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A market-based approach to allocation at open-loop recycling

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Abstract

Changes in the amount of recycled material delivered by, or used in, the life cycle of a product will affect the environmental burdens of other product life cycles. These indirect effects can potentially be taken into account through expansion of the system investigated to include the activities affected. Presently, the assessment of the indirect effects is often based on inaccurate assumptions. The indirect effects depend on, e.g. how the market for the recycled material reacts to a change in the supply of, or demand for, the recycled material. This, in turn, depends on political constraints, price elasticities, etc. in the markets for recycled material. This paper presents a model that takes the market aspects into consideration. It can be used in a life cycle assessment (LCA) to model the indirect effects either through system expansion or as a basis for allocation. It is designed for the use in change-oriented LCAs, but it can also be used in accounting type LCAs. The model is demonstrated in two theoretical cases: increased local collection for recycling of old corrugated containers and newsprint, respectively. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Environmental life cycle assessment; Life cycle inventory analysis; Methodology; Open-loop recycling; Allocation; System expansion; Price elasticity; Wastepaper

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1. Introduction

Environmental life cycle assessment (LCA) can be defined as the compilation and evaluation of the material and energy flows and of the potential environmental impacts of the life cycle of a product. The term product is in this context broadly defined to include not only physical products but also services. The product life cycle is here defined as the system, consisting of models of the technological activities used for the various stages of the product: from extraction of raw materials for the product and for ancillary materials and equipment, through the production and use of the product, to the disposal of the product, ancillary materials and equipment, if any. Life cycle inventory analysis (LCI) is the phase of an LCA in which the material and energy flows are compiled and quantified [1]. The framework of the LCI method has been described elsewhere [2,3]. A methodological distinction can be made between LCAs aiming at describing the consequences of changes, and LCAs aiming at mapping the environmental impacts that the product investigated is made accountable for [4]. In the first case, the methodological choices are based on the goal to describe the consequences. In the latter case, the methodological choices are based on conventions.

Open-loop recycling is here defined as the recycling of a material from one product life cycle into another. A methodological allocation problem arises in the LCI when the product life cycle investigated includes inflows or outflows of recycled material: what share of the environmental burdens of the primary production, recycling and final waste management of the material should be allocated to the product investigated, i.e. included in the LCI of the product investigated [5]? Environmental burdens are here defined as the resource demand, the emissions of pollutants, the waste generated, and the land transformation caused by the technological activities.

Many different solutions to this allocation problem have been suggested [5–17]. The choice of solution can have a decisive impact on the results of an LCI [17–20]. The International Organization for Standardization (ISO) recently presented a standard for LCI — ISO 14041 — which included an allocation procedure [21]. This procedure has been described and elucidated elsewhere (e.g. [22,23]). However, the ISO procedure has been criticised because it does not take into account the fact that different approaches to the allocation problem result in different types of information [24], nor does it take into account the relation between the method and the study goal [4,5]. The same ranking order of allocation methods is recommended for all LCA applications [21]. Hence, it may be necessary to revise the ISO procedure [24,25].

If the purpose of the LCA is to enhance the ability to anticipate the environmental consequences of our actions, the allocation procedure should result in information about the environmental consequences of our actions [5]. Open-loop recycling can have important consequences for the environmental burdens of activities outside the life cycle of the product investigated [19]. These consequences are in the following denoted indirect effects. The indirect effects depend on, e.g. how the market for the recycled material reacts to a change in the supply of, or demand for, the recycled material [24].

Indirect effects can potentially be taken into account through expansion of the system investigated to include the activities that are affected [26,27]. For this reason, the procedure to avoid allocation through system expansion is a characteristic feature in change-oriented LCAs [4]. However, in recent LCI practice, the system expansion, and hence the assessment of the indirect effects, is often based on inaccurate assumptions. Recycled material from the product life cycle investigated is in most cases assumed to replace virgin material in the expanded system, although the recycled material may, in fact, replace recycled material from other sources, completely different types of material or no material at all [24].

Since most activities in the global technological system are interrelated, an action may have indirect effects that propagate through the whole global technological system. This system is too complex to analyse on the level of detail used in an LCA. Hence, it is necessary to simplify the system [26]. The challenge is to simplify without losing too much relevant information. One simplification is obtained through the ceteris paribus assumption that the demand for the functions fulfilled by other product life cycles is constant. System expansion based on this assumption results in what is denoted a technological whole-system approach [26,27].

In conclusion, a feasible allocation procedure that results in information on how the market reacts to a change in the supply of, or demand for, the recycled material is needed to make LCA a more efficient tool for increasing the ability to anticipate the environmental consequences of our actions [24]. It is the purpose of this paper to present a conceptual model that can be used in such a procedure. The model describes the life cycle investigated as being connected to other life cycles through the market for recycled material. This model is a technological whole-system model based on the assumption that recycled material from the life cycle investigated replaces other materials of some kind. The model is applied in two theoretical cases of increased collection of material for recycling in the town of Gothenburg on the Swedish west coast. In one case — corrugated board — the recycling rate and the price of the recovered material are decided by the economic forces of demand and supply. In the other case — newsprint paper — the recycling rate is decided by ordinances issued by the national authorities.

2. The conceptual model

A cascade material is here defined as a material that, after use in one product life cycle, is recycled into other products. Outflows of cascade material of a specific type (e.g. steel scrap, aluminium scrap, old newsprint) from the life cycle investigated are sold in a market for this type of recycled material. The market can be more or less influenced by authorities. If the same type of cascade material is used for producing the product investigated, it is bought in the same market, although possibly at another point in time. This market also connects the product investigated to other product life cycles that use this type of cascade material or that deliver this type of cascade material to the market (Fig. 1).

If an action is taken, within the product life cycle investigated, which increases the amount of material that is collected for recycling from that life cycle (X), this can result in an increased use of the cascade material ($D + Y$) and/or in a reduced collection of the material in other product life cycles (S). If the market for recovered material is sufficiently free for the recycling rate to be decided by economic forces, the increased quantity supplied from the product life cycle investigated is likely to result in a reduction in the price of the recovered material ($\Delta P < 0$). This price reduction is likely to stimulate an increased use of the recovered material ($\Delta D + \Delta Y > 0$). On the other hand, the price reduction makes collection for recycling less profitable or more expensive. This is likely to result in a reduced collection of the material in other life cycles ($\Delta S < 0$). How much the quantity demanded is increased, and the quantity supplied from other products is reduced, depends on how sensitive the buyers and the organisations collecting the material are to a change in price.

If an action is taken, within the product life cycle investigated, which increases the quantity of cascade material that is used in the product (Y), the use in other products (D) can decrease and/or the collection of material for recycling ($S + X$) can increase. If the recycling rate is decided by economic forces, the indirect effects, again, depend on how sensitive the buyers and the organisations collecting the material are to a change in price.

When the flows of cascade material to and from the product life cycle investigated are small compared to the total flow in the market ($Y \ll D$; $X \ll S$), changes

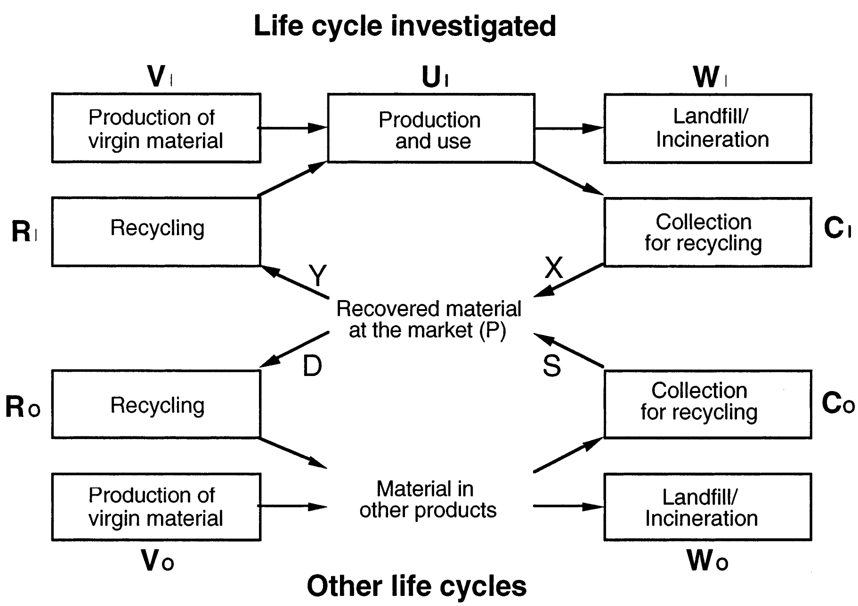

Fig. 1. The conceptual model of the life cycle investigated as connected to other life cycles through the market for recycled material.

in X or Y have marginal effects on the market. When a change in X has marginal effects on the market, the effects of this change on Y can be assumed to be negligible. Similarly, the effects on X of a change in Y can be assumed to be negligible. This means that the price elasticity of demand (η_D) can be defined as follows [28]:

$$\eta_D = \frac{\Delta D/D}{\Delta P/P}, \tag{1}$$

which is generally a negative number. A price elasticity of supply (η_S) can be defined in a similar way:

$$\eta_S = \frac{\Delta S/S}{\Delta P/P} \tag{2}$$

From these equations follows (since $Y \ll D$ and $X \ll S$):

$$\frac{\Delta D}{\Delta S} = \frac{D \cdot \eta_D}{S \cdot \eta_S} \approx \frac{\eta_D}{\eta_S} \tag{3}$$

If the amount of material that is collected for recycling in the product life cycle investigated is changed by ΔX, the effects on the demand of, and supply from, other life cycles (ΔD_X and ΔS_X) can be calculated as follows:

$$\Delta X = \Delta D_X - \Delta S_X \approx \Delta D_X \left(1 - \frac{\eta_S}{\eta_D}\right) \tag{4}$$

$$\Delta D_X \approx \frac{\Delta X}{1 - \frac{\eta_S}{\eta_D}} = \frac{\Delta X \eta_D}{\eta_\mathrm{D} - \eta_S} \tag{5}$$

$$\Delta S_X \approx \frac{\Delta X \eta_S}{\eta_D - \eta_S} \tag{6}$$

As indicated above, the model is based on the technological whole-system assumption that the demand for the functions fulfilled by other product life cycles is constant. This means that when the demand for recycled material in other product life cycles is increased by ΔD_X, the demand for virgin material is reduced correspondingly. The indirect effects ($\Delta \boldsymbol{B}_X$) of the change ΔX — i.e. the consequences for the environmental burdens of activities outside the life cycle of the product investigated — can be calculated as follows (see Fig. 1):

$$\Delta \boldsymbol{B}_X \approx \Delta D_X(\boldsymbol{R}_\mathrm{O} - A\boldsymbol{V}_\mathrm{O}) + \Delta S_X(\boldsymbol{C}_\mathrm{O} - \boldsymbol{W}_\mathrm{O}) \tag{7}$$

$$\Delta \boldsymbol{B}_X \approx \frac{\Delta X}{\eta_D - \eta_S}[\eta_D(\boldsymbol{R}_\mathrm{O} - A\boldsymbol{V}_\mathrm{O}) + \eta_S(\boldsymbol{C}_\mathrm{O} - \boldsymbol{W}_\mathrm{O})], \tag{8}$$

where the environmental burdens per unit material of the recycling processes, virgin material production, collection for recycling, and waste management of the other life cycles are denoted $\boldsymbol{R}_\mathrm{O}$, $\boldsymbol{V}_\mathrm{O}$, $\boldsymbol{C}_\mathrm{O}$ and $\boldsymbol{W}_\mathrm{O}$, respectively, and where A is a constant. This constant is introduced here because even when recycled material displaces

Table 1
Default estimates for the price elasticities of supply (η_S) and demand (η_D) for a few recovered materials (source: Palmer et al. [35])

	η_S	η_D
Paper and paperboard		
Newsprint	0.2	−0.12
Other	0.2	−0.16
Glass		
Beverage containers	0.5	−0.5
Metals		
Aluminium packagings	1.1	−0.80
Steel	1.4	−0.63
Plastics		
PET soft drink bottles	0.5	−0.1
HDPE liquid food containers	0.5	−0.1

virgin material, more than 1 kg of recycled material may be required to obtain sufficient functionality to replace 1 kg of virgin material. The vector notation is used here because the environmental burdens ($\boldsymbol{B}_X$, $\boldsymbol{R}_\mathrm{O}$, $\boldsymbol{V}_\mathrm{O}$, $\boldsymbol{C}_\mathrm{O}$ and $\boldsymbol{W}_\mathrm{O}$) are described through a set of parameters.

If the amount of cascade material that is used in the product life cycle investigated is changed by ΔY, the indirect effects ($\Delta\boldsymbol{B}_Y$) can be calculated in a similar way:

$$\Delta\boldsymbol{B}_Y \approx \frac{\Delta Y}{\eta_S - \eta_D}[\eta_D(\boldsymbol{R}_\mathrm{O} - A\boldsymbol{V}_\mathrm{O}) + \eta_S(\boldsymbol{C}_\mathrm{O} - \boldsymbol{W}_\mathrm{O})] \quad (9)$$

It should be noted that, in this model, the environmental burdens avoided through a unit outflow of the cascade material are the same as the environmental burdens caused by the unit use of the same cascade material, i.e.:

$$-\frac{\Delta B_X}{\Delta X} \approx \frac{\Delta B_Y}{\Delta Y} \approx \frac{1}{\eta_S - \eta_D}[\eta_D(\boldsymbol{R}_\mathrm{O} - A\boldsymbol{V}_\mathrm{O}) + \eta_S(\boldsymbol{C}_\mathrm{O} - \boldsymbol{W}_\mathrm{O})] \quad (10)$$

If allocation in open-loop recycling is avoided through system expansion based on this model, the environmental burdens credited to a product delivering a cascade material will correspond to the environmental burdens assigned to the product where the cascade material is used. In conclusion, a system expansion based on this model gives additive LCA results.

Several authors have estimated the price elasticities of supply and demand for, e.g. recovered paper (e.g. [29–34]) and steel scrap [29]. Palmer et al. [35] estimated the elasticities of supply and demand for several materials, based on earlier literature — ranging from 1977 to 1993 — as well as on their own analysis. The estimates of Palmer et al. are presented in Table 1.

The actual elasticities in a particular recycling case can differ significantly from the Palmer et al. estimates. For the price elasticity of supply of old newsprint, the literature includes estimates ranging from 0.06 to 1.70 [35]. The large difference between different estimates may depend on errors in individual estimates, but is, to some extent, caused by case specific factors such as the time and place where the material is collected for recycling. The price elasticities depend on, e.g. the collection schemes and the legislation that are implemented at that time and location. Price elasticities also vary with the time-horizon: in the long-term perspective, the buyers are able to adapt to changes in the price when making investments. Hence, the elasticity of demand is in general larger in a long-term perspective than in a short-term perspective [28,32]. The elasticity of supply can also be expected to be higher in a long-term perspective than in a short-term perspective [30]. These case specific factors are not taken into account when the general Palmer et al. estimates are used in an LCA. Hence, the estimates in Table 1 should be used as default values only, if more specific data are not available.

3. Case 1: corrugated board

The application of the conceptual model described above is here demonstrated for a case of increased collection for recycling of old corrugated containers (OCC). The case is theoretical in the sense that it is based in part on assumptions and information not validated. The aim is to illustrate the use of the model, but not to calculate the actual indirect effects of increased OCC collection.

Ordinances from the Swedish government require that 65% of the corrugated containers used in Sweden are reused or recycled [36,37]. However, when the first ordinance was introduced in 1994, the actual collection rate was already significantly higher [38]. From 1995 to 1997, the collection rate gradually increased from 77 to 84% [39–41]. The high collection rate is sustained, in part, through a fee (0.20 SEK/kg) which is levied on fillers and importers and used to financially support the collection and recycling system [42]. However, here it is assumed that the OCC recycling rate in effect is decided by economic forces of supply and demand and not by ordinances from national authorities.

In this theoretical case, it is assumed that the local authorities in Gothenburg make a decision which results in an increase in the OCC collection in Gothenburg (ΔX; see Fig. 2). The choice of corrugated containers to be used in Gothenburg is assumed not to be directly affected by this decision.

Old corrugated containers are traded on an international market. The flows of recycled fibres to and from Gothenburg are very small compared to the total flow in this market ($Y \ll D$; $X \ll S$). Hence, the indirect effects ($\Delta \boldsymbol{B}_X$) of the decision can be calculated from Eq. (8). The OCC is mainly used for the production of new paper and board products, and the virgin material replaced by OCC is mainly virgin chemical pulp. Hence, $\boldsymbol{V}_O$ in this model is the environmental burdens caused by forestry and chemical pulp production.

When OCC replaces virgin material, more than 1 kg (dry matter) of OCC is required to replace 1 kg (dry matter) of virgin pulp. This is due to losses of material in the recycling process and to the difference in quality between corrugated board based on secondary fibres and corrugated board based on virgin fibres. Here it is assumed that each kg of OCC used in other life cycles (D) replaces 0.8 kg of virgin chemical pulp.

With the default elasticities for paper and paperboard other than newsprint (see Table 1), Eq. (8) gives:

$$\Delta \boldsymbol{B}_X \approx \Delta X \cdot [0.44 \cdot (\boldsymbol{R}_\mathrm{O} - 0.8 \cdot \boldsymbol{V}_\mathrm{O}) - 0.56 \cdot (\boldsymbol{C}_\mathrm{O} - \boldsymbol{W}_\mathrm{O})], \quad (11)$$

which indicates that 44% of an increased flow of OCC from Gothenburg replaces virgin material and that the remaining 56% replaces OCC from other locations. As indicated above, the default elasticities do not take into account case specific factors such as the time and location of the OCC collection or the time-frame of the LCA. The broad range of elasticities reported by Palmer et al. [35] indicates that the share of OCC, which replaces virgin material, might be much less or much more than 44%. In conclusion, the indirect effects ($\Delta \boldsymbol{B}_X$) calculated from Eq. (11) should be considered as a best estimate with a high degree of uncertainty.

The indirect effects ($\Delta \boldsymbol{B}_Y$) of a decision — e.g. by a local retail trade company — which result in the use of corrugated containers with an increased share of recycled fibres in Gothenburg — can be calculated from Eq. (9). With the default figures in Table 1, the indirect effects can be expressed as follows:

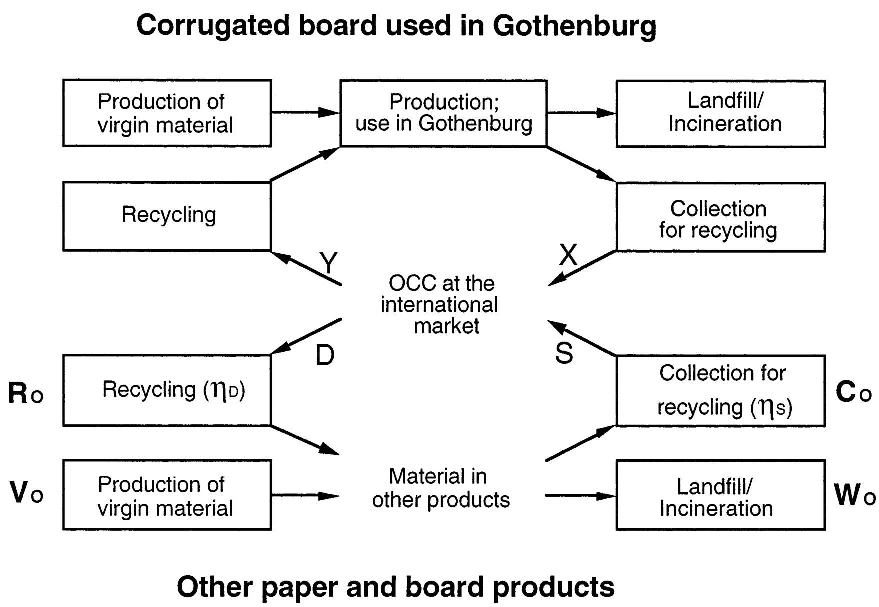

Fig. 2. Application of the conceptual model to the theoretical case of increased collection for recycling of old corrugated containers (OCC) in Gothenburg.

$$\Delta \boldsymbol{B}_Y \approx \Delta Y \cdot [-0.44 \cdot (\boldsymbol{R}_O - 0.8 \cdot \boldsymbol{V}_O) + 0.56 \cdot (\boldsymbol{C}_O - \boldsymbol{W}_O)], \quad (12)$$

where ΔY is the increased demand for recycled fibres for the production of the corrugated containers used in Gothenburg. This indicates that the alternative fate of the secondary fibres in the corrugated containers in Gothenburg to 44% is disposal of as final waste, and to 56% is recycling into other products (including corrugated containers used at other locations). A comparison of Eqs. (11) and (12) shows that the system expansion produces additive results in this case: the environmental burdens credited to a product delivering OCC to the market correspond to the environmental burdens assigned to the product where the OCC is used.

4. Case 2: newsprint

The second case concerns increased collection for recycling of old newsprint paper in Gothenburg. This case is also theoretical in the sense that it is based in part on assumptions and unvalidated information. The aim is to illustrate the use of the conceptual model, but not to calculate the actual indirect effects of increased collection of newsprint.

An ordinance from the Swedish government stipulates that 75% of the newspapers, magazines etc. used in Sweden must be collected for recycling or for other environmentally acceptable processing by the year 2000 [43]. An ordinance from the Swedish Environmental Protection Agency explains that collected old newsprint should be recycled unless there are special reasons for other types of processing [44]. The paper industry has taken on the responsibility for achieving this goal [38]. In 1998, the price of used Swedish newsprint (P_D) was SEK 550/ton [45,46]. In addition to the domestic, recovered material, Swedish pulp mills buy old newsprint in the international market for recycled fibres, where the prices (P_I) are significantly lower — e.g. SEK 130–470/metric ton in Germany, the UK, France and Italy — due to economic subsidies for the newsprint collection [45,46]. For this reason, there was a distinct difference between the Swedish and foreign markets for old newsprint [47]. Swedish paper mills did not want to buy more than what is required by law on the domestic market [45,48]. Hence, the recycling rate of newspapers, magazines etc. used in Sweden was, in effect, fixed by the ordinance from the government. The situation may change in 1999 [39,45], but in this theoretical case it is assumed that it will prevail. To assess the indirect effects of a local increase in the collection of newsprint, the model presented in Section 2 must in this case be modified to include two separate markets (see Fig. 3).

The flows of recycled fibres to and from Gothenburg are relatively small compared to the total flow of domestic old newsprint. A change in the collection rate in Gothenburg is assumed to have marginal effects on the national level. A marginal change in the price of domestic old newsprint will not affect the demand for this material, since the price of imported old newsprint will still be significantly lower. Hence, for marginal changes, the elasticity of demand for domestic old newsprint in Sweden (η_{DD}) is zero rather than the default value of 0.12, which is

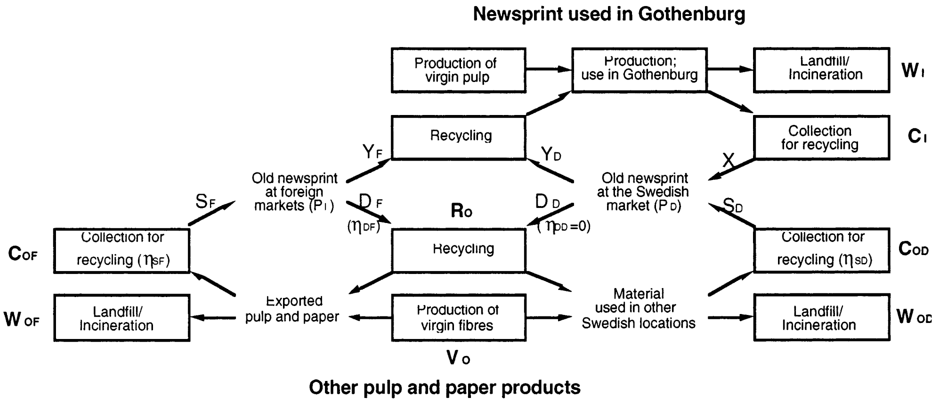

Fig. 3. Application of the conceptual model to the theoretical case of increased collection for recycling of used newsprint in Gothenburg.

presented in Table 1. If the wastepaper ordinances are assumed to be unaffected by a change in collection in Gothenburg, the indirect effects ($\Delta \boldsymbol{B}_X$) of the decision can be expressed as follows:

$$\Delta \boldsymbol{B}_X = \Delta X(\boldsymbol{W}_{OD} - \boldsymbol{C}_{OD}), \tag{13}$$

which indicates that an increased flow of old newsprint from Gothenburg in this theoretical case replaces recycled material from other Swedish locations only. The total effects ($\Delta \boldsymbol{B}$) of increased collection in Gothenburg on the environmental burdens could be small or even detrimental:

$$\Delta \boldsymbol{B} = \Delta X \cdot (\boldsymbol{W}_{OD} - \boldsymbol{W}_I + \boldsymbol{C}_I - \boldsymbol{C}_{OD}) \tag{14}$$

It should be noted that this calculation does not take into account the fact that ordinances can be affected by changes in the real world. For example, the target stipulated for the recycling rate can be increased if the current target is easily achieved. In this case, increased newsprint collection in Gothenburg can contribute to an increased total recycling rate of Swedish newsprint, which is likely to have significant beneficial effects on the environmental burdens [49]. However, the impact on the ordinances is difficult to quantify. This is unfortunate if it means that the impact on the ordinances is not taken into account in the assessment of paper collection in Gothenburg.

The indirect effects ($\Delta \boldsymbol{B}_Y$) of a decision — e.g. by a local daily newspaper — which results in the use of newsprint with an increased share of recycled fibres in Gothenburg will result in an increased use of secondary fibres (ΔY) in the product investigated. The increase may occur in the use of domestic and/or foreign secondary fibres (ΔY_D and/or ΔY_F):

$$\Delta Y = \Delta Y_D + \Delta Y_F \tag{15}$$

An increased use of domestic secondary fibres in the product investigated means that the wastepaper ordinances permit the paper producers to replace the same amount of domestic secondary fibres by less expensive, foreign secondary fibres in other products:

$$\Delta D_D = -\Delta Y_D \tag{16}$$

Hence, an increased use of domestic, secondary fibres in the product investigated has in this model the same effects as an increased use of foreign, secondary fibres in the product investigated. The collection rate for recycling of domestic, old newsprint is fixed through the wastepaper ordinances. Hence, it is unaffected by a change in the use of secondary fibres in the product investigated. The indirect effects of the increased use of secondary fibres can be expressed with a modification of Eq. (9):

$$\Delta \boldsymbol{B}_Y \approx \frac{\Delta Y}{\eta_{SF} - \eta_{DF}}[\eta_{DF}(\boldsymbol{R}_{\mathrm{O}} - A\boldsymbol{V}_{\mathrm{O}}) + \eta_{SF}(\boldsymbol{C}_{\mathrm{O}F} - \boldsymbol{W}_{\mathrm{O}F})] \tag{17}$$

A comparison of Eqs. (13) and (17) shows that the system expansion does not produce additive results in this case: the environmental burdens credited to a product delivering old newsprint to the Swedish market do not correspond to the environmental burdens assigned to the product where the newsprint is used. The reason is that markets with different price elasticities are affected by changes in the inflow and outflow of cascade material across the boundaries of the product life cycle investigated.

5. The 50/50 approximation

When the recycling rate is decided by economic forces and the elasticities of demand and supply are unknown, the indirect effects of changes in the flows of cascade material to and from the life cycle investigated are unknown. It is not known if an increased supply of recovered material from a specific product or a specific location will replace 100% virgin material, 100% recycled material from other sources, or anything in between. When the recycling rate is decided by national authorities, the indirect effects are also unknown unless the effects of changes in the cascade material flows on the legislation and ordinances can be estimated. This uncertainty is an important methodological problem when the indirect effects are significant for decisions, which may be based on, or inspired by, the LCA results.

One way to deal with the uncertainty is to make the assumption that 50% of an outflow of cascade material from the life cycle investigated replace virgin material and that the remaining 50% replace recycled material from other sources. To be consistent, an increased inflow of cascade material to the life cycle investigated should then in the base case be assumed to result in 50% increased collection and 50% reduced used of cascade material in other products. The large uncertainty in the assumption can be taken into account in a sensitivity analysis where the outflow of recycled material is assumed to replace, e.g. only virgin material.

Given the 50/50 assumption, the indirect effects of a change in the flow of cascade material to or from the life cycle investigated can be calculated from Eqs. (8) and (9) as follows:

$$\Delta \boldsymbol{B}_X \approx \Delta X \cdot [0.5 \cdot (\boldsymbol{R}_{\mathrm{O}} - A\boldsymbol{V}_{\mathrm{O}}) - 0.5 \cdot (\boldsymbol{C}_{\mathrm{O}} - \boldsymbol{W}_{\mathrm{O}})] \quad (18)$$

$$\Delta \boldsymbol{B}_Y \approx \Delta Y \cdot [-0.5 \cdot (\boldsymbol{R}_{\mathrm{O}} - A\boldsymbol{V}_{\mathrm{O}}) + 0.5 \cdot (\boldsymbol{C}_{\mathrm{O}} - \boldsymbol{W}_{\mathrm{O}})] \quad (19)$$

Eqs. (8) and (9) present linear relationships between the quantities of virgin and recycled material affected and the indirect effects on the environmental burdens. This means that, given the conceptual model presented in Section 2, the 50/50 assumption will minimise the maximum error in the estimation of the indirect effects. In this sense, the 50/50 assumption results in a crude approximation of the actual indirect effects. The approximation is good when the flows of cascade material to and from the life cycle investigated are small compared to the total flow in the market, the recycling rate is decided by economic forces, and the demand and supply are equally elastic, i.e.:

$$\eta_D \approx -\eta_S \quad (20)$$

6. The allocation approximation

As stated above (Section 1), system expansion is characteristic of change-oriented LCAs. Accounting type LCAs are typically constrained to the life cycle of the product investigated [4], although this depends on the conventions on which the accounting type LCA is based. When the LCA is constrained to the product life cycle investigated, an allocation of the environmental burdens of the primary production, recycling and final waste management of the cascade material is necessary. The conceptual model described in Section 2 can be used as a basis for an allocation method as well as for system expansion. If the environmental burdens of activities within the life cycle investigated are similar to the environmental burdens of the corresponding activities outside the life cycle investigated, i.e.:

$$\boldsymbol{V}_{\mathrm{O}} \approx \boldsymbol{V}_I = \boldsymbol{V}, \quad (21)$$

$$\boldsymbol{R}_{\mathrm{O}} \approx \boldsymbol{R}_I = \boldsymbol{R}, \quad (22)$$

$$\boldsymbol{W}_{\mathrm{O}} \approx \boldsymbol{W}_I = \boldsymbol{W}, \quad (23)$$

and

$$\boldsymbol{C}_{\mathrm{O}} \approx \boldsymbol{C}_I = \boldsymbol{C}, \quad (24)$$

similar results as for a system expansion are obtained if the environmental burdens allocated to a unit outflow of cascade material to the market for recovered material ($\boldsymbol{B}_X$) correspond to the indirect effects caused by a unit change in the outflow. The environmental burdens allocated to a unit inflow of cascade material to the market ($\boldsymbol{B}_Y$) should then correspond to the indirect effects of a unit change in the inflow (cf. Eq. (10)):

$$\boldsymbol{B}_X = \boldsymbol{B}_Y = \frac{1}{\eta_S - \eta_D}[\eta_D(\boldsymbol{R} - A\boldsymbol{V}) + \eta_S(\boldsymbol{C} - \boldsymbol{W})] = E \tag{25}$$

The entity E, which is defined by Eq. (25), can be denoted the environmental value of the cascade material in the market for recovered material. The conclusion is that system expansion is not always necessary in order to model the indirect effects of an action. When equations Eqs. (21)–(24) hold, an allocation according to Eq. (25) results in a good approximation of the system expansion. It can also be concluded that an accounting type LCA can take into account the indirect effects of recycling if the conventions, on which the accounting type LCA is based, allow for system expansion or for an allocation method that produces approximately the same results. The advantage of taking the indirect effects into account in an accounting type LCA is that the accounting results will give an indication of the consequences of any future action, which will affect the flows of cascade material to or from the life cycle investigated.

In the 50/50 allocation method which was presented in an earlier paper [50] and recommended for key issue identification by Lindfors et al. [51], half of the environmental burdens of virgin production and final waste management of a cascade material are allocated to the product life cycle where the cascade material is produced in the form of virgin material. The other half is allocated to the product life cycle where the cascade material is disposed of as final waste. Half of the environmental burdens of each recycling process are allocated to the product life cycle that supplies the cascade material to the recycling process. The other half is allocated to the product life cycle where the recycled material is utilised. In terms of Eq. (25), the environmental value of the cascade material in the market for recovered material can then be expressed as follows:

$$E = [-0.5\cdot(\boldsymbol{R} - \boldsymbol{V}) + 0.5\cdot(\boldsymbol{C} - \boldsymbol{W})] \tag{26}$$

When Eqs. (21)–(24) hold, and virgin material is replaced by recycled material on a kg by kg basis (i.e. $A = 1$), the 50/50 allocation method will give similar results as the 50/50 assumption discussed above. In this sense, the 50/50 allocation method is an approximation of system expansion with the 50/50 assumption. The conclusion is that the 50/50 allocation method results in a crude approximation of the indirect effects, based on a very crude estimate of how the market reacts to a change in the supply of, or demand for, the recycled material. The approximation is good when equations 20–24 hold, virgin material is replaced by recycled material on a kg by kg basis, and the flows of cascade material to and from the life cycle investigated are small compared to the total flow in the market.

7. Discussion

Although the examples above are theoretical, they demonstrate that the indirect effects of open-loop recycling can be estimated in terms of elasticities of supply and demand when the recycling rate is decided by economic forces. The condition is that decisions based on, or inspired by, the LCA results have marginal effects on the total market for the recycled material. When the recycling rate is decided by authorities, the concept of a market for recovered material, which connects the life cycle investigated to other life cycles, can still be used to estimate the indirect effects of recycling. However, in this case it may be necessary to adjust the conceptual model.

The conceptual model can be used for system expansion. It can also be used to calculate a basis for allocation, if the environmental burdens of activities within the product life cycle investigated are similar to the environmental burdens of corresponding activities in other life cycles. The conceptual model is designed for use in change-oriented LCAs. It can also be used in accounting type LCAs, if the conventions on which the accounting type LCA is based allows for system expansion or for an allocation method that produces approximately the same results. With the exception of the 50/50 allocation method discussed above, none of the existing approaches to allocation in open-loop recycling referred to in Section 1 takes into account the effects on the market in terms of price elasticities or similar.

In practice, it can be difficult to obtain adequate estimates for the elasticities of supply and demand. Furthermore, it will probably not be feasible in many cases to calculate such elasticities within an LCA. For calculation of the elasticities of supply and demand, an econometric model of the costs and preferences of suppliers and buyers must be constructed [28,33]. However, once the elasticities are calculated, they can be used in other case studies with a similar time-frame, etc. Hence, it is an important research task to calculate the elasticities of supply and demand for the most important markets for recovered material. Research on the elasticities of supply and demand for recovered paper is currently conducted in several locations [e.g. [52–54]]. When case-specific elasticity estimates are not available, the default data in Table 1 can be used or, as a last option, a 50/50 assumption can be made.

The examples in Sections 3 and 4 are sufficiently realistic to highlight several issues that should be considered when the conceptual model is applied. First, it is necessary to identify the cascade material or materials for which the market is significantly affected by a change in the flows to and from the life cycle investigated. In the cases above, it was assumed that the newsprint and OCC markets can be separately analysed. Although used newsprint and OCC compete in some applications, there are significant differences in quality due to, e.g. different fibre lengths.

Second, it is necessary to find out if the recycling rate for this material or these materials is decided by economic forces or by authorities. If the market for recovered material is stimulated by authorities through, e.g. subsidised collection for recycling, the actual recycling rate obtained can still be decided by economic forces. The OCC case illustrates that the recycling rate can be decided by economic forces even if a minimum recycling rate is stipulated by the authorities.

Third, the geographical structure of the market should be identified. In the theoretical cases above, the market for used Swedish newsprint is separate from the market for used newsprint from other countries. However, OCC is assumed to be traded on a single, international market.

Fourth, it should be decided whether or not the flows of cascade material to and from the life cycle investigated are sufficiently small compared to the total flow at the market, that actions within the life cycle investigated have marginal effects on the market. Eqs. (3)–(9) present approximations. Uncertainties in the elasticities of supply and demand and in the environmental burdens of activities outside the product life cycle investigated are likely to be large. The additional uncertainty introduced through these approximations are likely to be negligible in comparison, as long as the flows of cascade material to and from the life cycle investigated are small compared to the total flow in the market for the recovered material.

Fifth, the time aspects should be considered. It should be decided what time frame is relevant for the study of the indirect effects. The price elasticities are in general larger in a long-term perspective than in a short-term perspective [28,30,32]. Furthermore, the elasticities and ordinances can change over time. This is true also for $\boldsymbol{V}_{\mathrm{O}}$, $\boldsymbol{C}_{\mathrm{O}}$ and other parts of the model. For products with a long lifetime, they may be significantly different at the time of production of the product compared to the time of disposal.

Sixth, the virgin material competing with the cascade material should be identified. In many cases, it can be assumed that the competing virgin material is virgin material of the same type as the cascade material. For example, it was assumed above that the virgin material competing with OCC is mainly virgin, chemical pulp. However, for cascade plastics, a significant share of the competing virgin material may be, e.g. wood or concrete [55,56].

The examples above also indicate the existence of two drawbacks with ordinances that stipulate a minimum recycling rate. If the stipulated recycling rate is significantly lower than the recycling rate that is obtained in a free market, the OCC case indicates that the ordinances are ineffective. If the stipulated recycling rate on a national level is significantly higher than the recycling rate obtained in a free market, the newsprint case indicates that any initiative on the municipal or individual level to increase the collection for recycling is ineffective in terms of increasing the total recycling rate. Both of these potential drawbacks might be eliminated if the ordinances are frequently revised to maintain a steady pressure on the recycling system. Such a revision can include, e.g. an adjustment of the stipulated recycling rate.

The potential drawbacks are eliminated if the stipulated recycling rate is replaced by economic or fiscal instruments such as raw material taxes, subsidies for the collection of material for recycling or deposit/refund systems. The model indicates that such instruments would be effective in that the supply of, and/or demand for, recovered material would be stimulated. Hence, the recycling level would be higher than without any regulatory instruments. However, the actual recycling rate would still be decided by economic forces, and the model indicates that a municipal or individual initiative to increase the collection for recycling would result in an increase in the total recycling rate.

It goes beyond the scope of this paper to establish conclusive evidence on whether or not the drawbacks of the stipulated minimum recycling rates exist in reality. The models presented here are simplified representations of the real-world system. In the real world, the ordinances might have an effect on the actual recycling rate obtained, even if this recycling rate is significantly higher than the stipulated minimum recycling rate [38].

Finally, it should be made clear that this paper represents only one step towards making LCA a more efficient tool for increasing ability to anticipate the environmental consequences of ones actions. The conceptual model that is presented in this paper makes it possible to take certain market aspects into account, market aspects that are relevant for anticipating the consequences of changes in the flows of recycled material to or from the product life cycle investigated. Further methodological development is required to make it possible to take other market aspects into account. Market aspects influences, for example, the indirect effects of changes in the flow of co-products from the life cycle investigated. These indirect effects depends on how the market for the function provided by the co-product reacts to the change. The indirect effects can probably often be modelled through the use of price elasticities of demand for and supply of this function.

To accurately model the consequences of the actions on multioutput processes — i.e. processes with more than one product — the economic as well as the physical links between the products should be taken into account [24]. This is typically not the case in current LCI practice.

Market aspects, in fact, influences the consequences of our actions in almost every part of the system investigated. Most products, materials, and energy that are used in the various processes in the life cycle investigated are bought on a market. If one's actions means that more paper, steel, oil etc. is used in the life cycle investigated, this does not automatically result in the corresponding increase in the production of these goods. Instead, less goods may be used in other systems. To accurately take this fact into account, an analysis of the relevant market aspects is required for each part of the system investigated. This type of radically effect-oriented environmental assessment has been briefly discussed elsewhere [57].

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