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Modelling and analysis of international recycling between developed and developing countries

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Abstract

To deal with the complexity of recycling, a wide variety of models have been developed, each serving a specific purpose. Despite the current trend increasing international trade in recycling-related material flows, the international dimension of physical and economic relationships in recycling is often ignored in current models and analyses. This paper develops a formal model of an international material-product chain (MPC) that represents the mechanism behind international recycling. The attention is focused on the case of a developed and a developing country that exchange material commodities, final products and recyclable waste. Among others, the model demonstrates that taking into account environmental externalities results in higher levels of recycling. Moreover, we show that international recycling is mainly driven by regional differences in the quantity and quality of factor endowments and economic efficiency of recycling. Given that industrialised countries are relatively well endowed with recyclable waste, the recovery rate usually exceeds the utilisation rate. In developing countries, an opposite pattern is observed.

JEL classification: F1; O1; Q3; Q53; Q56

Keywords: Foreign trade; Secondary materials; Waste policy

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1. Introduction

To deal with the complexity of recycling, a wide variety of empirical models have been developed, each serving a specific purpose. All these models define analytical boundaries, i.e. no one model captures the complete system of economic and recycling processes. Usually, the international dimension of physical and economic relationships behind recycling is ignored. This is not in line with the current trend of increasing international trade in secondary materials that end up being recycled. For example, while in 1970 only 15% of the recovered copper scrap was traded internationally, this share grew to 48% in 1997. Similar increases in the trade intensity can be observed for waste paper and aluminium (Van Beukering, 2001).

The globalisation of the recycling market increases the need for analysis of the international material-product chain (MPC) that captures the various stages in the international life cycle of a material or physical product. The aim of this article is to develop a formal, two-country model that represents the basic economic mechanisms behind international recycling. Subsequently, the model will be analysed, where a comparison will be drawn between a world with recycling in autarkic economies and one with recycling in the context of an international system of trade relationships. Although the model is fairly general, the case of interaction between a developed and a developing country will be emphasised, as this currently seems to be the dominant pattern in international recycling (van Beukering, 2001).

The organisation of the article is as follows. In Section 2, the variety in approaches adopted by existing applied models that deal with (elements of) recycling is examined. Section 3 presents a conceptual model of international recycling, and provides a detailed discussion of the various elements it contains. In Section 4, this is translated into a set of formal models of recycling in autarkic and trading economies, which are subsequently analysed and compared. A final section concludes.

2. Characteristics of current recycling models

A review of 31 empirical quantitative studies has been conducted to gain insight into the variety of elements that are potentially relevant in analysing international recycling (see Table A.1 in Appendix A). The overview illustrates the diversity of studies but should not be considered as an exhaustive survey of empirical-quantitative, economic models of recycling.[1] Given the number of studies surveyed, however, it does provide a good indication of the variety of approaches found in the literature. This is reflected in four characteristics, relating to model objective, system boundary, spatial-geographical dimension and temporal features.

[1] Theoretical economic analyses of recycling include the following. Kandelaars and van den Bergh (1997a) adopt a partial static equilibrium framework. Dinan (1993) and Fullerton and Kinnaman (1995) study recycling with theoretical general equilibrium models. Dynamic models of recycling are studied in Lusky (1975), van den Bergh and Nijkamp (1994) and Kandelaars and van den Bergh (1997b). For the place of recycling models in the broader literature on economic models with material flows, see van den Bergh and Janssen (2004, notably chapter 2).

2.1. Objectives and model types

Three types of recycling models can be identified. (1) *Physical models* such as Substance Flow Analysis (SFA) and Life Cycle Analysis (LCA) describe the material flows or measure the impact of materials and products on the environment. They ignore economic, substitution and dynamic aspects of material flows (Kandelaars and van Dam, 1998). Because recycling has been traditionally treated as a technical problem, physical models seem to dominate: 14 out of 31 studies can be classified as such. (2) *Economic models*, such as partial and general equilibrium models, analyse the relationship between the use of materials and economic variables but mostly ignore the environmental impact and substitution between materials. Ten out of 31 studies are classified as economic models. (3) *Integrated models*, such as the material-product chain (MPC), are defined as a set of linked flows of materials and products and cover the complete life cycle of a material, often addressing mass balance explicitly. Only 7 out of 31 studies can be classified as integrated models.

Recycling models can also be classified as descriptive and scenario versus optimisation models. Descriptive and scenario models often include dynamic, causal relationships. *Optimisation* models apply an optimisation objective and usually focus on static relations between variables. These models often allow substitution between production factors, such as capital, labour, energy and materials (Anderson, 1987). Seventeen out of the 31 studies are driven by optimisation.

2.2. System boundaries

Recycling is embedded in a chain of economic and physical–technical processes and thus has potentially up- and down-stream effects. To address these, the vertical and horizontal system boundaries have to be determined with care. The *vertical* boundary follows from the choice of where in the life cycle to cut off the analysis. The *horizontal* boundary is the result of choosing between a focus on a single material or product and taking into account substitution effects between different materials (Kandelaars and van Dam, 1998).

Usually, a distinction is made between open- and closed-loop recycling (Boguski et al., 1994). *Closed-loop recycling* is a process in which the material of a physical product is recycled into the same produce, a process that may-in theory-be repeated endlessly. *Open-loop recycling* is a process in which the (virgin) material of a product is recycled in a product that after use is discarded. Open-loop recycling provides a more realistic representation of most types of current recycling (Finnveden, 1999). For certain materials, however, closed-loop recycling is a suitable form. For example, in the case of lead, lead-acid batteries are both the main source and destination of the recycling process (Socolow and Thomas, 1998).

2.3. Spatial-geographical setting

With the exception of logistic studies, most analyses of recycling tend to underestimate importance of the spatial dimension. Geographical factors, however, often play a crucial role both within and outside the focal area. Within the region, for example, the population density of the focal area determines to a large extent the success of recycling programmes. Moreover, a region may strongly depend on imports or exports of materials or material resources. Of the 31 surveyed studies, 11 assume closed regions, 13 include elements outside the region in an exogenous manner and 7 studies allow elements outside the region to influence the processes in the focal area.

International trade of secondary materials is growing rapidly. For example, while in 1970 only 15% of the recovered copper scrap was traded internationally, this share grew to 48% in 1997. Similar increases in the trade intensity can be observed for waste paper and aluminium (van Beukering, 2001). To analyse international recycling, it is important to separate recycling into waste recovery and utilisation phases. After all, secondary materials that are recovered and exported by a country can no longer be utilised by that country. In the survey, only 16 out of 31 studies clearly distinguish between the recovery and the utilisation of recyclable waste.

The spatial dimension is not only important from the perspective of economic trade of secondary materials. Environmental problems may also cross borders, i.e. environmental externalities may be of an international nature. Eder and Narodoslawsky (1999) propose a typology of a region's responsibility for environmental pressures, distinguishing responsibility for impacts inside and outside the boundaries of the region. Hoekstra and Janssen (2002) propose a similar approach in the context of trading countries.

2.4. Temporal features

Recycling studies can be static or dynamic in nature. Dynamic models allow to address changes in technology and demand, accumulation of capital and pollution and time lags in investment and R&D or in pollution impacts on welfare. Only 9 of 31 surveyed studies have explicitly addressed the temporal dimensions of recycling.

The specific economic relevance of incorporating dynamic processes in models of recycling systems varies with the application. For example, time lags in recycling processes take distinct forms for different materials (Grace et al., 1978). Most packaging materials have a lifetime of less than a year, while construction materials last more than 15 years. Time lags may also be due to recovery and utilisation. Recovery costs and commodity prices play an important role here. In addition, the physical features of materials count. For example, organic waste cannot be stored for a long period of time, and therefore has to be composted without much delay. Car tyres, on the other hand, are often stored in monofills for long periods of time before being recycled. Finally, environmental effects of (lack of) recycling activities may also occur with a delay.

In analysing recycling, the waste generation rate per capita income is likely to alter over time, with evident consequences for waste planning. Consumer preferences may change over time, thus affecting solid waste generation per capita or recycling itself. For example, Pei and Tilton (1999) study the factors affecting the income elasticity of metal demand. Especially in developing countries demand is sensitive to changes in income.

Product life extension is another factor that causes changes in the MPC. Positive economic and environmental effects may result from it, due to lower levels of production and disposed waste. Negative impacts are also possible, due to use of more materials per unit of product or due to a phenomenon known as the 'vintage effect', i.e. a lack of replacement of old, inefficient equipment (Conn, 1977; Navaretti et al., 1998).

3. A conceptual model of the international material-product chain

Since recycling is strongly dependent on up- and down-stream processes, the most relevant segments of the international MPC should be included in the analysis. These segments include the production of primary and secondary materials, the manufacturing of final products, the consumption of these products and the management of solid waste. Second, international trade in various parts of the MPC should be allowed. This trade can take place between different segments (inter-industry trade) and between similar segments (intra-industry trade). Third, the most fundamental elements that affect recycling in the MPC should be accounted for. Such model elements may include economic, environmental, institutional, dynamic and international aspects in each stage of the MPC.

Fig. 1 presents a conceptual model of international recycling that meets these requirements. This framework represents the MPCs of two hypothetical countries – A and B – which exchange of material commodities, final products and recyclable waste. Following the sequence of the segments in the MPC, the most relevant model elements that influence the domestic and international movement of material flows, are discussed below. Special attention is paid to the differences in the MPCs between developed and developing countries.

3.1. Production of raw commodities

In the production stage of the MPC, primary and secondary commodities are prepared for the manufacturing stage. The most important factors in determining the

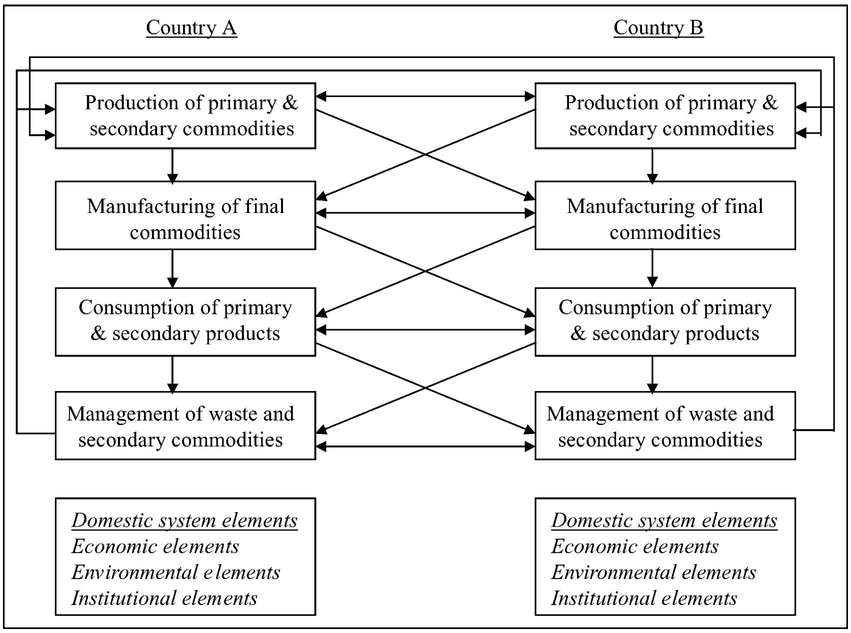

Fig. 1. A conceptual model of international recycling.

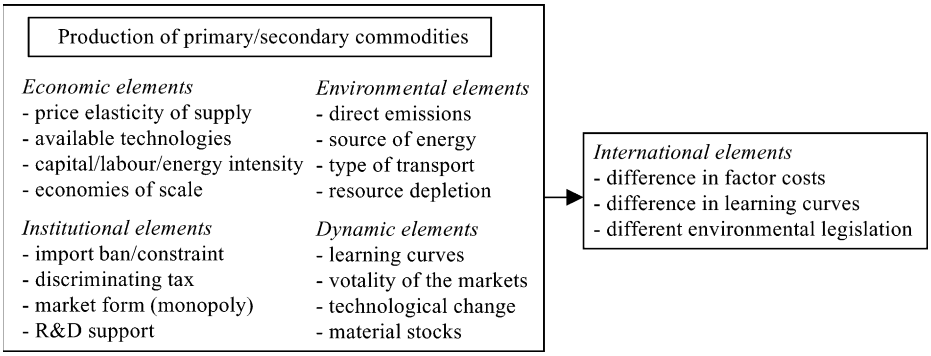

Fig. 2. Model elements: production of raw commodities.

level of recycling in the raw commodity production stage of the MPC are depicted in Fig. 2.

As financial motives often form a strong incentive for recycling, the relative costs and benefits of primary and secondary commodities predominantly determine the input choice of producers (Bower, 1977). The costs are determined by the purchase price of the inputs and the additional factors required to convert the materials into commodities. The benefits depend on the selling price of the commodities to the manufacturers.

Several differences exist between the secondary and the primary commodity industry. First, the scale of operation in the recycling industry is generally smaller than in the primary commodity industry. Second, primary production processes are generally energy and capital intensive and require limited and highly skilled labour, while secondary processes consume relatively little energy and are labour intensive. This is why an increase in energy prices promotes material recovery and utilisation (Bower, 1977). Third, the secondary commodity markets are often claimed to be more volatile than primary commodity markets (Yohe, 1979; Pearce and Grace, 1976). This is one of the reasons why recycling industries operate on a smaller scale. Risk-averse firms then refrain from investing in recycling activities (Butlin, 1977). Fourth, the secondary industry is less environmentally damaging than the primary industry (Bartone, 1990).

From an international perspective, there are several differences between developed and developing countries in this segment. First, the availability and costs of production factors vary significantly. Developing countries are well endowed with unskilled labour and primary natural resources. Capital, skilled labour and secondary resources are the abundant factors in developed countries. Second, the shape of and the position on the learning curve in the industry differs. Therefore, technological change is less easily accomplished in developing countries. High-transaction costs to switch to alternative, large-scale technologies prevent recycling firms in the South from making the change to these technologies. Instead, they tend to stick to technologies, which they have already been using for a long period of time (Navaretti et al., 1998). A third difference is relates to this, namely that the scale of operations in developing countries is generally smaller. A final difference is that environmental legislation is less strict in developing countries, which obviously will affect waste management, trade in materials and recycling.

3.2. Manufacturing of final commodities

Final commodities are intermediary products suitable to be directly converted into consumer goods (e.g. crude steel and Kraft paper). Most final commodities can be produced from primary and secondary commodities. The crucial factors that determine the recycling level in the manufacturing stage of the MPC are shown in Fig. 3.

The choice to use secondary materials in the final commodities depends on a number of factors. First, the substitutability of primary and secondary commodities in the manufacturing process varies across materials. For example, newspaper can be made of both wood pulp and waste paper. Until recently, writing paper could not use waste paper in its manufacture because the latter is of lower quality (Weaver et al., 1995). Second, manufacturers will only choose secondary materials if constant quality and quantity of supply is guaranteed. Secondary commodity inputs are generally of a more heterogeneous quality than primary materials. Therefore, there is a higher risk that the production process will malfunction due to the low quality of the inputs. Another source of uncertainty is the relative instability of the secondary commodities market, which jeopardises the continuity of the manufacturing process (van Beukering and Bouman, 2001). Third, the input choice has an effect on the environmental impacts of the manufacturing stage.

From an international perspective, various factors need to be taken into account. On the one hand, many developed countries have adopted legislation to encourage or mandate the utilisation of waste. Examples are mandated minimum recycled material content in selected products and government procurement practices that favour recycled materials. These policy interventions are uncommon in developing countries. Therefore, such product standards may create conflicts in international trade. On the other hand, manufacturers in the North are generally exposed to more stringent standards with regard to the utilisation of secondary materials. For example, it is strictly prohibited to use recycled materials in food packaging. Although similar restraints apply to producers in many developing countries, the level of enforcement there is much lower. An additional aspect is the large impact of transport costs of bulky final commodities. This may discourage the international trade of primary and secondary products. Finally, the labour costs are especially important in the manufacturing industry, which is relatively labour intensive. This creates a comparative advantage for manufacturing in developing countries.

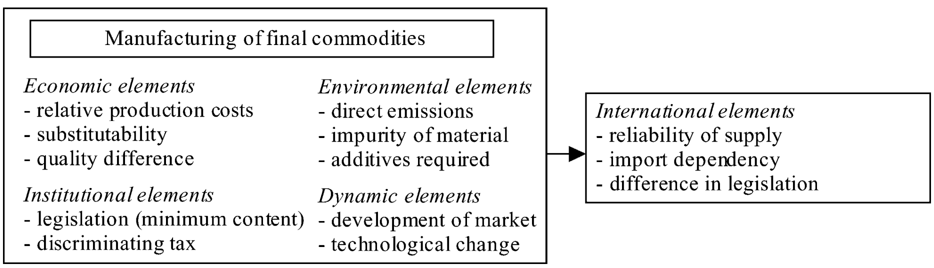

Fig. 3. Model elements: manufacturing of final commodities.

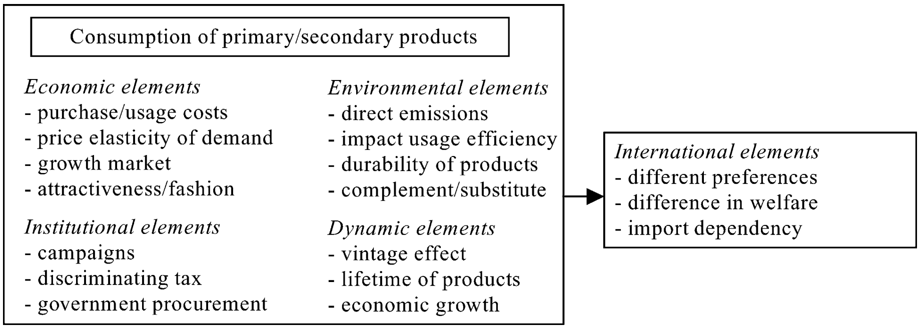

Fig. 4. Model elements: consumption of final products.

3.3. Consumption of final products

Consumers are important as customers of potentially recycled consumer products and as suppliers of recyclable materials. Consumer products are final goods generated in the final production (manufacturing) stage in the MPC before consumption (e.g. cars and books). These products may contain both primary and secondary commodities. The most important factors in determining the level of recycling in the consumption stage of the MPC are depicted in Fig. 4.

The willingness to recycle by consumers depends on a number of factors. First, consumers with high-income levels are more likely to voluntarily participate in recycling programmes (Jenkins et al., 1999; Hong et al., 1993). Secondly, this willingness declines if such recycling is time-intensive (Godbey, 1996; Jenkins et al., 1999). This implies that time and attitudes toward time are critical variables in any attempt to understand changes in the generation of municipal solid waste from household sources. Finally, the direct environmental effect of consuming secondary products may be more pronounced due to the vintage effect and their lower durability. For example, the lifetime extension of a product through increased reuse and recycling often results in relatively higher energy consumption levels because the technological improvements are not embodied in reused products, such as cars and refrigerators.

The international context plays a role in various ways. First, high-wages are closely correlated with strict environmental regulation and stronger environmental awareness (Dasgupta et al., 1996; Mani and Wheeler, 1998). Therefore recycling is promoted more in high-income countries (Jenkins et al., 1999; Hong et al., 1993). The demand for inexpensive secondary products, however, is especially large in poor countries (van Beukering, 1997). Secondly, cultural differences can have an impact on the purchasing behaviour of consumers. Kishino et al. (1999) show with respect to purchasing behaviour for toilet paper how Germans attach a higher importance to the environmental aspects of the product than Japanese.

3.4. Management of solid waste and other residues

The MPC waste stage deals with the management of solid waste and recyclable residues. Solid waste comprises residue materials that can no longer be converted into useful materials

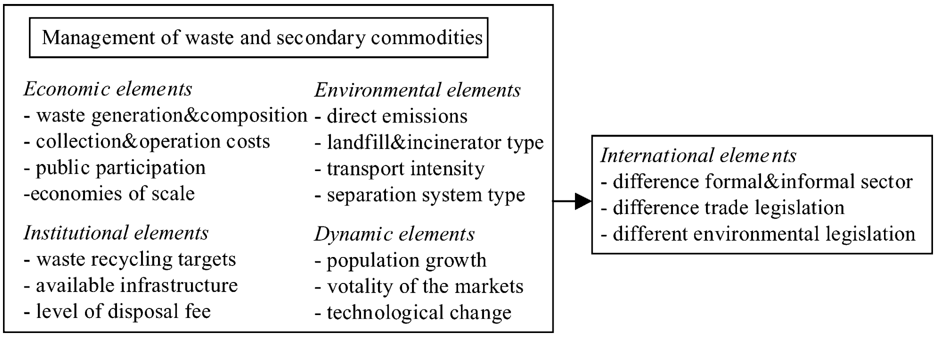

Fig. 5. Model elements: waste management of residues.

or products in an economically feasible manner. Recyclable residues are materials that are economically suitable for recovery. The main factors that determine the level of recycling in the waste management stage are shown in Fig. 5.

A number of issues are important to modelling this segment. First, due to degradation of products and materials, reuse and recycling ultimately will reach their limits. Then they should preferably be used for the generation of energy (‘thermo-recycling’). This form of sequential exploitation of the full potential of a resource is consistent with the notion of resource cascading (Sirkin and Ten Houten, 1993). Second, scale effects are relevant in the waste management stage. For example, a higher level of waste generation (per capita) allows for a higher efficiency of recovery (van Beukering and Bouman, 2001). Also the composition of waste from high-income households allows for a higher degree of recovery (Chang and Lin, 1997). Similar scale effects apply to waste collection and the operation of landfills and incinerators (Palmer et al., 1997). Third, because waste management services are traditionally not market driven, government legislation and its enforcement are critical to development of waste management and recycling. The existing type of infrastructure and recovery system often restricts future developments. In the Netherlands, for example, significant investments have been made in incineration capacity, as a result of which it is economically unattractive to switch to other types of waste management in the short-run.

The international context plays a role in the following ways. First, differences in legislation determine the direction and volume of certain material flows. For example, international differences in the disposal fee make it worthwhile to export waste materials as recyclable commodities, whereas in reality these flows are destined for disposal (Rosendorfová et al., 1998). Second, despite potential economic gains from trade, various international agreements, such as the Basel Convention, prohibit the international trade of certain hazardous recyclable materials. Third, especially in developing countries the existence of an informal recovery sector allows for large levels of recycling. In developed countries, the recovery sector is formally organised and often subsidised. Finally, the types of instruments used differ between countries. Developed countries increasingly use economic instruments to motivate households to minimise waste generation. In developing countries the administrative capacity is lacking to implement such policies.

4. A formal model of international recycling

To demonstrate the essential features and implications of the international dimension in recycling, a simple analytical model is developed. The model is of a static nature as is common in the literature on international trade theory. This implies that stocks are constant. As a result, the model is less suitable to address issues surrounding precious materials like silver and gold. The assumption is, however, not overly restrictive when describing recycling markets for certain bulky secondary materials, such as waste paper. Here, accumulation of stocks, if relevant at all, always is a short-run phenomenon and thus never has a structural character.

The model is developed in two steps. First, in Section 4.1, a two-region–one-material–one-product model with recycling is presented, where no trade between the regions is allowed. The resulting model represents a sort of 'autarkic' MPC. Next, Section 4.2 extends this to a model that allows for trade in primary commodities, recyclable waste and final products. This model represents an 'international' MPC with recycling.

The two regions represent high-income developed (industrialised) countries (ic) and low-income (developing) countries (dc). This distinction is applied as both regions reveal very different trade and recycling features. The distinction between the two regions in the model is based on differences in factor endowment of labour and primary and secondary resources. Developed countries are well endowed with secondary (recyclable waste) resources, capital and highly skilled labour. Developing countries are well endowed with primary resources and unskilled labour, while lacking capital. The developed countries therefore have a comparative advantage in the production of secondary commodities and the manufacturing of products from primary commodities. The developing countries have a comparative advantage in producing primary commodities and manufacturing final products from secondary commodities.

The optimal configuration of trade in secondary materials results from the minimisation of social costs at the system's level. The private costs are determined by the use of a number of production factors consisting of labour (L^i), capital (K^i) and extracted material (E^i). The costs for these production factors are p^i_L, p^i_K and p^i_E. Besides the private costs of these production factors, external costs are caused by the non-recycled waste flows (W). The costs of these external effects are denoted as p^i_W. The defined prices differ between the regions. The optimisation process is conducted under two conditions. The first is that the private costs are minimised. Private costs consist of the accumulated costs for labour, capital and materials. The second condition is that the social costs are minimised. The social costs are the sum of the private and the external costs. External costs are the costs related to using the production factor 'environment'.

Fig. 6 illustrates a situation in which the internalisation of external costs shifts the recycling equilibrium in a country. The x-axis ($0D$) presents the fixed demand, which can be satisfied by primary and secondary materials. Reading from left to right, the left y-axis depicts net benefits of the consumption of secondary materials. Reading from right to the left, the right y-axis represents the net benefits of the consumption of primary materials. Two negatively sloped net benefit functions have been drawn. Increased consumption of primary materials results, for example, from increased scarcity, which requires more extraction effort and thus higher costs. Increased consumption of secondary materials leads to

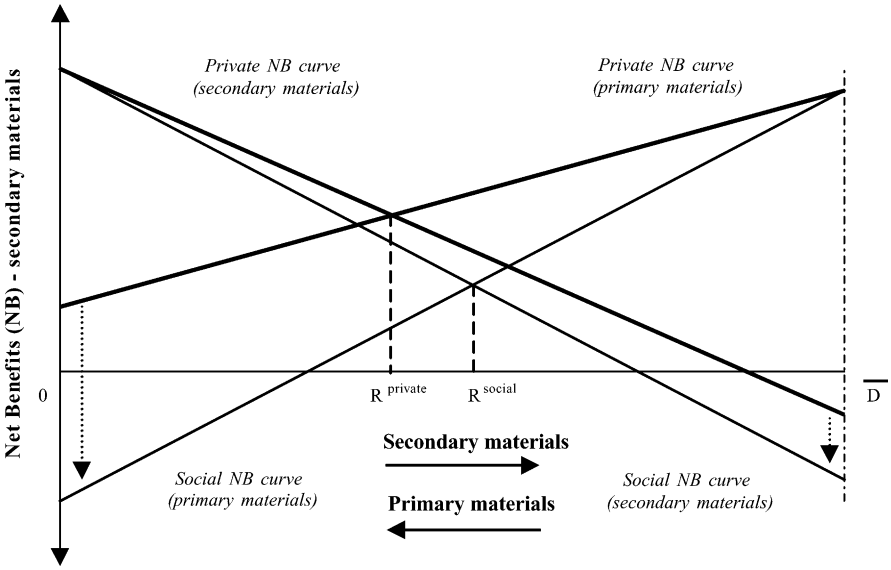

Fig. 6. Externalities of virgin and secondary production.

lower net benefits because, for example, a higher degree of recovery generally results in a lower quality of the recovered materials. Both marginal benefit curves intercept the horizontal axis. This indicates that, beyond a certain degree of primary or secondary utilisation, marginal costs exceed the marginal benefits.

In a situation, where the optimal material configuration is based on private costs only, the allocation of inputs is determined at R^{private}, where the marginal benefits of primary and secondary materials coincide. In this equilibrium, the overall demand is satisfied by an amount of $0R^{\text{private}}$ of secondary materials and an amount of $R^{\text{private}}D$ of primary materials. Due to internalisation of external costs, the recycling equilibrium will shift. In this case, it is assumed that both the production of primary and secondary materials generate negative externalities. Negative effects of secondary materials may result from potential health impacts on waste recovery workers. Negative effects of primary materials may result from the increased rate of depletion of natural resources. Therefore, the social net benefit curves for both materials lie below the private net benefit curves. Externalities of primary materials are larger than for secondary materials. In the new situation, the equilibrium shifts in favour of recycling (from R^{private} to R^{social}). The amount of secondary materials increases from $0R^{\text{private}}$ to $0R^{\text{social}}$. If negative externalities of recycling dominate, however, a shift in the opposite direction may occur.

4.1. The autarkic material-product chain

Here, we first present a model of the MPC for a two-country world under autarkic conditions. The two regions represent industrialised or developed countries (ic) and developing countries (dc). The regions differ in terms of factor prices, factor endowment for primary resources, per capita demand and economic efficiency in various stages of the MPC. No interaction occurs between the regions. The model describes interaction of physical and monetary dimensions, both covering the full life cycle of the material. The production factor dimension is exogenous, i.e. not made dependent on the economy: it only serves as a source of factor and resource inputs in the MPC. Changes in the production factors dimension influence the physical dimension through the monetary dimension. (Note that regions are denoted as superscripts and segments (stages in the MPC) are denoted by subscripts).

The static nature of the model implies exogenous process techniques. At the beginning of the MPC, a primary resource is extracted and processed into a primary commodity in the primary production segment (P). The secondary resource that is retrieved from the discharged waste flow is processed into a secondary commodity in the secondary segment (S). Both commodities are transformed into final products in the manufacturing segment (Q). This manufacturing process satisfies the exogenous demand (D). After consumption, the final products are either discarded to the waste management segment (W), or separated and supplied to the waste recovery segment (R). In the latter stage, the recyclable waste is cleaned and supplied to the secondary commodity segment. The production of P, S and the manufacturing of Q generate non-recycled waste as a by-product. These are denoted by W_P, W_S and W_Q, respectively.

The *production factor dimension* is exogenous. The stocks and prices of the factors: extracted resources (E), capital (K) and labour (L), are given. In other words, the MPC is a partial equilibrium model: the clearing of factor markets is not part of the optimisation process. Labour costs (p^i_L), capital costs (p^i_K) and resource costs (p^i_E) are applied to transfer the physical requirement for labour, capital and resources into monetary units. Labour, capital and waste are applicable for all segments in the MPC. Resources are only accounted for in the primary materials sector, which converts extracted resources (E) into primary materials (P). The external costs are driven by the amount of the non-recycled waste (W). This flow is accounted for by a price per physical unit of waste (p^i_W), which represents the environmental damage that is caused by the non-recycled waste. Examples of such environmental damage include, for example, groundwater pollution resulting from effluent leakage from landfills or health damage caused by air pollutants emitted by waste incinerators. Extracted resources, materials and waste flows are expressed in tonnes, capital in pieces of equipment and labour in number of workers.

The *monetary dimension* of the model covers accounting for the costs of the production factors and the non-recycled waste. A global planner determines the optimal configuration of the autarkic MPC with the aim of minimising the total costs (TC) of satisfying demand in both regions (i). The control variables of the global planner are the price of waste (p^i_W), and the primary resources (p^i_E). The objective function is formulated as:

$$\min \mathrm{TC} = \sum_{i\in\{\mathrm{ic},\mathrm{dc}\}} \sum_{j\in\{Q,P,S,R,D\}} p^i_L L^i_j + p^i_K K^i_j + p^i_E E^i_j + p^i_W W^i_j \tag{1}$$

Here, u^i denotes the utilisation rate and r^i the the recovery rate (these will be formally defined later on). The definition of the total costs (TC) varies, depending on the decision perspective of global planning. First, the planner can base the decision on private costs (PC), only. In this private objective function, the cost of using the production factor 'waste' (p_W)

is assumed to be zero:

$$\mathrm{PC} = \sum_{i \in \{\mathrm{ic,dc}\}} \sum_{j \in \{Q,P,S,R,D\}} p_L^i L_j^i + p_K^i K_j^i + p_E^i E_j^i \tag{2}$$

Secondly, the global planner can internalise the external costs in the decision framework. In this case, the cost of non-recycled waste (p_W) as denoted in Eq. (1) is not equal to zero. In this policy perspective the decision is based on the social costs rather than on the private costs.

$$\mathrm{EC} = \sum_{i \in \{\mathrm{ic,dc}\}} \sum_{j \in \{Q,P,S,R,D\}} p_W^i W_j^i \tag{3}$$

In the following, the basic relationships in the model are explained. The model is driven by exogenous demand for a physical commodity in both regions, expressed in tonnes:

$$D^i = \bar{D}^i \quad \text{for} \quad i = \mathrm{ic, dc} \tag{4}$$

In line with reality, the demand in developed countries exceeds the demand in developing countries:

$$D^{\mathrm{ic}} > D^{\mathrm{dc}} \tag{5}$$

Because the number of households in both regions is equal, the per capita consumption in industrialised countries exceeds the per capita demand in developing countries. As has been shown in Eq. (12), this difference is relevant for the efficiency of the recovery sector (R), because this sector generates economies of scale.

The output of manufacturing (Q) satisfies the demand:

$$D^i \leq Q^i \quad \text{for} \quad i = \mathrm{ic, dc} \tag{6}$$

4.1.1. Manufacturing segment

This single product type can be manufactured from two types of materials (M): primary and secondary materials (P and S). In addition, labour and capital are required for the manufacturing of the product. The quality of S is inferior to the quality P, i.e. manufacturing a certain amount of product with only one type of material requires more secondary material (S) than primary material (P). For example, in addition to filling materials the production of 1 tonne of writing paper requires only 0.9 tonne of wood pulp. The same product based on recycled materials requires 1.2 tonne of waste paper. Obviously, in reality also a combination of waste paper and wood pulp can be used to produce paper. The quality indicator of materials (ε) denotes the efficiency difference of using S versus P. The manufacturing process also generates a certain amount of non-recyclable waste (W_q). The production function of the manufacturing process is defined as:

$$\begin{aligned} Q^i &= f_Q^i(M_Q^i, K_Q^i, L_Q^i) \qquad \text{for} \quad i \in \{\mathrm{ic, dc}\} \\ &= f_Q^i(P^i + S^i/(1+\varepsilon^i), K_Q^i, L_Q^i) \end{aligned} \tag{7}$$

Secondary materials (ε) in industrialised countries have an equal or better quality than secondary materials in developing countries.

$$\varepsilon^{\mathrm{ic}} \leq \varepsilon^{\mathrm{dc}} \tag{8}$$

4.1.2. Production segment

In the production segment of the MPC, primary and secondary materials are produced. The production factors determine the production of primary materials. The stock of extracted resources available in the region (E^i) constrains the production of primary materials. Waste of resources in the primary production process is indicated by τ. For example, for the production of one tonne of primary aluminium roughly 2.5 tonnes of bauxite are required. Therefore, 1.5 tonnes are lost as non-recyclable waste. The primary production process generates a certain amount of non-recyclable waste (W_p).

The production function of the primary materials is defined as:

$$P^i = f^i_P(E^i/(1+\tau^i), K^i_P, L^i_P) \quad \text{for} \quad i \in \{\mathrm{ic}, \mathrm{dc}\} \tag{9}$$

In general, developing countries are better endowed in natural resources than industrialised countries. Therefore, the quality of primary resource materials in developing countries is assumed to be higher than primary materials in industrialised countries:

$$\tau^{\mathrm{ic}} > \tau^{\mathrm{dc}} \tag{10}$$

The production of secondary materials (S) from recovered materials (R) is dependent on the quality of the recyclable waste. The lower the quality of the recyclable waste, the higher is the efficiency loss during the secondary production process. This efficiency loss is indicated by φ. The interpretation of φ is similar to τ. For example, industrial plastics waste is generally more recyclable than household plastics waste because it is less contaminated and more homogeneous. The secondary production process generates a certain amount of non-recyclable waste (W_s).

The production function of secondary material is defined as:

$$S^i = f^i_S\left(\frac{R^i}{(1+\varphi^i), K^i_S, L^i_S}\right) \quad \text{for} \quad i \in \{\mathrm{ic}, \mathrm{dc}\} \tag{11}$$

The secondary material efficiency losses in developing countries are larger than the efficiency losses in industrialised countries:

$$\varphi^{\mathrm{dc}} > \varphi^{\mathrm{ic}} \tag{12}$$

Producing 1 tonne of primary materials generates more non-recyclable waste than producing 1 tonne of secondary production:

$$\frac{W^i_P}{P^i} > \frac{W^i_S}{S^i} \quad \text{for} \quad i \in \{\mathrm{ic}, \mathrm{dc}\} \tag{13}$$

4.1.3. Waste management and recovery segment

In the waste management and recovery segment, post-consumed products are converted into recyclable waste (R) and into non-recyclable waste (W), which is landfilled or incinerated. The processing of post-consumed products (D) into non-recyclable waste (W) requires 'capital' and 'labour'. D and W are expressed in tonnes.

In the recovery process, recyclable waste (R) is retrieved from post-consumed products (D). In the recovery process the factors labour and capital are required. Economies of scale apply to the recovery sector. The larger the demand per capita, the less production factor is required to recover one tonne of recyclable waste:

$$R^i = f_R^i(D^i, K_R^i, L_R^i) \quad \text{for} \quad i \in \{\text{ic, dc}\} \tag{14}$$

4.1.4. Material balance conditions

Various material balance conditions can be derived. These conditions are expressed in tonne. The material balance for the manufacturing process is defined as:

$$Q^i = P^i + S^i - W_Q^i \quad \text{for} \quad i \in \{\text{ic, dc}\} \tag{15}$$

A fixed portion of material loss (W_P) occurs during the primary production process:

$$W_P^i = E^i - P^i \quad \text{for} \quad i \in \{\text{ic, dc}\} \tag{16}$$

A fixed portion of material loss (W_s) occurs during the secondary production process:

$$W_S^i = R^i - S^i \quad \text{for} \quad i \in \{\text{ic, dc}\} \tag{17}$$

The total amount of disposed waste (W) is the portion of consumption that is not recovered ($D-R$) and the non-recyclable waste generated by the primary and secondary materials sector (W_P and W_S) and the manufacturing sector (W_Q). Although in reality a certain share of the production and manufacturing waste is recyclable, these recyclable materials are assumed to be processed internally and therefore are not treated separately.

$$W^i = D^i - R^i + W_P^i + W_S^i + W_Q^i \quad \text{for} \quad i \in \{\text{ic, dc}\} \tag{18}$$

4.1.5. Indicators

Several indicators present the results of the optimisation processes. The most important indicators are the utilisation rate (u^i) and the recovery rate (r^i). The utilisation rate (u^i) is the share of secondary materials (S) used in the manufacturing of final products (Q):

$$u^i = \frac{S^i}{Q^i} \quad \text{for} \quad i \in \{\text{ic, dc, world}\} \tag{19}$$

The recovery rate (r^i) is the amount of secondary materials recovered after consumption, (R) as a share of the final demand (D):

$$r^i = \frac{R^i}{D^i} \quad \text{for} \quad i \in \{\text{ic, dc, world}\} \tag{20}$$

The optimal value of these indicators will be determined by solving the optimisation model. These values are between 0 and 1, as the maximum percentage that can be utilised or recovered is 100%:

$$0 \leq u^i, r^i \leq 1 \quad \text{for} \quad i \in \{\text{ic, dc, world}\} \tag{21}$$

In the following several model-based results are presented.

4.1.6. Result 1: sinks and sources

Substituting (6), and the material balance conditions (15)–(17) in (18) gives:

$$W^i = D^i - R^i + E^i - P^i + R^i - S^i + P^i + S^i - Q^i = E^i \quad \text{for} \quad i \in \{\text{ic, dc}\} \quad (22)$$

This implies that in a closed economy the total amount of non-recycled waste is exactly equal to the total amount of primary resources extracted in that region. In other words, what goes in must eventually come out. Note that this result crucially depends on the static nature of the model, not allowing for embodied materials in capital goods.

4.1.7. Result 2: the relation between the utilisation and the recovery rate

Substituting (6) and (17) in (19), it follows that:

$$u^i = \frac{(R^i - W_S^i)}{D^i} \quad \text{for} \quad i \in \{\text{ic, dc, world}\} \quad (23)$$

and substituting (20) in (23) gives

$$u^i = \frac{r^i - W_S^i}{D^i} \quad \text{for} \quad i \in \{\text{ic, dc}\} \quad (24)$$

This implies that if the recycling sector is perfectly efficient ($W_S = 0$) and the economy is closed, the utilisation rate (u^i) equals the recovery rate (r^i). In other words, in a closed economy discrepancy between u^i and r^i is fully determined by wastes in the recycling sector. The higher W_S the less secondary materials are produced implying a lower utilisation rate.

4.1.8. Result 3: factor productivity

Eqs. (1)–(12), (14) and (22) imply optimisation of the following Lagrangian:

$$L = \sum_i \sum_j (p_L^i L_j^i + p_K^i K_j^i) + \sum_i (p_E^i + p_W^i) W^i + \lambda^i \left[f_Q^i \left\langle f_P^i \left\{ \frac{W^i}{1+\tau^i}, K_P^i, L_P^i \right\} + \frac{1}{1+\varepsilon^i} f^i \left\{ \frac{1}{1+\varphi^i} f^i(D^i, K_R^i, L_R^i), K_S^i, L_S^i \right\}, K_Q^i, L_Q^i \right\rangle - \bar{D}^i \right] \quad (25)$$

where $i \in$ ic, dc and $j \in P, S, W, R, Q$, with λ^i shadow prices of constraints.

Based on (25), marginal conditions can be derived about optimal factor and production levels within the autarkic MPC. From the condition:

$$\frac{\partial L}{\partial F_{Q^i}^i} = 0 \quad (26)$$

follows

$$\frac{p_L^i}{p_K^i} = \frac{\partial f_Q^i / \partial L_Q^i}{\partial f_Q^i / \partial K_Q^i} \quad (27)$$

This equation shows that the relation between the optimal use of labour and capital in the manufacturing sector (Q). These are standard equations of factor price ratios, which equal ratios of relative marginal productivity of factors. Similar conditions hold for all combinations $F = K$, L, W for $i = 1$, 2 and all segments: primary materials (P), secondary materials (S) and waste recovery (R). Note that the price of W is $p_E + p_W$, following from (22) (see (25)).

4.1.9. Result 4: factor allocation between the segments in the MPC

Cross-allocation of the homogenous factor capital (K) among the various segments in the MPC is based on the following relations:

$$\frac{\partial L}{\partial K_Q^i} = p_K + \lambda^i \frac{\partial f_Q^i}{\partial K_Q^i} = 0 \tag{28}$$

$$\frac{\partial L}{\partial K_P^i} = p_K + \lambda^i \frac{\partial f_Q^i}{\partial M_Q^i} \frac{\partial f_P^i}{\partial K_P^i} = 0 \tag{29}$$

$$\frac{\partial L}{\partial K_S^i} = p_K + \frac{\lambda^i}{1+\varepsilon} \frac{\partial f_Q^i}{\partial M_Q^i} \frac{\partial f_S^i}{\partial K_S^i} = 0 \tag{30}$$

$$\frac{\partial L}{\partial K_R^i} = p_K + \frac{\lambda^i}{(1+\varepsilon)(1+\varphi)} \frac{\partial f_Q^i}{\partial M_Q^i} \frac{\partial f_S^i}{\partial R^i} \frac{\partial f_R^i}{\partial K_R^i} = 0 \tag{31}$$

Combining (28) and (29) results in:

$$\frac{\partial f_Q^i}{\partial K_P^i} = \frac{\partial f_Q^i}{\partial f_E^i} \frac{\partial f_P^i}{\partial K_P^i} \tag{32}$$

This implies that the direct marginal contribution of capital to the manufacturing of final products (Q) is equal to its indirect marginal contribution via the production of primary materials and its contribution to final product manufacturing.

Combining (29) and (30) results in:

$$\frac{\partial f_P^i / \partial K_P^i}{\partial f_S^i / \partial K_S^i} = \frac{1}{1+\varepsilon^i} \tag{33}$$

implying that the direct marginal contribution of capital to the production of primary materials (P) is equal to the indirect marginal contribution of capital via the production of secondary materials. Reflecting the relation $M_Q = P + S/(1+\varepsilon)$ as shown in (7), this equation shows the contribution of capital allocated to either processes, given the contributions of primary and secondary materials to total materials in the manufacturing process. The higher the material loss in manufacturing due to the use of secondary materials (ε) the more capital will shift from the recycling sector (S) to the primary sector (P).

Combining (28) and (30) results in:

$$\frac{\partial f_S^i}{\partial K_S^i} = \frac{1}{1+\varphi^i}\frac{\partial f_S^i}{\partial R^i}\frac{\partial f_R^i}{\partial K_R^i} \tag{34}$$

This implies that the direct marginal contribution of capital to the production of secondary materials (*S*) is equal to its indirect marginal contribution via the recovery of waste (*R*) and its effect on the production of secondary materials. The higher the efficiency loss during secondary production (φ), the more capital shifts away from the recovery sector.

4.1.10. Result 5: internalisation of external costs

The optimisation results so far do not distinguish between private and social costs. The external costs are presented by p_w. In the following, the cross-allocation of the factor capital (*K*) between the various segments in the MPC is based on the social costs, in which the external costs are included:

$$\frac{\partial L}{\partial W^i} = p_R + p_W + \frac{\lambda^i}{1+\tau^i}\frac{\partial f_Q^i}{\partial M^i}\frac{\partial f_P^i}{\partial W^i} = 0 \tag{35}$$

Combining (31) and (35) results in:

$$\frac{p_K^i}{p_R^i + p_W^i} = \frac{1+\tau^i}{(1+\varepsilon^i)(1+\varphi^i)}\frac{\frac{\partial f_S^i}{\partial R^i}\frac{\partial f_R^i}{\partial K_R^i}}{\frac{\partial f_P^i}{\partial W^i}} \tag{36}$$

This implies that higher external costs shift capital away from the disposal sector towards the recovery sector.

4.1.11. Result 6: regional specialisation

In the present model, the allocation rules of the production factors (*L*, *K* and *E*) are independent of the quality indicator of secondary materials in the manufacturing process (ε), the efficiency loss during the secondary production process (φ) and the resource loss in the primary production process (τ). If all functions (f_Q, f_P, f_S, f_D and f_R) are identical between the regions and if we assume equal factor allocations between the regions then the following relations hold (see (22)):

$$W^{\text{ic}} = W^{\text{dc}} = W = E \tag{37}$$

$$R^{\text{ic}} = R^{\text{dc}} = R \tag{38}$$

Combining these with (10) and (12) gives

$$\frac{E}{1+\tau^{\text{ic}}} < \frac{E}{1+\tau^{\text{dc}}} \tag{39}$$

$$\frac{R}{1+\varphi^{\text{ic}}} > \frac{R}{1+\varphi^{\text{dc}}} \tag{40}$$

This implies that developing countries retrieve a larger share of their required materials from extracted primary resources while industrialised countries tend to focus more on the recovery of secondary materials. Equal allocation *rules*, however, do not necessarily imply equal allocation *proportions*. Therefore, (39) and (40) have been adjusted, although it is rather unlikely that sign reversal will occur. Moreover, production functions are not identical in industrialised and developing countries. Due to the slow rate of diffusion of technological innovations from industrialised to developing countries, the production functions are more 'efficient' in the former regions. This in turn leads to a reinforcement of inequalities in (39) and (40). Combining (9) and (39) gives:

$$P^{\mathrm{ic}} < P^{\mathrm{dc}} \tag{41}$$

This implies that given the current differences in efficiencies, developing countries specialise in the production of primary materials. Combining (11) and (40) results in

$$S^{\mathrm{ic}} > S^{\mathrm{dc}} \tag{42}$$

which means that industrialised countries specialise in the production of secondary materials.

4.2. The international material-product chain

Next, the autarkic MPC is extended to an international MPC. International trade is allowed for primary commodities (P), recyclable waste materials (R) and final products (Q). The domestic relationships remain unchanged. The production factors are assumed to be immobile and the optimisation rules as described for the autarkic MPC still hold for the international MPC. The main difference is the increased flexibility of the individual segments in the MPC to retrieve inputs and market their outputs. This may lead to an alternative configuration of the primary and secondary material flows, and thus a change in the utilisation and recovery rate in the respective MPCs in industrialised and developing countries. Moreover, the private, external and social costs are likely to change.

The internationalisation of the MPC only refers to certain material flows. The production factors 'capital' and 'labour' are assumed to be immobile between the two regions. Therefore, besides the changes in the material elements, the production functions remain the same in the open economies. Moreover, Results 3 and 4 remain the same. The main changes in the set of equations representing the international MPC are the material balance conditions. Therefore, only the latter category of equations is presented in this section. It should be kept in mind, however, that material balance equations only represent the consequence of the internationalisation of the MPC. The causes of changes in material flows are the factor prices and factor endowments in industrialised and developing countries. All material balance equations are expressed in tonnes.

4.2.1. International material balance conditions

Many of the relationships specified in Section 4.1 remain the same. Eq. (6) is replaced by (43). Domestic demand in both regions can be met through domestic and imported final products. The demand is defined as:

$$D^i = Q^i - Q^i_{\mathrm{exp}} + Q^i_{\mathrm{imp}} \quad \text{for } i = \mathrm{ic}, \mathrm{dc} \tag{43}$$

Eq. (44) replaces (15). The manufacturing process in both regions consumes domestic and imported primary materials and domestic secondary materials. Trade of secondary materials is assumed to be non-existent. The manufacturing of final goods in industrialised and developing countries is defined, respectively, as:

$$Q^i = P^i - P^i_{\mathrm{exp}} + P^i_{\mathrm{imp}} + S^i - W^i_Q \quad \text{for } i = \mathrm{ic}, \mathrm{dc} \tag{44}$$

In reality, processing of extracted resources into primary materials is conducted in the same country to avoid excessive transport costs and to increase the value added of that resource. Therefore, primary materials are assumed to be produced from domestic resources only.

Eq. (45) replaces (17). Secondary materials are produced from domestic and imported recyclable waste. Material waste (W_S) occurs during the secondary production process.

$$S^i = R^i - R^i_{\mathrm{exp}} + R^i_{\mathrm{imp}} - W^i_S \quad \text{for } i = \mathrm{ic}, \mathrm{dc} \tag{45}$$

In accordance with international legislation, trade of non-recyclable waste is assumed to be prohibited. Therefore, the material balance for the waste management process is similar to that of the domestic MPC represented in (18). Disposed waste is the sum of non-recovered consumer waste, non-recyclable waste from primary and secondary materials sectors and manufacturing:

$$W^i = D^i - R^i + W^i_p + W^i_s + W^i_q \quad \text{for } i = \mathrm{ic}, \mathrm{dc} \tag{46}$$

Assuming the p^i_W to be zero, thereby ignoring the external effects caused by non-recycled waste, the material balance restrictions of the international MPC allows the derivation of the several material balance conditions.

4.2.2. Result 7: open sinks and sources

By substituting (43), (44), (16) and (45) in (46), it follows that:

$$W^i = E^i + (R^i_{\mathrm{imp}} - R^i_{\mathrm{exp}}) + (P^i_{\mathrm{imp}} - P^i_{\mathrm{exp}}) + (Q^i_{\mathrm{imp}} - Q^i_{\mathrm{exp}}) \quad \text{for } i \in \{\mathrm{ic}, \mathrm{dc}\} \tag{47}$$

This replaces (22). The obvious conclusion from this result is that in an open economy the total amount of non-recycled waste is determined by the total amount of primary resources retrieved in that region plus the trade balance in physical terms for the other trade channels in the MPC. Result 1 in (22) is thus extended with a trade dimension for recyclable waste, primary materials and final products.

4.2.3. Result 8: the international relation between the utilisation and the recovery rate

Substituting (19) and (20) in (45) gives:

$$u^i = r^i \frac{D^i}{Q^i} + \frac{R^i_{\mathrm{imp}} - R^i_{\mathrm{exp}}}{Q^i} - \frac{W^i_S}{Q^i} \quad \text{for } i \in \{\mathrm{ic}, \mathrm{dc}\} \tag{48}$$

This replaces (24). Note that if $D^i = Q^i$ then it reduces to (24).

The result in (48) implies that if the economy is open, the utilisation rate (u^i) no longer automatically equals the recovery rate (r^i). In an open economy, discrepancies between u^i

and r^i are determined by (1) the trade balance of the final products (*D/Q)*; (2) the trade balance of recyclable waste ($R_{\text{imp}} - R_{\text{exp}}$); (3) the inefficiencies in the domestic recycling industry (W_s). The more a country is characterised as a net-importer of final products ($D > Q$), the more likely it is that the utilisation rate exceeds the recovery rate ($u > r$). Likewise, the more a country is characterised as a net-importer of recyclable waste, the more likely it is that the utilisation rate exceeds the recovery rate ($u > r$). Finally, the more inefficient the recycling sector is in processing secondary materials from recyclable waste, the fewer secondary materials become available for utilisation in final production. Therefore, in countries with large inefficiencies in the recycling industry (W_s), the recovery rate tends to exceed the utilisation rate ($r > u$).

4.2.4. Result 9: factor productivity and allocation in an open economy

If we substitute (47) in (25) then solving gives the conditions for an optimum in the open economy with trade. Results (26)–(36) remain the same. In addition, we have:

$$\frac{\partial f_Q^i}{\partial P_{\text{exp}}^i} = \frac{\partial f_Q^i}{\partial P_{\text{imp}}^i} \tag{49}$$

$$\frac{\partial f_S^i}{\partial R_{\text{exp}}^i} = \frac{\partial f_S^i}{\partial R_{\text{imp}}^i} \tag{50}$$

Eq. (49) means that in the optimum the marginal effect of primary imports and exports on manufacturing output need to be equal. Similarly, (50) states that in the optimum the marginal effect of imports and exports of recovered materials on the output of secondary materials production needs to be equal. These conditions restrict the flows of imports and exports of primary and secondary materials across countries.

4.2.5. Result 10: internalisation of external costs in an open economy

Additional results are based on $\partial L/\partial X = 0$ for $X = R_{\text{imp}}^i, R_{\text{exp}}^i, P_{\text{imp}}^i, P_{\text{exp}}^i, Q_{\text{imp}}^{\text{i}}, Q_{\text{exp}}^i$ cf. (36), one set of additional conditions is of the form:

$$\frac{p_K^i}{p_E^i + p_W^i} = \frac{1 + \tau^i}{(1 + \varepsilon^i)(1 + \varphi^i)} \frac{\frac{\partial f_S^i}{\partial R^i} \frac{\partial f_R^i}{\partial K_R^i}}{\frac{\partial f_P^i}{\partial E} \frac{\partial E}{\partial X}} \tag{51}$$

with X taking values as indicated above. Here, $\partial E/\partial X = 1$ for $X = W^i, R_{\text{imp}}^i, P_{\text{imp}}^i, Q_{\text{imp}}^{\text{i}}$ and $\partial E/\partial X = -1$ for $X = R_{\text{exp}}^i, P_{\text{exp}}^i, Q_{\text{exp}}^i$. This implies that higher external costs associated with waste shift capital away from disposal to recovery. In addition, it shows that such higher external costs stimulate exports of waste, manufactured output and primary resources, while they have a negative impact on imports of these. This relationship can is clearly visible in the waste market in industrialised countries. Higher external costs of solid waste have led to increased waste recovery and expansion of the waste exports.

5. Discussions and conclusions

International recycling has rather specific economic and environmental features and therefore is a complex activity to analyse. A review of characteristics of available models has been conducted to gain insight into the variety of elements that are potentially relevant in analysing international recycling. The main boundaries and model elements used in recycling models, such as objectives, systems, space and time, have been analysed. The review of recycling studies indicated that particularly the international linkages between recycling systems are often ignored. Given the current globalisation of the recycling market, analysing recycling in a closed context (a city, a region or a country) becomes increasingly invalid. Therefore, there is a need for modelling the international MPC, allowing for international interaction between various stages in the life cycle.

We developed a formal model of the international material-product chain (MPC) that represents the basic principles of international recycling. These principles include that the most relevant forward and backward linkages are incorporated in the analysis, that international trade is incorporated in various parts of the MPC, and that the most fundamental economic, environmental, institutional, dynamic and international elements that affect recycling are accounted for.

The model includes and links the MPCs of developed and developing countries that exchange material commodities, final products and recyclable waste. Various conclusions can be drawn from the model. First, as indicated in Result 1, the amount of non-recyclable waste, which represents environmental externalities of the MPC, equals the resource extraction in a closed economy. Increasing the internal efficiency of the processes in the autarkic MPC can minimise this flow.

Secondly, Result 5 demonstrates that taking into account environmental externalities in the process of minimising social costs results in higher levels of recycling. This result is confirmed by empirical studies that show that countries that apply high charges on waste disposal achieve especially high recycling levels (Johnstone, 1998; Van Beukering and Bouman, 2001).

Thirdly, as shown in Results 6 and 8, international recycling is mainly driven by regional differences in the quantity and quality of the factor endowment and economic efficiency. Results 9 and 10 add conditions to restrict the flows of imports and exports of primary and secondary materials across countries so as to arrive at an international social welfare optimum. These conditions are derived from the regular factor equalisation requirements and can be interpreted as international factor allocation rules. They lead to a deviation between waste recovery and utilisation in both regions, which due to Result 10 increases with the magnitude of the externalities associated with waste dumping. Assuming that industrialised countries are relatively well endowed with recyclable waste and negative external costs are effectively internalised, the recovery rate is likely to exceed the utilisation rate. In developing countries, the opposite pattern is likely to occur. This shift in trade pattern of recyclable materials suggested by our model analysis, namely as moving from developed to developing countries, is consistent with the findings of a number of empirical studies (Grace et al., 1978; Sharma et al., 1997; Johnstone, 1998; Van Beukering and Bouman, 2001; Duraiappah et al., 2002). Moreover, the fact that these studies cover a range of materials (paper, plastics, lead, non-ferrous metal) and

Table A.1
Overview of models on recycling

Study	Model type			Objective		Time		Spatial			Subject
	Physical	Economic	Integrated	Descriptive	Optimisation	Static	Dynamic	Closed passive	Open passive	Open active	
Ruth and Dell'Anno (1997)	x			x			x		x		Glass recycling in the US
Konijn et al. (1997)	x			x		x			x		Iron, steel and zinc in the Netherlands
Bouman et al. (1999)		x			x	x			x		Lead batteries in the Netherlands
McLaren et al. (1999)	x			x			x	x			Phone recycling in the UK/Sweden
Weaver et al. (1995)	x				x	x				x	Paper cycling in Europe
Byström and Lönnstedt (2000)	x			x		x				x	Paper cycling in Scandinavia
Michael (1998)		x			x	x			x		Paper cycling in the US
van Beukering and Duraiappah (1998)			x		x	x				x	Paper recycling in India
Nakamura (1999)	x			x		x			x		Paper recycling in the Netherlands
Leach et al. (1997)			x		x	x			x		Paper recycling in the UK
Wang et al. (1995)	x				x	x				x	Paper waste transport in Iowa
Fletcher and Mackay (1996)	x			x			x		x		Plastics recycling in Australia
Duraiappah et al. (2002)			x		x	x				x	Plastics recycling in India
Starreveld and van Ierland (1994)		x			x	x		x			Plastics recycling in the Netherlands
Duchin and Lange (1998)	x			x		x			x		Plastics recycling in the US
Kandelaars and van den Bergh (1997b)			x	x			x	x			Rain gutters in the Netherlands
van Beukering and Janssen (2001)			x	x			x		x		Tyres in Western-Europe
Kandelaars and van den Bergh (1997a)			x	x			x		x		Window frames in the Netherlands
Hunhammar (1995)	x			x		x			x		Transport and recycling in Sweden
Huhtala (1997)		x			x		x	x			Disposal /recycling in Finland
Morris and Holthausen (1994)		x		x		x			x		Waste from household behaviour
Bruvoll and Ibenholt (1997)		x			x						Waste generation in Norway
Daskalopoulos et al. (1998)		x			x	x		x			Waste management in Greece
Guangming et al. (1998)	x			x		x		x			Waste management in China
Diamadopoulos et al. (1995)	x				x	x		x			Waste management in Greece
Sundberg et al. (1994)			x		x	x		x			Waste management in Sweden
Gerlagh et al. (1999)		x			x	x			x		Waste management in India
Sudhir et al. (1996, 1997)	x			x			x	x			Waste management in India
Faaij et al. (1998)	x				x	x		x			Waste management in the Netherlands
Malarin and Vaughan (1997)		x			x	x				x	Waste management in Jamaica
Ley et al. (1997)		x			x	x				x	Waste flow interstate control in the US
Total	14	10	7	14	17	22	9	11	13	7	

countries (India, China, Europe) can be considered as supportive of the robustness of our results.

Appendix A. Empirical studies of recycling

Table A.1.

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