for use). • Recovered pallet destinations: 12% reused w/o repair, 53% repaired, 31% dismantled, 4% repurposed (mulch/fuel) • Weighted avg. one-way recovery distange (retailer to repair site) was 65km (range: 25-100km) • Transportation of recovered pallets most significant source of GHG, even at this short distance • Pooled and one-way pallets are all lumped together
Minimization of the environmental emissions of closed-loop supply chains: a case study of returnable transport assets management	(Bottani & Casella, 2018)	Scope: Optimize CO2, SOX, and NOX emissions and system costs of an italian FMCG company's closed pallet logistics system under different order points (OP) and minimum purchase quantities (MPQ) regarding the company's backhaul pickups (under a deferred exchange system) from its customers who receive unitized loads and generate empties.

		Objectives: Minimize emissions, minimize pallet out-of-stock events, maximize pallet utilization , maximize pallet rotation rate (min. cycle time), minimize the total number of pallets owned. Results: • Customer MPQ (min # of empties picked up on a backhaul) has a strong negative correlation with total emissions (r^2 = -0.68). In essence, higher MPQ = fewer backhaul trips = lower transport emissions • Increasing OP (qty held at company when company decides they must retrieve empties) reduces utilization (r^2 = -0.81), increasing cycle time and the number of pallets needed to service the system. • Transport for retrievals contributes 56-57% of total system CO2 emissions and ca. 91% of SOX and NOX emissions. • Even at a very low loss rate of 2.5% per cycle and damage-induced replacement rate of just 1% per year, the emissions from lost & damaged pallets total 38% of total system CO2 emissions. Minimizing loss rate is critical to minimizing system CO2 emissions. • Asset-efficient solutions with MPQ of 80-175 pallets can be had with little sacrifice to emissions. This opens the door to the use of low-capacity trucks which would further reduce costs & emissions (not studied here).
Returnable containers: an example of reverse logistics	(Kroon & Vrijens, 1995)	Good conceptual & mathematical model for the optimization of logistics costs in a returnable container CLSC.
Selection of pallet management strategies based on carbon emissions impact	(Carrano et al., 2015)	Provides bill of materials for single-use, buy/sell, and rental ""baseline"" designs EOL disposal mode dominates impacts under incineration w/ energy recovery: credits give incinerated pallets a negative CO2 balance due to displaced fossil electricity demand. Incineration w/energy recovery is by far more CO2-efficient than mulching or landfilling. • Perverse incentive to only use single-use pallets if forest churn is not considered. Should assume the goal is still to promote re-use.

		• Message: incinerate whenever disposal is necessary, but dispose as little as possible. Not considering incineration CO2 credits, materials and transport are the other largest emitters for all 3 systems. The use phase (i.e. transport) becomes the dominant emitter above k value: • 150km per pallet cycle under a leasing model • 675km per pallet cycle under a buy-sell model • 1040 km under a single-use model k value given by participants (USA stakeholders): 675km % of pallets lost after a given trip = 6% look inside paper p.263 for block & stringer pallet service lives under various loading & handling conditions In this scenario, leasing is carbon-optimal for short-haul applications (k = 100s kms) and single-use is carbon-optimal for long-haul applications (k = 1000s kms). Buy-sell is never carbon-optimal except for the extreme case of light loads and good handling for all trips.
Using Internet of Things technologies for a collaborative supply chain: Application to tracking of pallets and containers	(Gnimpieba et al., 2015)	

Appendix II. Formulas for calculating the costs of one-way and returnable container systems, not including capital and inventory costs.
Source: (Mollenkopf et al., 2005)

	Expendable Container Systems	Reusable Container Systems
Container Cost	$ECC=\frac{UCE}{PQ}=\$/part$	$RCC=\frac{UCR*N}{AV*CL}=\$/part$
Transportation Cost	$TCE=\frac{R*DD}{FOS*ADV}=\$/part$	$TCR=\frac{R*(1-d)*DD*2+NS*SR}{FOS*ADV}=\$/part$
Labor Cost	$LCE=TE*\frac{LR}{PQ}=\$/part$	$LCR=TR*\frac{LR}{PQ}=\$/part$
Disposal Cost	$DCE=\frac{DR*CW}{PQ}=\$/part$	
Recycling Revenue	$RRE=\frac{eRR*CW}{PQ}=\$/part$	$RRR=\frac{rRR*CW}{\frac{WD}{CT}*PQ*CL}=\$/part$

ADV = average daily volume, parts/day
AV = annual volume, parts/year
CL = container life, years
CT =cycle time, days for reusable containers
CW = container weight, lbs/container
d = discount rate
DCE = disposal cost, $/part
DD = delivery distance, miles (*2=round trip)
DR = disposal rate per lb, $/lb
eRR = recycling rate per lb (expendable containers), $/lb
ECC = expendable container cost per product, $/part
FOS = frequency of supply, days
LCE = labor cost for expendable system, $/part
LR = labor rate per hour, $/hour
N = number of containers to be purchased, as in Equation (9)
NS = number of stops
PQ = pack quantity, parts/container
R = rate per mile, $/mile
rRR = recycling rate per lb (reusable containers), $/lb
RCC = reusable container cost, $/part
SR = stop-off rate, $/stop
TCE = transportation cost for expendable systems, $/part
TCR = transportation cost for reusable container system, $/part
TE = time needed to handle expendable container, hours/container
TR = time needed to handle the reusable container, hours/container
UCE = unit cost of an expendable container, $/container
UCR = unit cost of reusable container, $/container
WD = working days per year

Appendix III. Complete questionnaire: "Circularity of the American Wood Pallet Industry."

Circularity of the American Wood Pallet Industry

Thank you for your participation in this survey! Your responses will be a part of the world's first published assessment of the level of circularity of the wood packaging industry. The information you provide will be used to create strategies for improving the resource efficiency of American wood pallet supply chains. The results of this survey will support a master's thesis at the International Institute for Industrial Environmental Economics at Lund University (Sweden). The thesis topic is "Circular Transformation of the American Wood Packaging Industry." At the end of the survey, you will have the chance to reserve free access to the thesis upon its publication later this year.

Instructions:
Progress through the nine sections of this survey in order. Each section contains questions about one aspect of wood pallet supply chain operations. The first question of each section, along with other selected questions, is required. Please do your best to answer each optional question that applies to your operations. All questions, required and optional, are equally important. If you feel you are unable to provide an answer to an optional question, it is okay to leave the question blank.

Privacy & Data Protection:
This survey is conducted in compliance with the General Data Protection Regulation (GDPR) of the European Union. Results from this assessment will be anonymized and presented in aggregate. No names of organizations nor contact information will be published. Your specific responses may be reported, but not in a capacity that will identify you or your organization. By way of publication, some non-identifying information from responses will be shared internationally.

Contact information for the distribution of this survey was collected from the member directory of the National Wood Pallet and Container Association, a publicly accessible source. If you provide consent to be contacted by answering 'Yes' to Section 9, Question 2, your contact information and responses may be used for Customer Relationship Management by Y.G. Packaging Solutions LLC, an American business organization affiliated with this research.

* Indicates required question

1. Name of organization: *

____

2. Number of employees: *

Mark only one oval.

- 1 - 10
- 11 - 50
- 51 - 100
- 101 - 200
- 201 - 1000
- More than 1000

3. Your name:

____

4. Position:

____

Pallet Design

Section 2 contains questions about the **designs**, or blueprints, of wood pallets used by the industry. If your operation creates, orders, or uses such designs, answer the questions in Section 2 as you are able.

5. Does your organization create or work with wood pallet designs? *

Mark only one oval.

- Yes
- No *Skip to question 9*

6. Does your organization produce designs with widely used dimensions?

Mark only one oval.

- ◯ Entirely custom dimensions
- ◯ Mostly custom dimensions
- ◯ Mostly widely used dimensions
- ◯ Entirely widely used dimensions

7. Does your organization produce designs which make use of standardized parts which are readily interchangeable?

Mark only one oval.

- ◯ Entirely custom (cut to order) parts
- ◯ Mostly custom parts
- ◯ Mostly standardized parts
- ◯ Entirely standardized parts

8. Does your organization use engineering software (or a third party engineering service) to create your wood pallet designs?

Mark only one oval.

- ◯ Yes, and we use it to reduce the environmental impact of our designs
- ◯ Yes, and low environmental impact is not a significant design factor
- ◯ No

Raw Material Procurement

Questions in Section 3 pertain to the **raw materials** used in wood pallet production, particularly timber. If you use any **virgin (new) wood** in your operations, please answer the relevant questions below.

9. Does your organization purchase virgin (new) wood material for pallet manufacturing and/or repair? *

Mark only one oval.

- Yes
- No *Skip to question 15*

10. In what form(s) does new wood arrive at your facility for processing? Select all that apply.

Check all that apply.

- Whole logs
- Cants of nonspecified sizes
- Cants of specified sizes
- Dimension lumber not cut to length
- Blocks, stringers, and/or deckboards cut to length
- Other:

11. What is the average distance, in miles, that new wood material travels from the supplier to your facility?

12. Does your organization import new wood material?

Mark only one oval.

- Yes - most or all of our wood is imported
- Yes - a minority of our wood is imported
- No

13. Where do you import new wood material from? Check all that apply.

Check all that apply.

- [ ] Canada
- [ ] Brazil
- [ ] Latin America - Other
- [ ] China
- [ ] Asia - Other
- [ ] Europe
- [ ] Other:

14. Is the wood you purchase certified by a forest certification scheme? (e.g. FSC, SFI)

Mark only one oval.

- ( ) Entirely non-certified wood
- ( ) Mostly non-certified wood
- ( ) Mostly certified wood
- ( ) Entirely certified wood

New Pallet Manufacturing

Section 4 contains questions for manufacturers of **new wood pallets** for **first-time use**. Please answer all questions that apply to your operations.

15. Does your organization manufacture new pallets? *

Mark only one oval.

- ( ) Yes
- ( ) No *Skip to question 20*

16. What quality control measures are used in your manufacturing process?

17. Where is scrap generated during your manufacturing process? How is the scrap used?

18. To what extent is automation used in your manufacturing process?

Mark only one oval.

- Entirely automated
- Mostly automated
- Mostly manual
- Entirely manual

19. Which forms of energy does your facility use? Check all that apply.

Check all that apply.

- [ ] Grid electricity
- [ ] Natural gas
- [ ] Biomass on-site (e.g. wood scrap in a boiler)
- [ ] Other renewables on-site (e.g. solar, wind)
- [ ] Other:

Delivery and Retrieval

Section 5 contains questions about your pallet logistics activities. Even if you do not move pallets with your own fleet, we appreciate your input here about how your pallets are transported.

20. Does your organization arrange transportation of pallets, through either your own fleet or through a third party logistics provider? *

Mark only one oval.

- ( ) Yes - outbound deliveries and retrieval of used pallets
- ( ) Yes - only outbound pallet deliveries
- ( ) Yes - only retrieval of used pallets
- ( ) No *Skip to question 35*

21. Which vehicle types do you use to transport pallets? Check all that apply.

Check all that apply.

- [ ] Truck - Diesel
- [ ] Truck - Gasoline
- [ ] Truck - Alternative fuel
- [ ] Truck - Electric
- [ ] Rail
- [ ] Barge / Cargo ship
- [ ] Other: ______________________

22. Which type(s) of trucks do you use to transport pallets? Check all that apply.

Check all that apply.

- [ ] Heavy duty truck / tractor trailer
- [ ] Medium duty / box / straight truck
- [ ] Light duty / pickup truck or van
- [ ] Other: ______________

23. Which quantities of pallets do you typically **deliver** to a customer in a single order? Check all that apply.

Check all that apply.

- [ ] 1-10
- [ ] 11-50
- [ ] 51-125
- [ ] 126-250
- [ ] 251-500
- [ ] 500+

24. What is your **average** one-way **delivery** distance in miles?

____

25. What is your **maximum** one-way **delivery** distance in miles?

____

26. Approximately what percentage of the time is a trailer or container fully loaded while on an outbound **delivery** trip? Enter a whole number from 0 to 100.

____

27. Which quantities of used pallets do you typically **retrieve** from a single location? Check all that apply.

Check all that apply.

- [ ] 1-10
- [ ] 11-50
- [ ] 51-125
- [ ] 126-250
- [ ] 251-500
- [ ] 500+

28. What is your **average** one-way **retrieval** distance in miles?

____

29. What is your **maximum** one-way **retrieval** distance in miles?

____

30. Approximately what percentage of the time is a trailer or container fully loaded while on a **retrieval** trip? Enter a whole number from 0 to 100.

____

31. Does your facility use **drop trailers** for retrieval of used pallets?

Mark only one oval.

- ( ) Yes
- ( ) No

32. Please describe the factors that most commonly cause you to **refuse retrieval** of used wood pallets.

33. Approximately what percentage of your total transport mileage comes from **empty** (deadhead) mileage? Enter a whole number from 0 to 100.

34. Please describe any efforts you make to reduce total vehicle miles travelled in your transportation & logistics activities.

Repair Activities

Section 6 contains questions about **repair activities** for wood pallets, including grading, component replacement, and refurbishment.

35. Does your organization repair used wood pallets? *

Mark only one oval.

- Yes
- No *Skip to question 41*

36. If your facility uses a **grading system** for used wood pallets, please describe that system here.

37. Do you use new wood or recycled wood in your repair activities? Parts salvaged from other pallets count as recycled wood.

Mark only one oval.

- ◯ Repairs made entirely using new wood
- ◯ Repairs made mostly using new wood
- ◯ Repairs made mostly using recycled wood
- ◯ Repairs made entirely using recycled wood

38. Which components does your operation **replace** with a new component when one is damaged?

Check all that apply.

- ☐ Exterior (lead) deckboards
- ☐ Interior deckboards
- ☐ Outer stringers
- ☐ Center stringers
- ☐ Blocks
- ☐ Stringerboards (block pallets)
- ☐ Other:

39. Which components does your operation **refurbish** when broken? (e.g. plate repair, companion stringer, and other repairs which do not involve replacing the damaged part altogether)

Check all that apply.

- [ ] Exterior (lead) deckboards
- [ ] Interior deckboards
- [ ] Outer stringers
- [ ] Center stringers
- [ ] Blocks
- [ ] Stringerboards (block pallets)
- [ ] Other:

40. Do you practice **pre-emptive remanufacturing**? This refers to strategically repairing or replacing parts which are still intact in order to reduce the frequency of repair services needed during the pallet's service life.

An everyday example of this is replacing a car's engine oil and cabin air filter at the same time so that only one service is necessary.

Mark only one oval.

- ( ) Yes
- ( ) No

Closed Loop Systems

Section 7 contains questions about **closed loop systems** for reusable pallets. We appreciate your responses here no matter what part of the reusable pallet supply chain you work with. Please only give responses that apply to closed loop systems and not other systems for reuse e.g. buy/sell models.

41. Do you work with closed loop systems for reusable wood pallets? *

In a closed loop system, one party retains ownership of the pallet for its entire service life. In an open system, used pallets are bought and sold freely throughout their service lives.

Mark only one oval.

- ( ) Yes
- ( ) No *Skip to question 49*

42. How does your organization work with closed loop pallet systems? Check all that apply.

Check all that apply.

- [ ] Pooling with rental model (e.g. CHEP blue pallets)
- [ ] Pooling with tradable deposits or receipts
- [ ] Service to pallets within a customer's closed loop system
- [ ] Production of new pallets for closed loop systems
- [ ] Other:

43. Do you practice **cross-docking**? This refers to the inspection and sorting of used pallets at the pickup point so that undamaged pallets may be recirculated immediately with no return trip to a service point.

Mark only one oval.

- ( ) No - all pallets are returned to a service point for inspection
- ( ) Yes - inspection performed by customer or other recipient of used pallet
- ( ) Yes - inspection performed by driver at time of retrieval
- ( ) Yes - inspection performed by another party
- ( ) Other: ______________________

44. Are the used pallets in your closed loop system **consolidated** by customers before pickup so that retrievals can be made in larger quantities?

An example of consolidation is a group of retailers sending their empty pallets upstream to their own distribution center for pickup, rather than staging smaller or less frequent pickups at each individual retailer.

Mark only one oval.

- Consolidation never happens - the empty pallets are only moved by us
- Consolidation happens occasionally and/or when convenient for the customers
- Consolidation happens frequently and/or is incentivized by us
- Consolidation always happens and/or less-than-truckload retrievals are never made
- Other:

45. How does your organization **incentivize consolidation?**

46. Are you able to track the chain of custody and/or locations of returnable pallets once they have left your facility?

Mark only one oval.

- Yes
- No

47. Are you able to track the condition and/or service history of individual pallets within your system?

Mark only one oval.

- ( ) Yes
- ( ) No

48. How do you work with your customers to prolong pallet service life and reduce the incidence of lost pallets?

____

End-of-Life Destination

Section 8 will ask a few questions about what happens to your pallets at the end of their service lives. This is the final section containing questions about your operations.

49. Does your organization collect damaged pallets and waste wood for end-of-life recycling and/or disposal, either on-site or from customers? *

Mark only one oval.

- ( ) Yes
- ( ) No *Skip to question 52*

50. Which of the following do these pallets undergo at end of life? Check all that apply.

Check all that apply.

- [ ] Intact components used in future pallet repairs
- [ ] Incineration with energy recovery (usable heat and/or electricity is generated)
- [ ] Incineration without energy recovery (e.g. open burn pit)
- [ ] Metal recycling
- [ ] Conversion to engineered wood products (e.g. MDF, OSB, LVL, CLT)
- [ ] Chipping for mulch, animal bedding, or similar
- [ ] Grinding into dust
- [ ] Pelletization
- [ ] Sent to landfill after disassembly
- [ ] Sent to landfill - no disassembly
- [ ] Sale to third party
- [ ] Donation to third party
- [ ] Other:

51. If there are circumstances which commonly cause your pallets to reach end-of-life when they could otherwise be reused or repaired, please describe them here.

More Information

Thank you for completing this survey! Your input will be part of the world's first published assessment of circular practices within the wood pallet industry. The results from this study will be used to provide economically viable recommendations to the industry to increase its sustainability ambition and tackle the challenges of the next generation proactively. These final questions will ask about your interest in staying informed and involved as our research continues.

52. Would you like free access to the thesis on publication, "Circular Transformation of the American Wood Packaging Industry"? This will include the results of this survey and a strategic guide for increasing the resource efficiency of the wood packaging industry. *

By selecting 'Yes' you consent to being contacted by an affiliate of Lund University.

Mark only one oval.

- Yes
- No

53. Would you like to know more about how adopting certain circular practices can benefit your business operations? *

By selecting 'Yes' you consent to being contacted by an affiliate of Y.G. Packaging Solutions LLC.

Mark only one oval.

- Yes
- No

Appendix IV. Independent variables, notes, sources, and assumptions for the expanded relative cost model.

Variable	Description	Notes	Assumption / Source
ADV	Average daily volume (parts/day)	Set to 100. For every day a customer is operating, they process 100 unit loads.	Set to 100.
CL	Container life (years) [R]	Mean time elapsed between the date of first hire and date of replacement	(Bengtsson & Logie, 2015; Gasol et al., 2008).
CRR	Container return rate [R]	1 + fraction lost and/or damaged after a hire	(Bengtsson & Logie, 2015): Pallet is relocated (new use phase) 2.9 times per year. (Bottani & Casella, 2018): Damage-induced replacement 1% per year. (Carrano et al., 2015): Loss rate per trip = 6%
CT	Cycle time (days) [R]	Mean time elapsed between hire n and hire (n+1)	[R]: (Bengtsson & Logie, 2015): Pallet is relocated (new use phase) 2.9 times per year. [R+]: Pooler will provide pallets from its total stock on a rotating schedule, assume CT = 10. There is no need to use the leased pallets to satisfy one particular customer. Resulting reduction in N is one of the main advantages of pooling vs. buy/sell for reusable packaging.
CW	Container weight, (lbs/container)	Weight of an empty container	[E]: (Carrano et al. 2019) expendable pallet weight = 13.79kg [R/R+]: (Carrano et al., 2015) 31.58 kg/container for leased block pallet
d	Round-trip discount rate [R]	Discount from carrier on round-trip shipments vs. one-way. NOT a financial discount rate	(Mollenkopf et al., 2005) 22%
DD	One-way delivery distance (mi)	DD * 2 = round trip delivery distance for an empty container	[R]: (Carrano et al., 2015) average "pallet-trip" distance in U.S. = 675 km [unclear if this is one-way or for an entire use cycle] [R+]: (Accorsi et al., 2019): Decentralized management of pooled pallets among retailers in Italy reduced system transport by 65%

DR	Disposal rate ($/lb)	Cost of disposal service at EOL	[FTL]: Assume 0 as FTL quantities will be picked up for free. [LTL]: Assume tipping rate of $54 per U.S. ton.
RR	Recycling rate ($/lb)	Revenues from recycled material at EOL	[E]: Assume material is not sold for recycling. [R]: Assume rate of $40 per U.S. ton for wood biomass.
FOS	Frequency of supply (days)	Mean time elapsed between deliveries of new containers to the customer	FTL: Set to 5. LTL: Set to 1.
LR	Labor rate ($/hr)	Average cost of a warehousing and logistics man-hour	(*Tables Created by BLS*, 2021)
NS	Number of stops [LTL]	For less-than-truckload (LTL) shipments. Mean number of stops made per order delivered.	[E]: Set to 4. Loading + unloading for delivery and disposal. [R+]: Set to 2 + TBF
PQ	Pack quantity (parts/container)	Set to 1. 1 container can transport exactly 1 unit load in all scenarios.	Set to 1.
PVF	Peak volume factor	Ratio of peak daily volume : average daily volume	Set to 1.5 at baseline. Based on observations from researcher's work in a factory setting.
RFT	FTL rate per mile ($/mile)	Rate charged by carrier for full truckload (FTL) shipments	DAT National avg. spot van rate, April 2022
RLT	LTL pound rate per mile ($/100lbs/mile)	Rate charged by carrier for less-than-truckload (LTL) shipments	[R]: Assume 20% rate reduction over expendable pallets because of increased load density.
SR	Stop-off rate ($/stop)	Additional charge on top of mileage rate charged by the delivery carrier for each stop (LTL scenario)	"Owner-operator time-value $86.44/hr (May 2022), assume each stop takes 1/2 hour https://www.zippia.com/driver-owner-operator-jobs/salary/"

TR	Handling time (hours/container)	Only includes activities which differ between systems (lowest handling time set to zero).	Assume expendable pallets create the lowest labor costs. Assume [R] induces 0.05 hr/container-hire additional labour and [R+] induces 0.1.
UCE	Unit cost ($/container) [E]	Cost to produce a new one-way container	(Roy et al., 2016) expendable unit cost = $5, indexed September 2015 -> April 2022 (U.S. Bureau of Labor Statistics, 2022a)
UCR	Unit cost ($/container) [R]	Cost to produce a new returnable container	(Roy et al., 2016) $22 replacement cost, indexed September 2015 -> April 2022 (U.S. Bureau of Labor Statistics, 2022a)
WD	Working days per year (days/year)	Number of days per year the customer is operational and consuming containers	Set to 250.
MARR	Minimum attractive rate of return (%)	I.E. opportunity cost of held capital. Determines holding costs related to capital sunk in packaging	Set to 25%.
OQ	Order quantity (containers)	# of containers received when replenishment arrives	[FTL]: Set to 500. [LTL]: Set to 100.
OP	Order point (containers)	Level of remaining stock at the customer facility at time replenishment order is placed	[FTL]: Set to 150. [LTL]: Set to 50.
OHE	Operational holding expense ($/container position/year)	Expenses related to customer's provision of inventory for empty containers (space and labor)	Assume 16 sqft. Needed to store 19 containers floor-stacked (based on interior dimensions of 53' trailer carrying 500 GMA pallets). https://www.prologis.com/what-we-do/resources/how-much-does-it-cost-to-rent-warehouse $1.10 / sqft / month total warehouse rent + operating costs

DF	Dwell fee ($/container/day) [R]	Fee charged to the customer when a container is held and not returned beyond the contracted allowable time	(Roy et al., 2016) $0.03/container/day dwell fee, indexed September 2015 -> April 2022
LRR	Per-container-trip loss rate (%) [R]	Chance the container will be lost or stolen after a given trip (NOT damaged)	[R]: (Carrano et al., 2015) 6% [R+]: Assume 1% due to improved inventory tracking.
LCF	Lost container fee ($/container) [R]	Typically equal to UCR (replacement cost)	Assume equal to UCR.
VCW	Vehicle curb weight (lbs)	Weight of unladen (empty) vehicle	[FTL]: Set to 35000. [LTL]: Set to 13140.
VLC	Vehicle load capacity (lbs) [LTL]	Total additional weight the vehicle is rated to carry	Set to 12859. (25000 – VCW – 1)
VEF	Vehicle emissions factor (kg CO2-eq./ton-mi)	CO2, CH4, and N2O emissions per ton-mile for medium- and heavy-duty trucks	(EPA, 2018): 0.202 kg CO2, 0.0020 kg CH4, 0.0015 kg N2O https://www.epa.gov/sites/default/files/2018-03/documents/emission-factors_mar_2018_0.pdf
NME	New manufacturing emissions (kg CO2/part)	Embodied material and new manufacturing emissions	[E]: (Carrano et al., 2015) 1.73 kg from materials, 0.44kg from mfg. [R]: (Tornese et al., 2016) materials and mfg. combined [R+]:
RME	Remanufacturing emissions (kg CO2/part) [R]	Embodied material and remanufacturing emissions from "repair" phase	[R]: (Tornese et al., 2016): Remanufacturing emissions for block pallets, average handling & load. 95%+ from materials [R+]: (Tornese et al., 2016): remfg. emissions of block pallets, light loading & good handling = 2.60 kg (Tornese et al., 2019): Pre-emptive remanufacturing reduces remfg. emissions by 29% for block pallets