ECO-DESIGN OF BOVINE HIDES AND ITS IMPACT ON THE GLOBAL WARMING POTENTIAL OF AUTOMOTIVE LEATHER

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ABSTRACT

The mitigation of anthropogenic global warming is seen as a challenge that requires coordinated action to be successful. The industrial sector appears as one that can achieve significant results relatively quickly, given its intensive use of natural resources and capacity for innovation. Among them, the automotive sector is a key player, both in the selection of energy sources and in the choice of materials that constitute the vehicles themselves. Life Cycle Assessments are essential so that automotive companies can conduct their research, development, and innovation processes quantitatively, measuring the impact of eco-design efforts on reducing emissions throughout the value chain. However, decisions are still made in a fragmented manner, so the potential to redesign production flows in a holistic way is underutilized. This paper fills a gap in the literature, exploring an integrated view of leather production - used in the upholstery of seats and other vehicle interior components - to question whether eco-design efforts have the potential to significantly reduce greenhouse gas emissions in the chain. The experiment proposed two alternative designs for bovine hides, measuring their emissions in the material's production chain and expanding the conventional boundaries of analysis to understand the impact of eco-design on material cutting efficiency. The results indicated that alternative designs for bovine skin have the potential to reduce the emissions added by leather to the total carbon footprint of the automobile.

Keywords: GHG Emission Reduction, Automotive Leather, Climate Change Mitigation, Co-production, Leather, Eco-design

1. Introduction

One of the most important challenges facing humanity in the 21st century is addressing climate change caused by anthropogenic global warming (IPCC AR6, 2021). In this context, Life Cycle Assessments (LCAs) are commonly used to quantify the externalities of production chains, enabling environmentally responsible and potentially transformative decision-making. However, a common frustration is that LCAs often limit themselves to cradle-to-gate system boundaries, which, in the case of leather production, extend from the sourcing of fresh hides to the finished leather. This approach evaluates the impacts of material production but ignores environmentally relevant downstream phases of the production chain. Among these are the leather cutting into final pieces, product assembly, use and end of life. Leather that performs better in the cutting room — where the utilization of their total area into useful pieces for sewing is high — exhibit better environmental and economic outcomes, as fewer inputs and raw materials are required to produce each piece. Thus, understanding which factors can influence the maximization of cutting efficiency is crucial for the environmental efforts of the sector.

A significant opportunity for addressing the decarbonization challenges in the use of leather for automotive seats lies in the fact that bovine hides, as a by-product of the animal protein production chain, are purchased by tanneries in the original shape generated during the dehiding process at the slaughterhouse. The hide can represent 3.5% of a slaughterhouse's total revenue (European Commission, 2018), but the general perception that this number is obsolete directed this work to obtain primary and updated data for this value.

Purchasing the hide by weight and selling it by area, the tannery's natural and traditional logic is to preserve the largest possible area. However, this rationale is detrimental from an environmental efficiency standpoint. Parts that are processed and continue in the value chain are often unsuitable for use, whether they have very narrow extremities or areas with a high concentration of natural marks, such as tick bites or wounds. Thus, later, during the cutting stage of the finished leather, something that could have been previously trimmed and directed as raw material for another production chain (such as gelatin, for example) ends up becoming waste.

It is also crucial to consider that value chains are often fragmented, with multiple parties performing distinct industrial activities. From a holistic perspective, the efficiency achieved in the process influences the environmental impact of the parts as well as the whole, making it essential to unlock an integrated and collaborative view of relevant variables for successful decarbonization journeys, together with the reduction of other environmental impacts (Jiang et al., 2019).

When conducting na LCA, the system boundaries to be considered depend on the objectives of the analysis being carried out (Häfliger et al., 2017). Inadequate selection of system boundaries and functional units can lead to low confidence in the analyses or to erroneous conclusions, and consequently, to decision-making with results contrary to the intended objectives (Reap et al., 2008).

Consumer goods companies can also focus their design, research, and industrial efforts on developing lower-emission, more durable, transparent products that are industrialized according to a circular logic (Klassen & Whybark, 1999; Pagell & Wu, 2009). According to Liu et al. (2021), at least 80% of the environmental impact of a production chain is a consequence of the design phase. In this sense, eco-design is an approach that allows the integration of environmental variables into the process of product and process conception and development, aiming to minimize their environmental impacts throughout the life cycle (Boks, 2006).

A life cycle thinking approach unlocks naturally limited views of the responsibility of each production stage in the total impact of the product. It then becomes possible to engage in proactive and long-term collaboration between different links in the chain for a lower environmental impact, which is fundamental for achieving the globally outlined climate goals (Beske & Seuring, 2014).

The present work aimed to expand the system boundaries generally considered for an LCA of a material like Leather — including the leather cutting stage — and to evaluate the effect that different eco-design proposals for bovine hides would have on the contribution of leather to the total greenhouse gas (GHG) emissions in the production of automotive seats.

2. Material and Methods

The experiment in question was structured to compare the Global Warming Potential over 100 years (GWP100) from a Life Cycle Assessment (LCA) perspective.

Since leather is a natural material with an irregular surface and natural marks generated during the animal's life (Omoloso et al., 2021), it is crucial to quantify the environmental impact of its value chain by taking into account the cutting efficiency. This means focusing on the environmental impact per net area of leather rather than per gross area.

2.1 Experiment Design

The experiment focused on Brazilian zebu bovine leather produced for automotive upholstery. Two leather design formats were proposed to verify whether this intervention would impact the material's global warming potential.

Since this intervention would affect the material balance of the process due to its impact on the mass generation of different collagenous co-products and the leather itself, it is understood that interventions in the formats alone would influence the global warming potential of the leather from such production processes. To properly quantify the impact of the proposed designs, the study expanded the conventional system boundaries: instead of focusing solely on cradle-to-gate processes (in this case, from farm to finished leather), the cutting stage of leather into automotive seat parts was also considered, thus measuring the impact of the leather format on cutting efficiency. The dependent variable to be monitored would be the global warming potential per net area, expressed in kg CO2 eq. / m² net, instead of kg CO2 eq. / m² gross.

To achieve this goal, the experiment was designed with the isolation of the Cutting Yield variable at the end of the process—calculated as shown in Equation 1—while ensuring that the other variables remained stable across sample groups. To achieve this, the supplier slaughterhouse was selected for having a low standard deviation in hide sizes, ensuring that the sample groups would have similar leather sizes.

$$Cutting\ Yield = \frac{Net\ Area\ (m^2)}{Gross\ Area\ (m^2)} \qquad (1)$$

2.2 Variables and Measurements

In addition to the variables whose data were individually collected for each leather, multiple other pieces of information were necessary for the execution of the LCAs. To enable proper material allocation in products, co-products, and waste, the dry matter content of the hide, leather, co-products, and waste generated at each stage of the process was measured in the laboratory. Combined with the material balance of each of the three leather format proposals evaluated in this study, three independent LCAs were conducted.

2.3 Statistical Analysis

For the statistical analysis phase, non-parametric methods were used given the nature of the results obtained from the experiment, which demonstrated non-normal characteristics in the statistical data. The Shapiro-Wilk test was used to test the normality of the variable Cutting Yield (Dudley, 2012). To assess whether there was a difference between the medians of three groups of independent samples, two sequential non-parametric tests were used: the Kruskal-Wallis test (Dodge, 2008) and the Dunn test (Dinno, 2015) for multiple comparisons.

2.4 System Boundary Expansion

To properly assess the impact of the intervention in the leather design on the climate change impact of the production of the material, it was decided to include the leather cutting stage in the quantitative measurement based on an expansion of the system boundaries. To this end, the expanded GWP (GWP100exp) was calculated according to the expression established in Equation 2.

$$GWP100_{exp} = \frac{\text{GWP100}}{Cutting\ Yield} \quad (2)$$

3. Results and Discussion

The difference established between the three sample groups was solely related to the format assigned to the hides at the stage of limed hides before tanning. The segregation of the sample groups occurred after the second fleshing stage, when the hides had already gone through the stages of fresh hide trimming, first fleshing, soaking, and liming.

Subsequently, the hides were individually identified according to their sample groups and numbered in ascending order from 1 to 200 with holes and scratches on the grain, allowing for traceability hide by hide throughout the process.

After segregation and identification, the 600 hides (200 for each sample group) went through the splitting process. After splitting, the three distinct sample groups underwent the design differentiation proposed in this experiment. At this stage, the collagen-rich material had not yet undergone definitive chemical transformations, thus maintaining its mechanical, functional, and nutritional properties (Joseph & Nithya, 2008). The bovine hide at this point is commonly known as limed hide. The differentiation was carried out using pneumatic knives to cut the bovine hides at the limed hide stage into three pre-established distinct patterns.

- Shape A:

The hide is treated conventionally. Only excess fat and very irregular parts are trimmed. This production method can be considered the international standard in the market, aiming to maximize the preserved hide area. Two examples of zebu hides at the limed stage without interference in their conventional format can be seen in Figure 1.

Figure 1 – Limed hides in Shape A (conventional).

- Shape B:

Two longitudinal cuts were made on each side of the hide, removing two contiguous strips along its entire length. Additionally, transverse cuts were made in the neck/head area, following the hide's shape. Finally, any potential non-usable shapes generated were also removed. Figure 2 shows the hide trimming and its shape after the intervention.

Figure 2 - Hides at the limed stage in Shape B. On the left, the hide before the intervention; in the middle, an example of the trimming; and on the right, the shape after the intervention.

- Shape C:

Longitudinal trimmings were made to a lesser extent than in Shape B, merely ensuring greater homogenization of the hide's edges. In the neck/head area, the trimming is done similarly to Format B. Figure 3 shows the hide trimming according to Shape C.

Figure 3 - Hides at the limed stage in Shape C. On the left, the hide before the intervention; in the middle, an example of the trimming; and on the right, the shape after the intervention.

After the differentiation, the hides were once again gathered and kept mixed for the Tanning stage onwards up to the finished leather cutting stage, avoiding the impact of other variables, with data being collected for every material input or output. As they were individually identified, this allowed for the identification of hides at any stage for data collection purposes.

At the tanning stage the hide is converted into leather in a rotating drum called a Drum. Tanning is a crucial and symbolic step in the production process, as it is when the hides undergo a chemical stabilization process. This step involves the transformation of biological substrates into materials that resist bacterial biodegradation (Covington, 2019), making them non-putrescible (Joseph & Nithya, 2008). For this study, the most widely used leather tanning technology was employed, which is tanning with chromium sulfate. After tanning, the leather undergoes multiple physical and chemical processes focused on the automotive sector application.

A central aspect of the present study's proposal was the expansion of the conventional boundaries of a leather Life Cycle Assessment (LCA) system to account for the impact of cutting yield on the product's global warming potential. For the study, all leather pieces that made up the interior of a compact SUV vehicle were considered. Typically, leather is currently used only in the seat parts that come into contact with the user's skin. For the rear and underside regions of the seats, polymer-based materials, such as polyurethane (PU) or polyvinyl chloride (PVC), are generally applied.

The same automotive kit was used to cut all three sample groups, with cutting yield being measured per piece. In the vehicle interior in question, leather was present in eight components, namely: Left front headrest; Right front headrest; Left front seat; Right front seat; Complete rear seat; Left rear headrest; Center rear headrest; Right rear headrest. Figure 4 exemplifies the cutting process carried out for all hides.

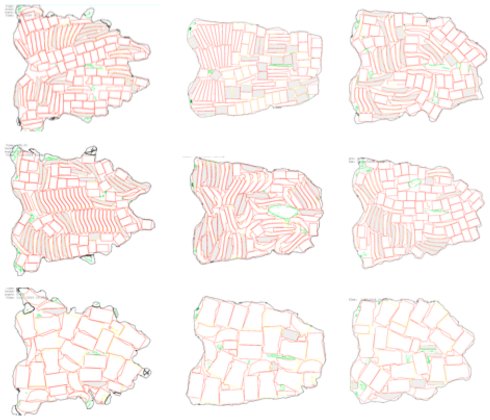

Figure 4 - Pieces positioned for cutting. On the left, hides of Shape A; in the center, Shape B; and on the right, Shape C.

3.1 Variables and Measurements

Crucial for understanding the impact of interventions on the generation of co-products was the calculation of the Co-production Rate, which is the percentage of the total mass of the fresh hide received by the tannery that was allocated to other value chains as raw material. The co-production results are expressed in Table 1.

Table 1 – Co-production rate

	Shape A		Shape B		Shape C	
	Gross Matter (kg)	Dry Matter (kg)	Gross Matter (kg)	Dry Matter (kg)	Gross Matter (kg)	Dry Matter (kg)
Total Co-products	37.99	11.52	43.82	12.93	43.50	12.51
Co-production Rate	78.36%	69.01%	90.39%	77.46%	89.72%	74.97%

Source: Author

Table 1 shows that Shape B has the highest Co-production Rate, while Shape A results in the lowest generation of co-products. The higher co-production in Shapes B and C was expected, as the hides are cut to a greater extent.

3.2 Life Cycle Assessment

Three distinct attributional LCAs were conducted, one for each sample group. These were carried out according to ISO 14040 and 14044:2006 standards. Modeling was performed using the IPCC AR6 GWP 100 method, excluding biogenic CO_2 (IPCC 2021), utilizing the SIMAPRO 9.4.0.2 tool and the ECOINVENT 3.8 database. The emissions inventory used for cattle farming was the "Beef cattle {BR} | technology mix | production mix, at farm | 1 kg of live-weight | LCI result," available in the Environmental Footprint 3.1 - Agrofoods database. Its selection was based on seeking greater geographical representativeness and data quality. Allocation was conducted according to the guidelines established by the Product Environmental Footprint Category Rules Guidance Version 6.3 of May 2018 (European Commission, 2018), commonly known as PEFCR Guidance. The system boundaries initially set for the LCAs were from cradle-to-gate of the automotive leather production value chain, covering from the sourcing of raw materials and inputs to the production of the finished product.

3.3 Environmental Indicators

Table 2 displays a comparison between the shapes, with percentage results expressing the differences relative to Shape A. It shows a consistent improvement in environmental indicators when comparing Shapes B and C to the original Shape A.

Table 2 - Comparison of environmental indicators. Percentage data establishes a comparison with Format A

	Measurement Unit	Shape A	Shape B	%	Shape C	%
Raw Material	kg/m²	3.38E+00	2.95E+00	-13%	3.00E+00	-11%
Allocated Water	l/m²	7.21E+01	6.36E+01	-12%	6.57E+01	-9%
Thermal Energy	kWh/m²	3.03E+00	2.79E+00	-8%	2.75E+00	-9%
Electric Energy	kWh/m²	2.27E+00	2.37E+00	4%	2.20E+00	-3%
Chemicals	kg/m²	2.02E+00	1.89E+00	-6%	1.90E+00	-6%
Transportation	tkm/m²	7.53E+00	7.39E+00	-2%	7.40E+00	-2%
Emissions to Water	g/m²	1.76E+02	1.61E+02	-8%	1.64E+02	-7%
Waste	kg/m²	1.85E+00	1.50E+00	-19%	1.69E+00	-9%
Effluent	l/m²	6.44E+01	5.69E+01	-12%	5.87E+01	-9%

Source: Author

3.4 Absolute Results of Global Warming Potential from Cradle-to-Gate

A horizontal comparison between the three designs can be seen in Table 3, which establishes the relative difference in impact using Shape A as the reference. It is noted that the results for Shapes B and C showed lower values than the ones for Shape A.

Table 3 - Comparison of Global Warming Potential by Net Area. Relative data uses Shape A as the reference

	GWP100 (kg CO_2 eq. / gross m²)	%
Shape A	1.06E+01	-
Shape B	9.63E+00	-9.54%
Shape C	9.75E+00	-8.46%

Source: Author

3.5 Cutting Yield

After cutting the leather, it was possible to compare the cutting yield of the three sample groups. Table 4 presents the descriptive statistics of the database constructed for the tests, including the variables of Cutting Yield, Gross Area, Net Area, and Waste Area. Additionally, the table presents the sample size, considering the aggregated value of the three shapes in the Cutting stage. The other columns present statistical measures of range (Minimum, Maximum, and IQR - interquartile range), the Median, the Mean, and the Standard Deviation.

Table 4 - Descriptive statistics of the cutting stage

	Measurement Unit	n	Min.	Max.	Median	Interquartile Range (iqr)	Mean	Standard Deviation
Cutting Yield	%	586	0.645	0.891	0.755	0.05	0.756	0.038
Gross Area	m^2	586	2.55	5.64	4.34	0.853	4.31	0.55
Net Area	m^2	586	1.79	4.36	3.28	0.554	3.25	0.396
Waste Area	m^2	586	0.447	1.76	1.04	0.343	1.06	0.242

Source: Author

It can be noted that out of the 600 hides originally designated for the experiment, only 586 proceeded to the cutting stage, representing 97.7% of the total. The 14 missing hides were discarded due to process reasons, such as deformation or the presence of stains.

Table 5 displays the descriptive statistics for the leather cutting stage by Shape.

Table 5 - Descriptive Statistics of Cutting Yield by Shape

Shape	n	Min.	Max.	Median	Interquartile Range (iqr)	Mean	Standard Deviation
A	197	0.645	0.891	0.731	0.041	0.731	0.034
B	198	0.670	0.857	0.769	0.046	0.770	0.034
C	191	0.691	0.881	0.765	0.038	0.767	0.031

Source: Author

3.5.1 Kruskal-Wallis Test

The Kruskal-Wallis test resulted in a p-value lower than 5% for all four tested variables (Cutting Yield, Gross Area, Net Area, and Waste Area), indicating that the hypothesis that all medians are equal was rejected for each. Therefore, it is assumed that there is a statistical difference in at least one of the comparisons. Table 6 displays the results of the Kruskal-Wallis tests for the different analyzed variables.

Table 6 - Kruskal-Wallis Test results

	p
Cutting Yield	8.77E-33
Gross Area	2.63E-93
Net Area	2.13E-71
Waste Area	1.23E-79

Next, an effort was made to identify which shapes showed differences between the medians of cutting yield.

3.5.2 Dunn Test

The Dunn Test allows for evaluating which groups showed statistical differences that could infer distinctions. This result is crucial for properly testing the hypothesis that intervention in the leather design would bring significant differences in GHG emissions from the process. Table 7 presents the results of the statistical tests for the Cutting Yield variable.

Table 7 - Dunn Test for Cutting Yield

Shapes		N Sample		Statistical Parameters		
Group 1	Group 2	N1	N2	Statistics	p	p-adj
A	B	197	198	11.0	5.19e-28	1.56e-27
A	C	197	191	9.98	1.87e-23	5.61e-23
B	C	198	191	-0.895	3.71e-01	1.00e+00

Source: Author

It can be observed that the adjusted p-value was lower than 5% for the comparisons A-B and A-C, indicating that there is a statistical difference in cutting yield between Shapes A and B, as well as between Shapes A and C. In other words, the shapes representing eco-design have significant differences in cutting yield when compared to the benchmark in Shape A. When comparing Shapes B and C, no statistical difference could be identified.

3.6 System Boundary Expansion

After exploring the cradle-to-gate LCA results and the cutting yields, to properly test the hypothesis in this experiment, the system boundaries were expanded. To provide a broader view of the supply chain compared to cradle-to-gate LCAs, a new functional unit that included the cutting stage was defined (Reap et al., 2008). By analyzing impacts per Net Area instead of Gross Area, it is possible to understand more comprehensively the effect of interventions in the design of bovine hides on the Global Warming Potential. Thus, the results shown in Table 8 were obtained by dividing the median by the cutting yield.

Table 8 - System Boundary Expansion with the Inclusion of the Cutting Stage

	GWP100 (cradle-to-gate)	Cutting Yield	$GWP100_{exp}$ (expansion)
	kg CO_2 eq. / gross m^2	net m^2 / gross m^2	kg CO_2 eq. / net m^2
Shape A	10.60	0.731	14.50
Shape B	9.63	0.769	12.52
Shape C	9.75	0.765	12.75

Table 9 compares the GWP100 results when considering Net Area as the functional unit. Comparing these results with those based on Gross Area shown in Table 3, it is noted that the differences between both Shapes B and C and Shape A are more pronounced. While the difference from cradle-to-gate between Shape A and the average of Shapes B and C is 9.00%, expanding the system boundaries increases this difference to 12.88%. This fact is explained by the greater cutting efficiency observed in these formats.

Table 9 – Comparison of Global Warming Potential by Net Area. Relative data uses Shape A as the reference

	$GWP100_{exp}$ (kg CO_2 eq. / net m²)	%
Shape A	1.45E+01	-
Shape B	1.25E+01	-13.64%
Shape C	1.27E+01	-12.11%

4. Conclusions

4.1 Main Results and Contributions

Long-term and short-term choices by companies and governments have a direct impact on the global economy and environmental preservation. Therefore, in relation to supply chains, it is crucial to understand how such decisions impact their externalities (Söderholm & Tilton, 2012).

In the assessment proposed by this study, it was observed that intervention in the design chosen for the trimming of hides is an important route for maximizing coproduct generation and cutting yield for automotive seats, thereby increasing the efficiency of the supply chain and reducing total GHG emissions per square meter of net material used. For the experiment in question, this fact was statistically confirmed by the analytical process which indicated a difference in Cutting Yield among the shapes. Thus, even though eco-designs showed higher global warming potential results, the fact that they demonstrate higher cutting yield and coproduct rate suggests the need for further investigation, as these benefits would not be covered in a cradle-to-gate LCA of automotive leather.

Practically, for advancing in the decarbonization of the automotive sector, the conclusion is that these differences are relevant in supporting the decision-making in the business realm, such as formulating more environmentally responsible seating portfolios and cleaner production processes, with lower waste generation and impacts throughout the entire production chain.

In alignment with Hertwich and Wood (2018) and Söderholm and Tilton (2012), the pursuit of efficiency in the use of resources through better practices in the leather cutting stage proves feasible and has implications for the impact across the entire product lifecycle. Advancing to process and product designs that propose more sustainable production systems is a pressing challenge for the upholstery industry, with the exploration of the implications of product and process design being an important route for scientific and industrial investigation.

4.2 Recommendations for Future Research

For future research, it is expected to integrate cutting yield studies into LCAs of leather from other sources and applications to determine whether the potential benefits of interventions observed in this study are valid for other production systems. Due to the nature of the products, leather for furniture upholstery or accessories like watches and bracelets have considerably different quality requirements, which has significant implications for the Cutting Yield. Future studies could explore the consequences of piece sizes and shapes on production process efficiency.

Exploring different tanning methods (e.g., vegetable tannins, zeolites) would also be important, as the different nature of the leather implies changes in material flows: some that were previously waste may become co-products or vice versa. Additionally, a change in the tanning method could affect other key variables such as leather expansion rates in each production stage.

As highlighted by Kong et al. (2016) and Liu et al. (2021), within the scope of research and business innovation it is also crucial to point out the significant opportunity for creative collaboration between automotive seat designers and tanneries. In this context, it would be possible to adjust leather designs, seat designs, or the synchronization of both to maximize material utilization. This endeavor is surrounded by complexities motivated by aesthetic aspirations but would likely generate significant economic and environmental gains. This collaborative approach could also be extended to other aspects of the value chain, such as optimizing transportation or managing packaging and waste (Habib et al., 2022), ultimately creating value for the entire chain, including the final consumer (Flynn et al., 2009).

From a broader perspective, it is essential to expand the understanding of how to integrate process traceability practices and foster internal and matrix capabilities within supply chains (Garcia-Torres et al., 2018). Its intrinsic complexity should also prompt questions about potential improvements in collaborative governance for sustainability within the supply chain (Fraser et al., 2020).

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REFERENCES

BESKE, Philip; SEURING, Stefan. Putting sustainability into supply chain management. **Supply Chain Management: An International Journal**, p. 322-331.

BOKS, Casper. The Soft Side of Ecodesign. **Journal of Cleaner Production** , v. 14, p. 1346-1356, 11 December 2006. DOI https://doi.org/10.1016/j.jclepro.2005.11.015. Available: https://www.sciencedirect.com/science/article/abs/pii/S0959652605002428.

COVINGTON, Anthony. **Tanning chemistry**: The Science of Leather, 2019.

DINNO, Alexis. Nonparametric Pairwise Multiple Comparisons in Independent Groups Using Dunn's Test. **The Stata Journal**, v. 15, n. 1, p. 292-300, 01 April 2015. DOI https://doi.org/10.1177/1536867X1501500117. Available: https://journals.sagepub.com/doi/10.1177/1536867X1501500117.

DODGE, Yadolah. **The Concise Encyclopedia of Statistics**: With 247 Tables. 2008. ISBN 978-0-387-32833-1

DUDLEY, R. The Shapiro-Wilk Test for Normality. **MIT Mathematics**, 12 September 2012. Available: https://math.mit.edu/~rmd/46512/shapiro.pdf.

IPCC AR6 (Intergovernmental Panel on Climate Change). Summary for Policymakers. In: MASSON-DELMOTTE, V., P. ZHAI, A. PIRANI, S. L. CONNORS, C. PÉAN, S. BERGER, N. CAUD, Y. CHEN, L. GOLDFARB, M. I. GOMIS, M. HUANG, K. LEITZELL, E. LONNOY, J.B.R. MATTHEWS, T. K. MAYCOCK, T. WATERFIELD, O. YELEKÇI, R. YU AND B. ZHOU (Eds). Climate Change 2021:The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2021.

EUROPEAN COMMISSION. Version 6.3 – May 2018. **Product Environmental Footprint Category 2 Rules Guidance**, 07 May 2018. Available: https://eplca.jrc.ec.europa.eu/permalink/PEFCR_guidance_v6.3-2.pdf.

FLYNN, Barbara; HUO, Baofeng; ZHAO, Xiande. The Impact of Supply Chain Integration on Performance: A Contingency and Configuration Approach. **Journal of Operations**

Management, v. 28, n. 1, p. 58-71, 17 June 2009. DOI http://dx.doi.org/10.1016/j.jom.2009.06.001. Available: https://onlinelibrary.wiley.com/doi/10.1016/j.jom.2009.06.001.

FRASER, Iain; MULLER, Martin; SCHWARZKOPF, Julia. Transparency for Multi-Tier Sustainable Supply Chain Management: A Case Study of a Multi-tier Transparency Approach for SSCM in the Automotive Industry. **Sustainability**, v. 12, n. 5, p. 1-24, 28 February 2020. DOI http://dx.doi.org/10.3390/su12051814. Available: https://www.mdpi.com/2071-1050/12/5/1814.

GARCIA-TORRES, Sofia; ALBAREDA, Laura; REY-GARCIA, Marta; SEURING, Stefan. Traceability for sustainability – literature review and conceptual framework. **Supply Chain Management**, v. 24, n. 1, p. 1-24, 04 October 2018. DOI 10.1108/SCM-04-2018-0152. Available: https://www.emerald.com/insight/content/doi/10.1108/SCM-04-2018-0152/full/html.

HABIB, Mohammad; BALASUBRAMANIAN, Sreejith; SHUKLA, Vinaya; CHITAKUNYE, David; CHANCHAICHUJIT, Janya. Practices and Performance Outcomes of Green Supply Chain Management Initiatives in the Garment Industry. **Management of Environmental Quality**, v. 33, n. 4, p. 1-37, 22 February 2022. Available: https://www.emerald.com/insight/content/doi/10.1108/MEQ-08-2021-0189/full/html.

HÄFLIGER, Ian-Frederic; JOHN, Viola; PASSER, Alexander; LASVAUX, Sebastien; HOXHA, Endrit; SAADE, Marcella; HABERT, Guillaume. Buildings Environmental Impacts' Sensitivity Related to LCA Modelling Choices of Construction Materials. **Journal of Cleaner Production**, v. 156, p. 805-816, 10 July 2017. DOI https://doi.org/10.1016/j.jclepro.2017.04.052. Available: https://www.sciencedirect.com/science/article/abs/pii/S0959652617307618.

HERTWICH, Edgar; WOOD, Richard. The growing importance of scope 3 greenhouse gas emissions from industry. **Environmental Research Letters**, v. 13, n. 10, p. 1-10, 5 October 2018. DOI https://doi.org/10.1088/1748-9326/aae19a. Avaiable: https://iopscience.iop.org/article/10.1088/1748-9326/aae19a.

JOSEPH, Kurian; NITHYA, N. Material flows in the life cycle of leather. **Journal of Cleaner Production**, p. 676-682, 21 December 2008. DOI 10.1016/j.jclepro.2008.11.018. Available: https://www.sciencedirect.com/science/article/abs/pii/S0959652608002916.

KLASSEN, Robert D.; WHYBARK, D. Clay. The Impact of Environmental Technologies on Manufacturing Performance. **The Academy of Management Journal**, v. 42, n. 6, p. 599-615, 17 December 1999. Available: http://www.jstor.org/stable/256982.

KONG, Ting; FENG, Taiwen; YE, Chunming. Advanced Manufacturing Technologies and Green Innovation: The Role of Internal Environmental Collaboration. **Sustainability**, v. 8, n. 10, p. 1-18, 21 October 2016. DOI 10.3390/su8101056. Available: https://www.mdpi.com/2071-1050/8/10/1056.

LIU, Junjun; GENG, Yong; CHEN, Biao; XIA, Xiqiang. The Effect of a Supplier's Eco-Design on the Economic Benefits of a Supply Chain and Associated Coordination. **International Journal of Environmental Research and Public Health**, v. 18, p. 1-18, 18 December 2021. DOI https://doi.org/10.3390/ijerph182413357. Available: https://www.mdpi.com/1660-4601/18/24/13357.

OMOLOSO, Oluwaseyi; MORTIMER, Kathleen; WISE, William; JRAISAT, Luai. Sustainability Research in the Leather Industry: A Critical Review of Progress and Opportunities for Future Research. **Journal of Cleaner Production**, v. 285, p. 1-11, 20 February 2021. DOI https://doi.org/10.1016/j.jclepro.2020.125441. Available: https://www.sciencedirect.com/science/article/abs/pii/S0959652620354871?via%3Dihub.

PAGELL, Mark; WU, Zhaohui. Building a More Complete Theory of Sustainable Supply Chain Management Using Case Studies of 10 Exemplars. **Journal of Supply Chain Management**, v. 45, n. 2, p. 37-56, 25 March 2009. DOI https://doi.org/10.1111/j.1745-493X.2009.03162.x. Available: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1745-493X.2009.03162.x.

REAP, John; ROMAN, Felipe; DUNCAN, Scott; BRAS, Bert. A survey of unresolved problems in life cycle assessment: Part 1: goal and scope and inventory analysis. **The International Journal of Life Cycle Assessment**, [*S. l.*], v. 13, p. 290-300, 20 May 2008. DOI 10.1007/s11367-008-0008-x. Available: https://link.springer.com/article/10.1007/s11367-008-0008-x.

SÖDERHOLM, Patrik; TILTON, John. Material efficiency: An Economic Perspective. **Resources, Conservation and Recycling**, v. 61, p. 75-82, 05 April 2012. DOI 10.1016/j.resconrec.2012.01.003. Available: https://www.sciencedirect.com/science/article/abs/pii/S0921344912000043?via%3Dihub.