2018

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Maria Grazia Gnoni
University of Salento, mariagrazia.gnoni@unisalento.it

Fabiana Tornese
University of Salento, fabiana.tornese@unisalento.it

Brian K. Thorn
Rochester Institute of Technology, bkteie@rit.edu

Andres L. Carrano
Georgia Southern University, acarrano@fairfield.edu

Jennifer A. Pazour
Rensselaer Polytechnic Institute, pazouj@rpi.edu

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Maria Grazia Gnoni
Department of Innovation Engineering)
University of Salento
Lecce, Italy
mariagrazia.gnoni@unisalento.it

Fabiana Tornese
Department of Innovation Engineering)
University of Salento
Lecce, Italy
fabiana.tornese@unisalento.it

Brian K. Thorn
Department of Industrial and Systems Engineering
Rochester Institute of Technology
Rochester, USA
bkteie@rit.edu

Andres L. Carrano
Department of Manufacturing Engineering
Georgia Southern University
Statesboro, USA
acarrano@georgiasouthern.edu

Jennifer A.Pazour
Department of Industrial and Systems Engineering
Rensselaer Polytechnic Institute
Troy, USA
pazouj@rpi.edu

***Abstract*— A circular economy (CE) is an economic system where products and services are traded in closed loops or 'cycles'. This work develops a framework for assessing the extent to which product supply chains incorporate circular economy principles, and applies this framework to a specific material handling application, the wooden pallet supply chain. The main decisions affecting circularity and the most common decision alternatives for the wooden pallet supply chain are identified for the *Pre-manufacturing, manufacturing, product delivery, customer use, and end-of-life* phases. A streamlined life cycle assessment tool is developed for supporting a quick analysis about how the level of adoption of CE strategies could support environmental sustainability in pallet supply chains. A questionnaire, scoring, and assessment are presented for each phase of a pallet supply chain to reduce input and use of natural resources, reduce emission levels, reduce valuable materials losses, increase share of renewable and recyclable resources, and increase the value of durability of products. A case study is used to test the proposed method and present a contrast between two scenarios.**

***Keywords*— pallet, product chain, circular economy, Environmental sustainability, streamlined LCA**

I. Introduction

A circular economy (CE) is an economic system where products and services are traded in closed loops or 'cycles'. It is characterized as an economy that is regenerative by design, with the aim to retain as much value as possible of products, parts and materials [1]. The aim is to create a system that allows for the long life, effective reuse, refurbishment, remanufacturing and recycling of products and materials [2], which requires changing consumption patterns and creating new business models and systems [3]. The main strategic pillars of a circular economy can be summarized as "Less resource and material consumption"; "Less waste and emissions" and "Decoupling resource use from value creation". These pillars need to be evaluated in a coordinated way as, in some cases, conflicting objectives can occur.

As an example, when analyzing reverse logistics of plastic packaging, if the distance to the recycling facility overcomes specific environmental targets, incineration or re-use may be warranted. The implementation of efficient reverse logistic systems represents an enabling factor for an effective transition from a linear to a circular economy [4] [5]. New models and approaches are required to design and manage effective closed-loop networks, where end-of-life products are recovered, reused and remanufactured. Direct and reverse flows have to be effectively synchronized in order to optimize the economic and environmental performances of the system.

The aim of this study is to propose a quick, but effective, assessment method to quantitatively evaluate the "circularity" level of a whole product chain. While literature exists that develops reference models for the circular economy [6] [7] [8], few are able to seamlessly integrate quantitative impacts easily measurable, such as the amount of renewable materials or reusable items – and qualitative ones, which are less tangible, like the extension of a product's life cycle.

When analyzing product chains, adopting the circular economy paradigm forces the development of new measurement indicators. Based on literature reviews and technical reports, we propose a framework to support the development of a set of operational KPIs to "measure" the degree of "circularity" of a specific product chain. The proposed framework is based on the Streamlined Life Cycle Analysis (SLCA) model: traditional LCA analysis are usually expensive, time consuming and often limited in their application as they are strictly dependent on data availability. SLCA is a much quicker and cheaper approach to assessment, which provides a combination of qualitative and quantitative approaches to evaluate such an impact [9] [10].

The proposed methodology aims to integrate a qualitative assessment of the level of circularity to a quantitative measurement of their environmental impact thus allowing a global assessment of benefits due to the adoption of a CE strategy in a product chain.

The paper is organized as follows: in Section 2, a discussion about relationship between CE and environmental sustainability is discussed through a quick literature analysis; an analysis of main critical features characterizing pallet supply chain is in Section 3, the streamlined LCA based methodology and test cases are in Section 4 and 5, respectively. Conclusions and directions for future research are presented in Section 6.

II. Relationships Between Sustainability and Circular economy: a critical analysis

In 1987, the United Nation's World Commission on Environment and Development released the oft-cited report, "Our Common Future" (aka "the Brundtland Report") [11]. The report coined the term "sustainable development" and defined it thusly: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." In the view of the commission, the pursuit of sustainable development requires a number of important components. Among them:

• "an economic system that is able to generate surpluses and technical knowledge on a self-reliant and sustained basis

• a production system that respects the obligation to preserve the ecological base for development

• an international system that fosters sustainable patterns of trade and finance"

Over the past several decades, numerous contributions have helped elucidate the concepts of sustainable development, or more broadly, "sustainability". A wider definition of sustainability [12] includes economic terms, by suggesting that it is "an economic state where the demands placed upon the environment by people and commerce can be met without reducing the capacity of the environment to provide for future generations". In 1994, John Elkington introduced the notion of the "triple bottom line", a concept that encourages the evaluation of activities across financial, social, and environmental dimensions [13]. He later recast the 3 dimensions as "People, Planet, and Profit". McDonough and Braungart [14] utilized an ecological model to describe systems where wastes from processes become inputs to other processes. They sloganized this model with the metaphor "waste = food".

Within the past decade, the notion of the "Circular Economy" (CE) has emerged, in part, as a result of efforts to synthesize several schools of thought on sustainability into a single construct. The circular economy paradigm stands as a potential approach for increasing the efficiency of resource use, and for achieving a better balance and harmony between the economy, the environment, and society. A circular economy is described as: "an economy that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. It is conceived as a continuous positive development cycle that preserves and enhances natural capital, optimizes resource yields, and minimizes system risks by managing finite stocks and renewable flows. It works effectively at every scale. This economic model seeks to ultimately decouple global economic development from finite resource consumption." [15]. The acceptance of the three dimensional sustainability construct was enhanced by the subsequent development of quantitative measures to describe systems. As imperfect and incomplete as they may be, tools like Carbon/Water footprints, Embodied Energy calculations, and Life Cycle Assessment have helped propel the sustainability construct into the public's conscience. Researchers have noted the need for similar tools to quantify the degree of circularity in economic systems [16] [17]. The work of this research develops a framework for assessing the extent to which product supply chains incorporate circular economy principles, and applies this framework to a specific material handling application, the wooden pallet supply chain.

III. The wooden pallet supply chain

The wooden pallet supply chain is a complex product network and the manner in which pallets are managed throughout their lifecycle phases produces a notable difference in terms of environmental and economic impacts [18] [19]. This work explores the impact that decisions made throughout the wooden pallet supply chain phases affect its overall "circularity" level. In Figure 1 we map the wooden pallet supply chain phases to the circular economy pillars. Each of these phases are detailed below, where we point out the main decisions affecting circularity and the most common decision alternatives.

- *Pre-manufacturing phase:* Requires determining the design and material use of the pallets. The main decisions regard (1) material selection, common alternatives are virgin wood (either from responsibly managed forests or not), and recycled wood; (2) pallet type selection, common standardized alternatives are block, and stringer pallet, as well as non-standard pallets.
- *Manufacturing phase:* Requires determining the processes, energy sources, and technologies used to manufacture pallets. The main decisions regard (1) processes and technologies (e.g. "adopting processes and technologies may reduce scraps and improve quality") and (2) energy consumption selection (renewable energy sources or not).
- *Product delivery phase:* Requires determining the type of product delivered on the pallets and the product's supply chain structure. The main decisions regard (1) loading and handling policies of products carried on the pallet; (2) quantity of products per pallet – one pallet per product (e.g., appliances); versus multiple cases per pallet; (3) transportation practices (including type of trucks, loading capacities, and routing policies); and (4) supply chain characteristics (e.g., number of supply chain echelons, number of supply chain participants, global vs. domestic). The first two decisions impact the load of the pallet, which influences the durability and its useful life. The third and fourth influence the distance travelled, as well as the likelihood that policies implemented to create circularity will be successful. For example, pallet pooling providers seek to enter a business arrangement with most large retailers and distributors that receive goods on pooled pallets to ensure reliable return of their pallet assets. Within such arrangements, they become "participant distributors" (PD). PDs contractually guarantee the return of the pooled pallets to the issuing providers, sometimes in exchange for a fee, and through their network of pallet recyclers. This effectively closes the loop and guarantees the eventual return of pallets. However, when pallet users deliver their products to non-participant distributors (NPD), these pallets are effectively considered lost thus impacting the available inventory of assets. Aggravating matters further, the mix of PDs and NPDs is not always known with certainty, changes

dynamically with individual product demands, and is subjected to change at any point in time [20].

- *Customer use:* Requires determining the ownership, tracking, reverse logistics, and repair policies of the pallets by the users of the pallets. There are two main pallet ownership strategies: an open loop approach (known as white wood or limited-use pallets) and a closed-loop approach (such as pallet pooling, or rental systems). Pallets can use technology to improve tracking and thus retrieval of pallets. Reverse logistics policies include *cross-docked* versus *take-back* approaches. Repair policies include either outsourced or in-house repair.
- *End of life*: Require decisions regarding end-of-life scenario choices, which include *incineration, mulching, down-cycling, and landfilling.*

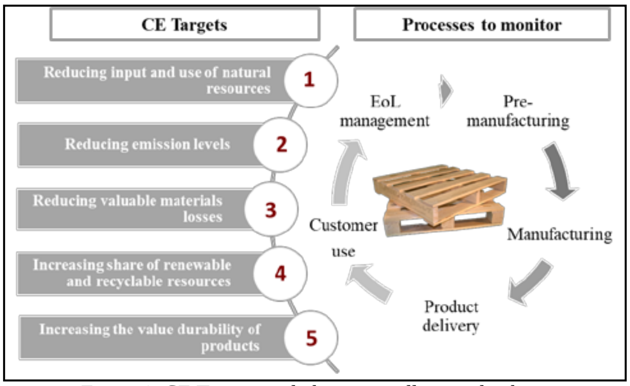

Figure 1. CE Targets and phases in pallet supply chain

Alternatives defined especially at the design (e.g. pallet types and materials), the use (closed or open loops) and end-of-life (e.g., incineration, mulch, and landfill) phases heavily affect its overall "circularity" level. Empirical studies have shown pallet design and service environment conditions can cause a variation of more than 500% in actual durability with an average ranging between 58-298 damage-free handlings [21]. The choice of pallet supply chain management approaches impact circularity, e.g., in an open loop approach, the ownership of the pallet is transferred to the end user with the arrival of the product. In this model, the pallet is not expected to come back to the distributor or manufacturer and it would likely be disposed to a landfill or given a brief use before being discarded. This single-use, open-loop practice, though convenient in some instances, is not sustainable in the long run and results in tremendous waste and resource consumption. *End-of-Life* choices are significant as pallets are estimated to be responsible for 2-3% of all waste landfilled in the U.S. [21].

IV. The Methodology Proposal

The aim is to develop a fast, but effective tool for simultaneously evaluating the degree of adoption of CE principles while providing a quick estimate of the environmental impacts in a product supply chain. The proposed methodology derives from a Streamlined Life Cycle Assessment (SLCA) proposed by [22]. The SLCA is a strategic approach to assess product sustainability (e.g. environmental impacts) faster than traditional LCA methods. Although SLCAs are qualitative in nature, they allow quick identification of the most critical impacts in a product or service throughout the life cycle and with regards to five stressors. Broadly, the proposed method is based on a matrix approach that allows for evaluation of potential impacts of several supply chain stages – including from raw materials production to end of life management- based on selected environmental impacts. Usually, a severity ranking evaluation scale is introduced to quantitatively estimate the environmental performance of the product chain in analysis. Starting from this approach, we propose an SLCA-inspired matrix based methodology aiming to integrate CE strategies and environmental sustainability assessment. A flowchart of this methodology is presented in Figure 2. A description of all steps is detailed next.

Step 1: CE compliance level assessment matrix development. First, the level of adoption of a CE strategy must be checked: thus, an evaluation matrix (defined as matrix 1) is proposed to analyse tools and models adopted (or to be adopted). Matrix 1 assesses quantitatively the level of compliance of a specific pallet supply chain to the CE strategy. The matrix columns are the life cycle phases identified in Section 3 (from pre-manufacturing to manufacturing, product delivery, customer use and end of life); the rows are targets to be fully compliant to a CE strategy (Figure 1). These CE targets have been extracted from a recent European study [23].

CE targets include:

- *Target 1- Reducing input and use of natural resources (T1)*: the focus of this target is to point out alternative solutions that could be adopted in pallet supply chains to increase the productivity of input materials.
- *Target 2- Reducing emission levels (T2):* the focus of this target is to point out alternative solutions that could be adopted in pallet supply chains to reduce energy consumption and emissions from processes.
- *Target 3- Reducing valuable materials losses (T3)*: the focus of this target is to point out alternative solutions that could be adopted in pallet supply chains to increase component re-use or re-manufacturing (this action preserves more value than just recycling the materials).
- *Target 4- Increasing share of renewable and recyclable resources (T4)*: The focus of this target is to share resources (e.g. materials, energy, products, scraps, etc.) in cascade cycles which could be developed also in different product chains. One example is industrial symbiosis.
- *Target 5- Increasing the value durability of products (T5)*: the focus is on alternative solutions that could be adopted in pallet supply chains to increase the length of the product use phase.

TABLE 1. THE MATRIX 1 WITH QUESTIONS

	Target to be achieved				
	Reducing input and use of natural resources	***Reducing emission levels***	***Reducing valuable materials losses***	***Increasing share of renewable and recyclable resources***	***Increasing the value durability of products***
Pre-manufacturing	Are you adopting mixed materials?	Are you adopting standardized pallet structures?	Are you using standardized components?	Are you using certified wood in pallets?	Are you adopting more durable raw materials?
Manufacturing	Are you reducing /recycling scraps in wooden pallet production?	Are you adopting manual process for pallet production?	Are you using refurbished components in pallet production?	Are you using any renewable source of energy?	Are you adopting quality control in manufacturing?
Product delivery	Are you adopting fuel-efficient vehicles?	Are you adopting policies for optimizing pallet delivery?	Are you adopting a tracking system for pallets?	Are you adopting green transportation practices?	Are you supporting appropriate handling of pallets?
Customer use:	Are you adopting closed loops?	Are you adopting any maintenance policy on used pallet?	Are you adopting closed loops with condition tracking system?	Are you using renewable energy sources in remanufacturing/refurbishing?	Are you promoting alternative uses of pallet after its use phase?
End Of Life (EOL)	Are you adopting energy recovery for EOL?	Are you dismantling pallet before landfill?	Are you recycling wood from retired pallets?	Are you adopting pre-emptive pallet remanufacturing? Are you using light loading of pallets?	Are you supporting highest value retirement option for components?

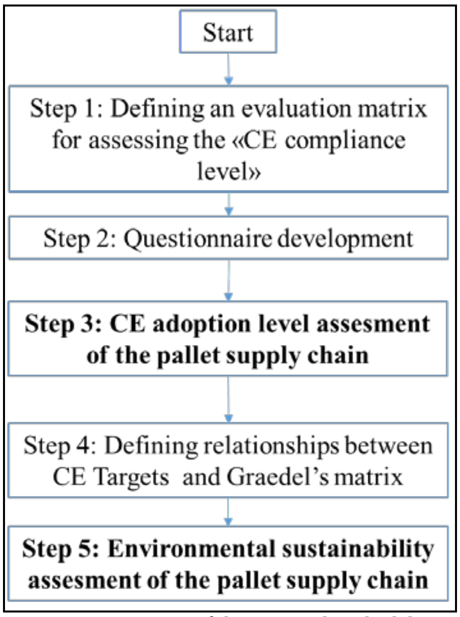

Figure 2. Main steps of the proposed methodology

Step 2: Questionnaire development. Traditionally, the SLCA adopts a questionnaire to support the score assignment process. Questions must be developed for each supply chain stage and for each environmental impact introduced. Thus, differently from the traditional questionnaire [22], we propose a new set of questions to evaluate how such targets characterizing the CE strategies are applied in a specific product chain. A set of 25 questions are developed for each intersection of a CE target and a life cycle phase. A firm should answer these questions to evaluate potential actions adopted (or to be adopted) in each stage of a pallet supply chain. Proposed questions are shown in Table 1.

Step 3: CE adoption level assessment of the pallet supply chain. With the general directive of measuring CE compliance level of a pallet supply chain, rules were defined for this matrix based on the idea that "the higher the score, the better":

- if the answer is yes – i.e. a specific action or behaviour has been adopted; thus, the firm is "compliant" to this CE target. The value to be assigned is 1 as interventions to support CE strategy have been adopted in that phase of a specific pallet supply chain;
- if the answer is no – i.e. no action is developed- the value to be assigned is 0, which denotes non-compliance to a target in a specific life cycle phase.

After answering questions and identifying values for each matrix element, a first qualitative assessment could be carried out at this preliminary stage by summing all values in the matrix. Then, from a strategic point of view, a firm's level of adoption of a CE strategy in the analysed pallet supply chain can be evaluated by the following ranges:

- If the estimated total value is between 0 - 8: the overall level of compliance to CE is low;
- If the estimated total value is between 9 - 17: the overall level of compliance to CE is medium;
- If the estimated total value is between 18 - 25: the overall level of compliance to CE is high.

As CE and environmental sustainability are connected, answers provided at this stage will be connected to the following score evaluation process which aims to quantify the impact of adopting CE strategy by evaluating the overall environmental sustainability of the product chain in analysis.

Step 4: Defining relationships between CE Targets and Graedel's matrix. At this stage, we adopt a traditional SLCA matrix to quantitatively measure the circularity level of a pallet supply chain through quantifying its environmental impact. The Graedel matrix is usually adopted in SLCA to evaluate the overall environmental sustainability of a product/service supply chain. This is a 5x5 matrix where stages in the product chain – i.e. Pre-manufacturing, Manufacturing, Product delivery, Customer use, and End of Life (EOL) – are connected with environmentally-related attributes, i.e. Material choice, Energy use, Solid, Liquid and Gaseous residues. Compared to the traditional Graedel matrix, a shift between rows and column is proposed. As defined previously, given a relationship between CE adoption level and environmental sustainability exists, we propose to adopt results obtained in matrix 1 t to support the score assignment process for matrix 2. Potential connections between targets to be achieved by adopting CE strategy (i.e. rows in the first proposed matrix) and environmentally-related attributes – defined traditionally by [22] - have been connected based on expert judgments. Results are depicted in Figure 3.

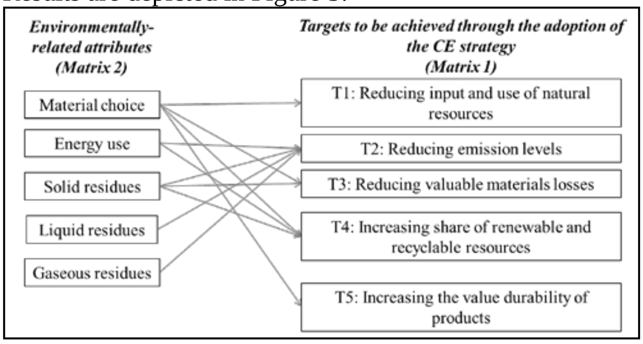

Figure 3. Connection between CE and Environmental sustainability matrix

Thus, based on their specific definitions, connections between CE targets defined in the first matrix and environmentally related attributes introduced in the Graedel matrix are outlined:

- For evaluating the value to be assigned to "Material choice" attribute, answers provided for T1, T3, T4 and T5 questions shall be considered. As an example, if all answers for questions regarding T1, T3, T4 and T5 are negative for a specific life cycle stage, likely the environmental sustainability will decrease; thus scores assigned in the second matrix will be very low;
- For evaluating the value to be assigned to "Energy use" attribute, answers provided for T2 and T4 questions shall be considered;
- For evaluating the value to be assigned to "Solid residues" attribute, answers provided for T2 and T4 questions shall be considered;
- For evaluating the value to be assigned to "Liquid residues" and "Gaseous residues" attribute, answers provided for T2 questions shall be considered.

These qualitative relationships will substitute traditional questions used by [22] to support the score assignment process in the environmental sustainability matrix.

Step 5 Environmental sustainability assessment of the pallet supply chain. The evaluation scale – from 4 to 0- traditionally proposed by Gradel has been adopted:

- 4 equal "No impact";
- 3 equal "Better than average";
- 2 equal "Average";
- 1 equal "Poorer than average"
- 0 equal "Very high impact".

The first and second matrix have common row values, i.e. stages characterizing the pallet supply chain; thus, answers provided for the first matrix assessment process could be used to provide scores to be assigned in the second matrix elements.

Once an evaluation has been made for each (second) matrix element the overall *Environmentally Responsible Product Rating* (R_{ERP}) is computed as the sum of the matrix element values

$$R_{ERP} = \sum_i \sum_j M_{i,j}$$

where i is the row value, j is the column, M_{ij} is the score assigned to each matrix element.

Because there are 25 cells in the matrix (with values of 0 to 4), a maximum rating of 100 can be obtained outlining the best performance in terms of environmental sustainability.

TABLE 2. THE ENVIRONMENTAL SUSTAINABILITY MATRIX (I.E. MATRIX 2)

	Environmentally-related attribute					
	Material choice	*energy use*	*solid residues*	*Liquid residues*	*Gaseous residues*	*total*
Pre-manufacturing						
Manufacturing						
Product delivery						
Customer use:						
End Of Life (EOL)						

V. THE TEST CASE

Two configurations of pallet supply chains are introduced to validate the proposed methodology. Supply chain stages, decisions, and alternatives for the two cases are described next.

A. Case A:

Pre-manufacturing: Pallet type A is an inexpensive, "whitewood" 48 inch x 40 inch pallet. Pallet A started out as a 60 foot (20 meter) tall white pine tree in a softwood forest in upstate NY. The pine was cut down in the woods, the limbs were removed and the tree was trucked to a mill 50 miles from the forest. At the mill, the tree was debarked and then sectioned into various grades of lumber. The core of the tree became a 8 inch x 8 inch x 48 inch "cant" from which pallet components would be cut. The waste material from the milling operations (sawdust, bark, wood chips) was collected and set aside for use as landscape mulch, animal bedding, and fuel for an onsite boiler system.

Manufacturing: The cant was cut into pallet components (stringers, deck boards).

TABLE 3. FIRST MATRIX RESULTS FOR THE TWO PALLET SUPPLY CHAINS

	Target											
	T1		**T2**		**T3**		**T4**		**T5**		**Total**	
	Case A	Case B	Case A	Case B	Case A	Case B	Case A	Case B	Case A	Case B	Case A	Case B
Pre-manufacturing	0	0	1	1	1	1	0	0	0	1	2	3
Manufacturing	0	0	1	1	0	0	0	0	0	0	1	1
Product delivery	0	0	0	0	0	0	0	0	0	1	0	1
Customer use	0	1	0	1	0	0	0	0	0	1	0	3
EOL	0	1	0	1	0	1	0	0	0	1	0	4
										Final Score	**3**	**12**

Product delivery: Pallets were usually shipped from the lumber yard via truck 200 miles to a manufacturer of high end bathroom fixtures.

Customer use: At this location, pallets were loaded with toilet components and shipped via truck to final customers. No reverse logistics is applied, as pallets are single use. In this case, ownership of the pallet was transferred along with ownership of the pallet load, so the pallet belonged to the end customer.

EOL: As the end customer had no applications for a used pallet, it was relegated to the municipal solid waste stream and disposed of in a landfill.

B. Case B

Pre-manufacturing: Pallet type B is a robust, 48 inch x 40 inch stringer pallet. It started out as 60 foot (20 meter) tall white ash tree in a mixed hardwood forest in upstate NY. The ash tree was cut down in the woods, the limbs were removed and the tree was trucked to a mill 50 miles from the forest. At the mill, the tree was debarked and then sectioned into various grades of lumber. The core of the tree became a 8 inch x 8 inch x 48 inch “cant” from which pallet components would be cut. The waste material from the milling operations (sawdust, bark, wood chips) was collected and set aside for use as landscape mulch, animal bedding, and fuel for an onsite boiler system.

Manufacturing: The cant was cut into pallet components (stringers, deck boards).

Product delivery: Pallets were shipped from the lumber yard via truck 200 miles to a large manufacturer of pharmaceutical products.

Customer use: These pallets entered a “pool” of recirculating pallets, managed by third party on behalf of the pharmaceutical manufacturer. At this location the pallet was loaded with pharmaceutical products and shipped via truck 500 miles to a distribution center. From the DC, the pallet load was shipped 200 miles to a retail location. After being unloaded at the retail location, the pallet was returned to a pallet repair depot (50 miles via truck) where inspection revealed that one lead-board needed to be replaced. The repair was made, the pallet was heat treated, and then returned to the pharmaceutical manufacturer (500 miles via truck). This cycle (manufacturer → distribution center → repair center → manufacturer) was repeated several times until, at the repair center, the pallet was deemed unrecoverable. At this point the pallet was retired.

EOL: Old pallets were shredded using a diesel powered “Wood Hog”. The steel nails were recovered for recycling and the mulched wood was set aside for use as landscape mulch and boiler fuel.

C. Analysis

Based on these data, the proposed methodology has been applied for comparing the two pallet supply chains. At first, based on questionnaire development proposed in the previous section, the first matrix regarding the CE compliance level has been compiled for each test case: results are reported in Table 3. Data show a higher CE compliance for the Case B (the final score 12 versus 3). The higher CE compliance is due to the contribution of two phase “Customer use” and “EOL” where the two supply chains adopt different logistics solutions. The cases adopt closed (Case B) versus open loops (Case A), as well as have different maintenance policies and end-of-life strategies.

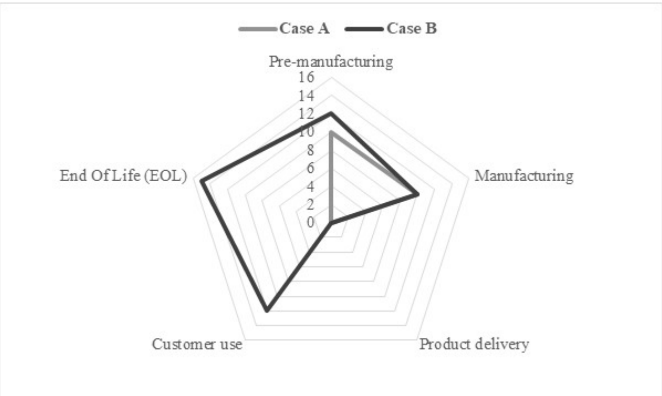

Figure 4. Total score estimated for Case A and B for each phase in the pallet supply chain

Next, the second matrix has been compiled based on qualitative relationships outlined between CE targets and environmental sustainability attributes (see previous section). Results obtained shows R_{ERP} equal to 20 and 49 for case A and case B, respectively. These data confirm the previous result obtained for case B: it is also characterized by a higher value of environmental sustainability.

VI. Conclusions and Future Research

CE is an emergent strategy for increasing environmental performance of product chains all over the world. Few recent papers have assessed how the adoption of a CE strategy could modify environmental sustainability of such a supply chain.

This paper proposes a matrix approach based on streamlined LCA to evaluate in a systematic way how the level of adoption of the CE strategy could influence the environmental sustainability of a product chain. Two matrixes have been used: the first one for assessing the overall compliance level to CE strategy of a specific supply chain. The latter allows firms to quantify environmental sustainability using a traditional streamlined LCA matrix. Differently from the traditional matrix, the score assignment process is now developed by evaluating results obtained in the first evaluation matrix, i.e. based on the estimated compliance level to CE. The methodology has been developed for a specific product chain: the pallet supply chain. Although pallets are low-price products, the quantity used in logistics activities all over the world is huge. In addition, pallets exhibit characteristics that make them ideal as a use case: (1) varying open and closed loop business models are common; (2) repair and remanufacturing are possible; and (3) different end-of-life scenarios exist.

The developed methodology has been applied to compare two different test cases of pallet supply chains; results obtained illustrate the potential of the developed methodology in comparing complex supply chains.

Further developments are needed to better align the connections between the two matrixes. This will create a quantitative way to better outline connections between the adoption of CE and environmental sustainability performance in a supply chain.

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