Attributional and consequential life cycle assessments in a circular economy with integration of a quality indicator: A case study of cascading wood products

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Abstract
The growing popularity of the concepts of circular economy and resource cascade has intensified the need for consistent handling of multifunctionality-related challenges when modeling multiple cycles in life cycle assessment (LCA). In LCA, end-of-life upcycling and downcycling effects (also known as quality changes), triggered by the presence of multiple life cycles, have only recently begun to be studied from a consequential perspective, and no studies exist investigating attributional aspects. In this paper, a novel approach that considers quality in attributional LCA is proposed. The attributional, cut-off, open loop, and proposed approaches are compared in the form of a cascading case study. The implications of integrating quality in both perspectives are contrasted by modeling the same case study under a consequential perspective. By performing sensitivity analysis on the quality parameters in attributional LCA, we found that the integration of quality influences the results of the proposed approach by up to 15%. In the case of consequential LCA, the implementation of quality yields an influence between 97% and 138% of the results for each unit variation of quality. Comparison between the two perspectives of quality shows the same trend of supporting high-quality cascades. However, the attributional perspective of quality accomplishes this by redistributing impacts, while the consequential perspective affects the external benefits generated by the cascade. Considering the influence of quality on the results of both perspectives, future work should focus on establishing the technical or economic properties that would allow for practical use of quality in various circular economy and resource cascade applications.

Keywords
circular economy, closed loop, industrial ecology, open loop, quality, recycling

1 | INTRODUCTION

Resource cascade and circular economy are concepts that have recently gained increasing attention from the scientific community (Campbell-Johnston et al., 2020). Resource cascade is defined as the sequential use of a material’s quality before it reaches final disposal (Sirkin & ten Houten, 1994); circular economy is more broad and implies recirculation of materials in a given life cycle (or multiple life cycles) and contrasts with the linear economy of make-use-dispose (Mair & Stern, 2017).

In life cycle assessment (LCA), the presence of multiple cycles amplifies instances of multifunctionality and hence, application of end-of-life (EoL) allocation. There are currently multiple approaches to handle EoL allocation (Aliacker et al., 2017; Borg et al., 2001; Schrijvers et al., 2016b). For
example, the issue is sometimes solved using a strict definition of system boundaries, such as the cut-off and 50/50 approaches (Ekvall & Tillman, 1997). Other solutions take the form of a relay race where a part of the life cycle inventory trickles to downstream cycles; for example, the linearly degressive (Allacker et al., 2017), the open loop proposed by Schrijvers et al. (2016b), the quality degradation (Rehberger & Hiete, 2019), or the embodied burdens approach (Koffler & Finkbeiner, 2018). Certain approaches also rely on system expansion followed by substitution, such as the value-corrected substitution (Koffler & Florin, 2013), the equation proposed by Gala et al. (2015), or the avoided burdens approach (Heijungs & Guinée, 2007).

A lack of clear guidance regarding LCA standards is not the primary reason for the abundance of approaches (Ekvall et al., 2016; Schrijvers et al., 2016a; Werner et al., 2007). Rather, referring to previous publications, the explanation consists of two facts: first, there is more than one perspective for looking at EoL multifunctionality; and second, there are three levels to the EoL multifunctionality issue. The two main perspectives are attributional and consequential, both of which tackle EoL multifunctionality differently (Guinée et al., 2018; Schrijvers et al., 2020). Attributional LCA provides "information on what portion of global burdens can be associated to a specific product life cycle" (Guinée et al., 2018, p. 2). Conducting an attributional LCA of "all final products, one would end up with the total environmental burdens worldwide" (Pelletier et al., 2015, p. 3). To solve EoL multifunctionality of a single product, a partitioning approach is used to assign flows between the studied life cycle and others (Schrijvers et al., 2020). Consequential LCA, on the other hand, provide information on the environmental burdens that occur directly or indirectly as a consequence of a decision (usually represented by changes in demand for a product or service) (Guinée et al., 2018). The recognized approach to solve consequential EoL multifunctionality is system expansion followed by substitution (Guinée et al., 2018; Schrijvers et al., 2020). In this case, the additional life cycle is included in the study, and the avoided processes or products are subtracted.

For the two perspectives (attributional and consequential), the approaches must resolve the three levels of the EoL multifunctionality issue: the inclusion or exclusion of the recycling process, dependency between two consecutive life cycles, and upcycling or downcycling across multiple life cycles (Ekvall & Tillman, 1997). All three levels are relevant to attributional LCA because it seeks a definite answer to the question of what activities are to be allocated with a consistent methodology to produce fair results for all cycles. However, consequential LCA avoids the first two levels because all the affected cycles are included as consequences; although the third level (i.e., upcycling or downcycling across multiple life cycles) remains applicable, as avoided products also depend on the properties of the recycled materials (Eriksen et al., 2019; Geyer et al., 2016; Rigamonti et al., 2018).

Despite the popularity of both the resource cascade and circular economy concepts, considerations for upcycling or downcycling (also referred to as quality or change in inherent properties) remain scarce in recent LCA studies (Laurent et al., 2014; Zink et al., 2016). Yet, questions regarding why and how residues are recovered depend not only on their quantities, but also on their quality (Amin et al., 2007; Kim et al., 1997; Rigamonti et al., 2018). Further, quality is at the root of what will become of the product in its next (now multifunctional) life cycle. Products sustaining high degradation (loss of quality) are treated as waste (López Ruiz et al., 2020). Conversely, products that show improved properties, or at least preserve them, are treated as valuable resources to be recovered. This is why quality is identified as a core concept of resource cascades (Sirkkinen & ten Houten, 1994). Additionally, a clear modeling trend can be observed in LCA: incorporation of quality is attained through the use of substitution factors (Rigamonti et al., 2020), implying a consequential perspective. The substitution factors are used to compare how recycled products are functionally equivalent to their substituted products (Civancik-Uslu et al., 2019; Eriksen et al., 2019; Vadenbo et al., 2017). However, depending on the study, the implemented substitution factors may come in wide ranges of values and are often poorly justified (Viau et al., 2020). This suggests that the magnitude of the influence of quality, when it is integrated into modeling, is not completely understood. Further, considering that both attributional and consequential perspectives yield different information when applied to the same system (such as a cascade) (Ekvall et al., 2016), the integration of quality in an attributional perspective is necessary. This is yet to be explored despite being identified as relevant.

The aim of this study, therefore, is determination of how important is the integration of quality (downcycling and upcycling) as a key parameter for solving multifunctionality in LCA of cascades, as well as identification of how a clear distinction between perspectives (attributional and consequential) affects the integration of quality. For this purpose, a case study of a wood cascade is used. The paper is structured as follows: Section 2 describes the case study, relevant EoL approaches for attributional and consequential perspectives, and how quality factors are implemented in both perspectives. Section 3 presents and discusses the results according to the perspectives and the influence of quality. Finally, Section 4 summarizes the main findings of the study.

2 | METHODS

2.1 | Case study

To better understand the approaches, a case study involving a five-step cascade of wood products in Montreal, Quebec (Canada) was used for all modeling approaches. Wood products hold a long-standing history as an example of various cascade uses, along with policies providing incentives to maximize their use (Olsson et al., 2016). Current challenges of cascading wood products include their physical properties (i.e., particle size or presence of chemicals) (Jarre et al., 2020) and modeling of their environmental impacts due to the availability of numerous modeling approaches (Thonemann & Schumann, 2018). While this case study is comprehensive of these two specific challenges, it is noteworthy that the methodology

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FIGURE 1  Breakdown of the five step recycling loops (E_v, virgin production; A, assembly activities; E_RC, production from recycled content; U, use phase; E_d, landfill activities; D, disassembly activities; E_RRE, EoL recycling activities.)

TABLE 1  Terminology used in formulas

| Coefficient | Description |
|-------------|-------------|
| E_{tot(n)}  | Total life cycle inventory (LCI) associated with the n^{th} life cycle |
| E_v         | LCI associated with virgin production (cradle to factory gate) |
| E_RC        | LCI associated with production from recycled content * |
| A           | LCI associated with assembly activities (transport included) |
| E_d         | LCI associated with landfill activities (transport included) |
| D           | LCI associated with disassembly activities |
| E_RRE       | LCI associated with end-of-life recycling (transport included) ** |
| RC          | Ratio of product made from recycled materials |
| RRE         | Ratio of the product sent for recycling at end of life |
| C           | Conversion efficiency ratio |
| F           | Relative economic value ratio between virgin material and recycled material. If no economic allocation, F = 1 |
| F_{(n-1)}   | Relative economic value ratio between virgin material and recycled material in previous life cycle. If no economic allocation, F_{(n-1)} = 1 |
| E_{tot(n-1)}| Total LCI associated with the (n−1)^{th} life cycle |
| FU_i        | Quantity associated with the functional unit |
| Rate        | Ratio processing efficiency/quantity required to meet FU_i |
| Q           | Quality indicator |
| E_{tot}     | Total LCI associated with a consequential model |
| E_{prim}    | LCI associated with primary production and management at the end of life |
| E_{RE}      | LCI associated with recycled content, from point of substitution to the end of life |
| d           | Substitution ratio |
| r           | Recovery ratio |
| c           | Conversion efficiency ratio |
| E_{disp}    | LCI associated with displaced products |
| E_{alt}     | LCI associated with alternative products required to fulfill demand from neighboring systems |

*In the case of the cut-off approach, the whole recycling process is to be included.  
**In the case of the cut-off approach, none of the recycling process is included.

developed here also concerns other resource cascades (metals, plastics, etc.) (Mair & Stern, 2017; Sirkin & ten Houten, 1994). Thus, without any loss of the global objective, the cascade of wood products is summarized in Figure 1. The terminology used in Figure 1 and in the remainder of the paper is presented in Table 1.

The first cycle consists of softwood lumber used in the construction of a commercial building. At the building’s EoL, the softwood lumber is extracted from the debris to be recycled into glued-laminated timber and then utilized in the construction of a second building. At the end of the second building’s life cycle, the recycled glued-laminated timber is ground into oriented strand board (OSB) and returned into the industry. The fourth cycle transforms the OSB into a particle board to be used as furniture. Once the particle board reaches its EoL, the latter is sent for energy recovery in a biomass valorization factory. Note that given the objective of the present study and to avoid unnecessary complexity, the “use” phase for each material cycle was not modeled, and hence, appears faded in Figure 1. When comparing the approach results, its inclusion or exclusion will not influence the obtained conclusions. Again, in order to hold to the main objective, temporal effects such as improvement of technologies and rise of new end-markets for secondhand products are not considered.
The Brightway2 software (Mutel, 2017), along with the ecoinvent 3.5 databases (Wernet et al., 2016) were used for modeling. The IMPACT2002+ impact assessment method was also used (Humbert et al., 2012). An online repository has been created to allow full access to the scripts and inventories (https://github.com/xtanguay/EoL_recycling_approaches). Section 1 of Supporting Information S1 provides an inventory sample, including details on data handling.

2.2 Attributional perspective with no integration of quality

Attributional modeling of the system was undertaken with two existing approaches and compared with a proposed approach, which integrates quality (Section 2.3). The first reference approach is the cut-off approach, which partitions life cycles based on system boundaries; this approach is common and fairly easy to apply (Allacker et al., 2017; De Wolf et al., 2020; D. L. Schrijvers et al., 2016b). The second is the open-loop approach recently assessed by Schrijvers et al (2016b), which is an example of a relay race approach. Distinctions between partitioning based on system boundaries and that based on the relay race approach are also depicted in Section 1 of Supporting Information S1.

The functional unit for attributional modeling of each cycle is treatment of 1 m$^3$ of wood products. For the final step in the cascade, the functional unit is to provide 1 kWh of electricity.

2.2.1 Cut-off approach

The cut-off approach is also referred to as the 100:0 approach, or the recycled content approach (Allacker et al., 2017; Schrijvers et al., 2016b), because it does not shift any inventory upstream or downstream. This approach simplifies the EoL allocation problem using boundaries that exclude the recycling process from the life cycle under study. The formula summarizing this approach is presented in equation 1:

$$E_{tot[n]} = E_v \cdot (1 - RC) + RC \cdot E_{RC} + A + D + RRE \cdot E_{RRE} + E_d \cdot (1 - RRE)$$

(1)

2.2.2 Open loop approach

The studied open loop approach has been proposed in the development process of a framework for consistent allocation in EoL recycling situations (Schrijvers et al., 2016b). This approach partitions the environmental impacts of a whole life cycle through a downstream shift of inventory. The boundaries for waste treatment at EoL are set where the material reverts to a usable state. The approach does not require predicting the total number of life cycles in order to be applicable, which is one of its main advantages over the other approaches (Allacker et al., 2017; Baumann & Tillman, 2004; Ekvall & Tillman, 1997). The formula is shown in equation 2 below.

$$E_{tot[n]} = \left[ E_v \cdot (1 - RC) + RC \cdot \left( E_{RC} + E_{tot[n-1]} \cdot F_{(n-1)} \right) + A + D + RRE \cdot E_{RRE} + E_d \cdot (1 - RRE) \right] \cdot \frac{1}{1 + RRE \cdot C \cdot F}$$

(2)

2.3 Attributional perspective integrating quality

Existing approaches that focus on integrating quality as an allocation parameter often make it the sole parameter, or require knowledge of the number of future life cycles (see Ekvall & Tillman, 1997; Rehberger & Hiete, 2019). To avoid these limitations, the proposed approach builds on the structure of the open loop from Section 2.2.2. Using quality to acknowledge upcycling and downcycling, this approach is suitable for both open as well as closed loops. The proposed approach is shown in equation 3:

$$E_{tot[n]} = \left[ E_v \cdot (1 - RC) + RC \cdot E_{RC} + E_{tot[n-1]} \cdot \frac{1 - b_{(n-1)}}{b_{(n-1)}} \cdot \frac{CR}{C_{RRE(n-1)}} + A + D + RRE \cdot E_{RRE} + E_d \cdot (1 - E_{RRE}) \right] \cdot b_{(n)}$$

(3)

where

$$\frac{CR}{C_{RRE(n-1)}} = \left[ \frac{FU \cdot RC}{Rate} \cdot \frac{1}{RRE^{(n-1)} \cdot FU_{(n-1)}} \right]$$

(3.1)

$$b_{(n)} = \frac{1}{1 + RRE \cdot Q}$$

(3.2)
Three changes distinguish the proposed approach from the open loop approach. The terms \((1 - b_{(n-1)})/(b_{(n-1)})\) in equation 3 are added to properly link the unallocated inventory from the previous life cycle to the new one (change 1). Equation 3.1 is added to ensure continuity between successive functional units (change 2). Use of equation 3.1 is further detailed in Section 2 of Supporting Information S1. Equation 3.2 introduces quality amidst the partitioning factor (change 3). Upcycling and downcycling cases are introduced through quantified changes in inherent properties or market values with \(Q = Q_f/Q_i\). The partitioning factor is therefore based on the quantity of useful material delivered (through RRE) and a factor that accounts for improvement, preservation, or degradation of the function served (through Q).

### 2.4 Consequential perspective with no integration of quality

To solve the issue of multifunctionality, consequential models use system expansion, followed by substitution to isolate the consequences of the change. In turn, the consequences are modeled through the marginal technologies affected (Weidema, 2003). In recycling systems, the main competitors are often thought to be primary materials (Zink et al., 2016). In some cases, a product in a cascade may also be a complement of the original product from which the cascade is derived, enabling the substitution of the very first product in the cascade (Thomas, 2003). Diverging residues from their original application also implies that the original demand should remain fulfilled in its former field of use (i.e., a process formerly using residual wood for energy valorization requires an alternative energy source to fulfill its original demand). Equation 4 can be used to illustrate the behavior expected from a cascade system (Zink & Geyer, 2019):

\[
E_{\text{tot}} = E_{\text{prim}} + E_{\text{rec}} - \frac{d \cdot r \cdot c}{1 - (1 - d) \cdot r \cdot c} \cdot E_{\text{disp}} - d \cdot E_{\text{prim}}' + E_{\text{alt}}
\]

The principles of consequential modeling are applied to the case study. The competing products are identified as their virgin counterparts. The former utilization of wood residues in all cases is valorization for energy production. The alternative energy source replacing the residues is the forecasted long-term marginal supplier for electricity in the province of Quebec (Azari-Jafari et al., 2019). Additional details on modeling and selection of marginal technologies is provided in Section 1.2 of Supporting Information S1. More advanced models to identify affected marginal technologies (such as partial or general equilibrium models) are beyond the scope of this study. Again, this also neglects potential evolution of markets, which could provide alternative substitute on scenarios with technologies that may yield better environmental performance (Jarre et al., 2020; Schaubroeck et al., 2020), which is also beyond the scope for this study. The consequential model uses a functional unit of cascading 1 m³ of softwood lumber. Thus, the boundaries have been redefined and are summarized in Figure 2.

### 2.5 Consequential perspective integrating quality

A precise assessment of the substitution ratio \((d)\) would require a market-based model, such as a partial equilibrium model that considers price elasticity between competing materials. Such models allow for consideration of complex economic relationships between different substituting
FIGURE 3  Attributional modeling results for resource cascades and their equivalents when using virgin materials (A, cut-off; A’, cut-off with virgin materials; B, open loop; B’, open loop with virgin materials; C, proposed approach; C’, proposed approach with virgin materials; 100% refers to the most polluting case.) Underlying data used to create this figure can be found in Supporting Information S2.

and substituted products (Zink et al., 2016). One of the factors assessed is the functional equivalence of the products under consideration (Vadenbo et al., 2017), which entails quality in the case of secondary materials (Eriksen et al., 2019; Viau et al., 2020). In the absence of such a refined model (as it is beyond the scope of this paper), variations in the substitution factor remain a viable way to reach the objectives of the current study and hence express the effects of quality on a consequential model.

3 | RESULTS AND DISCUSSION

3.1 | Attributional perspective with no integration of quality

The cascade results were computed under the three attributional approaches, as shown in Figure 3. The equivalents of each cascade cycle using exclusively virgin materials (using typical values for the province of Quebec such as RC = 0 and RRE = 0.53) were also modeled and compared to their equivalent using recycled materials. These cycles are indicated in Figure 3 by the sign (’). The data used to create this figure and the subsequent ones can be found in Supporting Information S2.

Regarding the overall results for A, B, and C (all damage indicators considered), the difference in results from a single damage indicator can range from less than 10% between two approaches (i.e., the difference in total cascade A vs. B in the climate change indicator) to as high as almost 25% (i.e., the difference in total cascade A vs. C in the ecosystem quality indicator). This corroborates the assumption that choice of EoL allocation approach impacts the results of resource cascade systems (Nicholson et al., 2009; Sfez et al., 2019).

Since the cut-off approach does not transfer any inventory to other cycles, this approach is suitable for isolating the environmental contributions of relative cycles. For instance, in the climate change damage category, the first step remains the same for both cascading and virgin production routes (i.e., A vs. A’—softwood lumber contributions). However, this observation changes for the second cycle of the cascade (glued-laminated timber). This change is explained by an increase in transportation distance of the recycled materials. This is also observed for the particle board cycle. These effects are in line with the results of a recent study (Deschamps et al., 2018) that compared different recycling solutions for waste glass in the province of Quebec, showing that transportation distance plays a significant role in environmental impact performance. However, this opposes the findings of another similar study (Höglmeier et al., 2014) in which cascade utilization of wood residue was compared with virgin-sourced equivalents in Switzerland; in this study, the transport distances were found to be negligible. This finding emphasizes the need for consideration of regionalized transport distances.

The results of the ecosystem quality damage indicator display a noticeable difference in both cascade and virgin production routes (i.e., A vs. A’—glued-laminated timber), where the cut-off allocation of the cascaded system is greatly inferior to the virgin alternative; however, this is only observed for this particular approach. This is a peculiar aspect of cascading forestry products, as cascaded wood residue products do not require any further forestry activities (i.e., supplementary extraction of roundwood, which is a significant contributor to the aforementioned damage indicator) (Risse et al., 2017). This leads to extreme cases as exhibited in this damage category, where the total results for A outperform all others while the total results for A’ perform worse by a large margin against all others. This highlights the shortcomings of locking burdens in individual cycles, as seen in the cut-off approach. In fact, it will systematically fail to raise awareness regarding the inefficient life cycle when consuming high quantity of a recycled product, since it comes burden free. This is in line with recent observations from existing literature (De Wolf et al., 2020; Johnson et al., 2013).
Considering B and C, both of which are based on the allocation factor \( 1/(1 + RRE) \) (as quality is set to 1 in C), a very high contribution of the fifth life cycle of cascade B is noted. This is explained by the double counting issues seen in equation 2. Two sources of double counting are identified: incoherence between two successive functional units and re-allocation of a burden previously assigned. The first source of double counting becomes explicit when there is a great difference between the quantities required to fulfill the subsequent functional unit (i.e., the fifth cycle, energy valorization, only requires 1.206 \cdot 10^{-3} \) of the particle board's functional unit to meet 1 kWh). The downstream allocated inventory in equation 2 \((E_{tot}^{n-1})\) should be proportional to this change and not just the recycled content rate \((RC)\) as in equation 2. The re-allocation of burden, identified as the second source of double counting, refers to confusion regarding what is to be allocated. In equation 2, \( E_{tot}^{n-1} \) is directly used as an input, even though it refers to the impacts assigned to the previous life cycle. To properly perform allocation between two functions, the second function (here, the second life cycle) should receive the unassigned inventory, which is not the case in equation 2. Further details on the double counting effect (with an applied example) are provided in Section 3 of Supporting Information S1. Considering that physical correctness (thus, absence of double counting) is of paramount importance (Allacker et al., 2017; International Standard Association, 2006; Klöpffer, 1996), mathematical balancing of equation 2 becomes a necessity. This has been addressed in the development of equation 3 (see changes 1 and 2), which is based on equation 2.

In contrast to B and C, identical results are found in the non-cascading systems B’ and C’. This underlines the need for physical correctness in the approaches. Indeed, physical correctness cannot be applied in waste management studies that focus on system that consists of a single life cycle. However, these results do not consider the influence of the quality factor. The following subsection illustrates the behavior of the results upon integration of the quality factor.

### 3.2 Attributional perspective integrating quality: Effects of upcycling and downcycling

The results were re-computed focusing on the quality factor of equation 3. A sample of quality factors ranging from 0 to 1.5 were used to account for materials reaching the state of waste \((Q = 0)\) and display the overall trend for upcycling cases in Figure 4.

Figure 4 shows that the cascading total environmental impacts decrease while the quality factor increases. Such results are explained by the multiplicative inverse relationship of the allocation factor \(b_{tot} \) and the quality factor in equation 3.2. Thus, the quality factor acknowledges upcycling situations with reduced inventory allocated to the cycle under study, while the allocated inventory increases in downcycling situations. This resulting trend supports higher quality cascades as they are expected to lead to lower impacts (Högmeier et al., 2014; Risse et al., 2019; Taskhiri et al., 2016). The consideration for change in inherent properties, whether positive or negative, is therefore explicitly integrated and encouraged by the trends observed for the approach. Considering C \((Q = 1)\) as a baseline, the influence of quality ranges from 10% to 15% on the overall cascade for three of the four indicators.

One exception to the decreasing trend is observed for the ecosystem quality indicator. This observation can be considered as a continuation of the conclusions of Section 3.1: the ecosystem quality indicator exhibits its lowest value with an approach that dissociates the most contributing cycle from the others. As the quality factor increases, burdens from the first cycle, which dominate the results of A in Figure 3, are shared with the downstream life cycles. This redistribution binds cycles by ensuring that recycled materials do not always come burden free, which is a shortcoming of the cut-off approach. Further, considering C \((Q = 1)\) as a baseline, the absence of this bind (result A) reduces the indicator by 27% of the overall cascade result. The case of upcycling (result E) only induces an overall increase of 2.3%. Again, this is explained by the strong influence of the first cycle on this indicator.

When the quality factor is equal to 0 (result A in Figure 4), the proposed approach and the cut-off approach results become almost equal (with only minor differences due to the life cycle boundaries definition, where the cut-off approach excludes recycling activities and the proposed
approach includes these activities until the point of substitution). This is explained by the redistribution factor in equation 3.2 converging to a unit value (no redistribution to downstream cycles). In other words, these results reiterate that the cut-off approach has no consideration for quality (i.e., upcycling and downcycling) (Ekvall & Tillman, 1997).

3.3 Consequential perspective with no integration of quality

Figure 5 compares the behaviors of the previous attributional system with the consequential one. Here, the attributional functional units were modified to match the cascading consequential functional unit (i.e., 1 m$^3$ of softwood lumber only yields 0.3604 m$^3$ of glued-laminated timber due to the combination of recovery, recycling, and reprocessing rates). The avoided emissions correspond to the avoided processes indicated in Figure 2. Further, consequential results cannot be disaggregated per cycle due to the system expansion; the cascade is to be considered as the whole complex system. Consequential results consider a substitution factor of 1. The total emissions (diamond markers) may exceed 100%, or even lead to less than 100% of results A and B, due to substitution and reliance on marginal datasets.

The results show that the cascade system with $d = 1$ provides benefits in three of the four damage categories but has no benefits for the human health indicator (2.6%). Such results suggest that cascading timber products could be beneficial. A recent literature review found that the environmental performance of wood cascades is still unclear (Thonemann & Schumann, 2018). More recently, a consequential LCA of wood cascading with global warming as the sole environmental indicator was conducted (Faraca et al., 2019). The study found that all reviewed scenarios provided benefits versus global warming. Thus, the present findings side with the idea that cascading wood products has environmental benefits.

Combining all cycles of an attributional cascade generates a total system that resolves all EoL multifunctionality problems with an unambiguous solution (Klöpffer, 1996). This is shown by the equivalent environmental performance between A and B. This demonstrates that the final results using attributional LCA are always equal, irrespective of the EoL allocation approach (Ekvall et al., 2016; Plevin et al., 2014). This underlines that contrary to the consequential perspective, an attributional LCA model of waste management and resource cascading is not a suitable perspective for integration of the concepts of environmental benefit.

3.4 Consequential perspective integrating quality: Effects of upcycling and downcycling

In the absence of a market-based substitution factor that integrates quality effects, values ranging from null to 1.25 are used in Figure 6 in order to highlight the influence of upcycling and downcycling on the overall results.

As shown in Figure 6, a reduction of the substitution factor to 0.75 negates almost all environmental benefits (except for ecosystem quality, with a small percentage of 3.7%). In fact, the consideration of quality in secondary products exerts great influence on their benefits. Such implementation of a substitution factor that acknowledges quality changes when moving from different cycles of a cascade was applied in a recent study exclusively focusing on greenhouse gases (Faraca et al., 2019). In this study, technical and market-based substitution factors were applied to closed loop recycling of particle boards from different grades (quality levels) of waste wood; this study also highlighted the strong influence of quality over
substitution benefits, as the increase in the number of life cycles reduced the substitution potential from qualitative and quantitative perspectives. However, this study used fixed substitution factors, which reached as low as 0.6, and only focused on particle boards and energy valorization.

Compared with the outcomes presented in Section 3.2, consequential modeling with the consideration of quality also supports high-quality cascades. In fact, improving the quality factor in the attributional perspective decreases the burdens associated with a cascade’s cycle and connects cycles with one another. On the other hand, improving the quality factor in consequential perspectives also decreases cascade burdens by increasing external benefits. Considering a unit variation of quality ($\Delta d = 1$), the influence of quality in consequential perspectives ranges from 97% (human health indicator) to 138% (ecosystem quality indicator). In other words, for this case study, the influence of quality is almost 10 times more important in the consequential perspective than in the attributional one.

4 | CONCLUSIONS

Considering the recent increased attention toward the concepts of circular economy and resource cascades, it becomes evident that the LCA community needs to continue discussing the challenges of EoL and multifunctionality. Changes in quality are one of these challenges. This study explored the integration of quality changes when cascade systems are modeled from attributional and consequential LCA perspectives. Hence, EoL methodologies (cut-off, open loop, and substitution) were compared focusing on the influence of quality. This study proposed a new attributional approach that considers the number of life cycles and issues related to downcycling and upcycling. A cascade consisting of five wood products (softwood lumber, glued-laminated timber, oriented strand board, particle board, and energy valorization of wood chips) was investigated for this purpose.

The cut-off approach dissociated the cycles between one another and was unable to acknowledge quality, thereby leading to the conclusion that it is very nearly analogous to a special case of the new approach with $Q = 0$. The open loop approach, meanwhile, generated double counting issues.

Consequential results showed that cascaded wood has the potential to reduce environmental impacts through the benefits of substitution. Integrating a sensitivity analysis to quality in the consequential perspective highlighted the susceptibility of resource cascades in providing contrasting results when this parameter is neglected.

Comparison between attributional and consequential results led to the following conclusions: attributional LCA of EoL approaches do not properly identify environmental benefits of waste management. Integrating quality in an attributional model reconnects life cycles in a cascade and shifts attention towards efficient cascades by favoring those that are high quality. In this case study, the influence of quality on the attributional perspective represents ±10–15% of the overall cascade (aside from one indicator that was found to be highly influenced by a single cycle and ranged between –27 and +3%). Integrating quality in the consequential perspective also supports high-quality cascades, but affects the external benefits generated by the cascade. The influence of modeling quality on overall consequential results ranged between 97% and 138% for each unit variation of quality (thus the substitution factor). This caused the influence of quality to be approximately 10 times more important in the consequential perspective than that in the attributional perspective.

This paper presented a single scenario exhibiting a cascade with a single type of material (wood products) and focused mainly on the sensitivity of the results while dealing with quality (in either upcycling or downcycling situations). However, the technical properties and end markets associated with exact identification of the quality factors applicable to the products under study were beyond the scope of this research. Thus, we recommend further studies on how we can determine the corresponding values for quality factors. This recommendation could also be applied to other material types (i.e., metals, plastics) in order to assess the global significance of a quantitative inclusion of quality.
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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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