TI 2000-12/3
Tinbergen Institute Discussion Paper

Optimal Multi-Regional Patterns of Economic Development and Material Resource Use

Marco A. Janssen
Jeroen C.J.M. van den Bergh

Tinbergen Institute
The Tinbergen Institute is the institute for economic research of the Erasmus Universiteit Rotterdam, Universiteit van Amsterdam and Vrije Universiteit Amsterdam.

Tinbergen Institute Amsterdam
Keizersgracht 482
1017 EG Amsterdam
The Netherlands
Tel.: +31.(0)20.5513500
Fax: +31.(0)20.5513555

Tinbergen Institute Rotterdam
Burg. Oudlaan 50
3062 PA Rotterdam
The Netherlands
Tel.: +31.(0)10.4088900
Fax: +31.(0)10.4089031

Optimal Multi-Regional Patterns of Economic Development and Material Resource Use

Marco A. Janssen and Jeroen C.J.M van den Bergh

Department of Spatial Economics
Free University
De Boelelaan 1105
1081 HV Amsterdam
the Netherlands
Phone: +31 20 44 46090
Fax: +31 20 44 46004
e-mail: m.janssen@econ.vu.nl / jbergh@econ.vu.nl

Abstract
Regional economic activities require materials that can be extracted domestically or imported from other regions. Analysis of optimal patterns of combined economic development and materials use should be discussed in relation to trade and the environment. A model is presented that optimises long-term welfare of a 2-region economic system with trade in virgin and recycled materials as well as consumer goods. The only difference between the regions concerns the size of their domestic materials resources. Numerical optimisation experiments show that trade of resources and goods increases the carrying capacity of the regions and their levels of welfare. Furthermore, regions are shown to specialise in certain economic sectors.

Keywords
Industrial Metabolism, Trade, Economic growth, Regional Sustainability

abbreviated title of the article**:** *Optimal Physical Economic Development*

Introduction

An economic system consumes material inputs, processes them into usable forms, and eliminates the wastes from the process. The total of physical processes that convert raw materials into finished products and wastes show similarity with metabolism in organisms and has therefore been referred to as "industrial metabolism" (Ayres and Simones, 1994). The extraction, use and disposal of materials cause significant pressure on the environment. From an environmental economics perspective optimal economic development should balance the cost and benefits of material use.

The concept of industrial metabolism is used to analyse material flows from an integrated perspective that allows studying system-wide effects of and problem shifting due to environmental policies. Thus we can trace the rebound effects of policies. For example, when cars become more fuel efficient, consumers tend to use larger cars and travel more kilometres, so that the net energy saving effect is less significant. Moreover, reducing waste in one part of the system can lead to more emissions in another part of the system. For example, end-off-pipe measures to reduce pollution to water and air can lead to highly polluted waste, which has to be burned or dumped in landfills. In addition, the trade-off between energy and material use can be studied. For example, recycling of materials reduces besides the demand for resources also the demand for energy although recovering of materials can require much energy. Burning of waste paper is in some cases more desirable from an environmental perspective than recycling. Leach et al. (1997) studied the options for waste paper treatment in the UK. This paper is mainly produced in Sweden, where renewable energy sources are used in the production (pulp). Recycling in the UK requires fossil energy. Burning waste paper will generate energy. Finally, production and recycling can shift to other regions. Reduction of the energy intensity of emissions in OECD countries and the increase of energy intensity of economies in non-OECD countries can partly be explained by migration of energy intensive industries from OECD to non-OECD countries (Suri and Chapman, 1998). With the phenomenon of globalisation and the increase of international trade, this spatial dimension is of increasing importance.

The analysis presented here focuses the attention on the spatial dimension. These flows are composed of primary (raw) materials, secondary (recovered) materials, and materials incorporated in products. Trade in the context of environmental quality is therefore a focus of spatial industrial metabolism (Janssen and van den Bergh, 1999). The two-region model as presented in this paper includes primary materials, secondary materials and materials incorporated in products. This allows to take into account the net use of materials in the different parts in the product chain and regions. The regions differ only in their carrying capacity of the renewable material resource, which leads to interregional material flows.

The organisation of this paper is as follows. Section 2 discussed theories and concepts relating to economic growth, trade and development. Section 3 presents a model that describes the physical dimension of an economic system. Numerical experiments with the model are presented in Section 4. Section 5 concludes.

2. Economic Growth, Trade and the Environment

The growth debate has extended its attention to the relation between economic growth and material use, using concepts like decoupling, dematerialisation, Factor 4 and the "Environmental Kuznets Curve" (EKC). The EKC hypothesis reflects a relationship between environmental pressure and income per capita that consists of three phases: (1) initially income growth goes along with possibly progressively increasing environmental pressure; (2) further income growth leads to a increase, at a decreasing rate, of environmental pressure until it reaches a maximum; (3) further income growth beyond this critical level leads to a reduction of environmental pressure. An explanation for this pattern is that at higher income levels individuals will attach more value to environmental quality; this means that they are willing to spend more income on less damaging consumption (cleaner products, services), as well as to provide democratic support for stringent environmental policies. This theory has generated its own body of empirical research (de Bruyn and Heintz, 1999). The main implication of the EKC is that growth by itself would be able to solve environmental problems. This is regarded as an interesting addition to the traditional view that considered economic growth and environmental protection as antitheses. It should be noted that the EKC describes but does not explain the three phases. The empirical support for the EKC hypothesis is very doubtful, as it is based on indicators that are partial, from both environmental and spatial perspectives. In relation to the spatial perspective adopted hereafter, it is worthwhile to mention that part of the reduction of environmental pressure at high incomes can be explained by the relocation of polluting production activities to less wealthy regions (Suri and Chapman, 1998).

De Bruyn and Opschoor (1997) question the inverted-U-shape relationship between environmental pressure and income, and propose a N-shape relationship, reflecting a relinking of economic growth and environmental pressure. During times of radical changes in the technological and institutional paradigms, the relationship between environmental pressure and income may be altered due to substitution and technological development. Relinking occurs when the easy options of substitution and technological improvement have been exhausted.

An increase in trade is often claimed to result in increasing environmental pressure due to increased transport, resource extraction and pollution in certain regions. It is, however, also supposed to contribute to international competition becoming more intensive, thus leading to improved efficiency. A novel way of analysing the impact of increasing trade flows on the environment is to view trading partners as an interconnected product chain (Beukering et al., 2000). Globalisation of the product chain will lead to an optimal allocation in terms of production costs of various segments over a larger region. Beukering et al. explain the various flows of international material product chain using different theories of trade. The Heckscher-Ohlin theorem can be used to explain trade between different sectors in the product chain as a result of relative factor endowments. Other theories can provide explanations on intra-sectoral trade. For example, Fujita et al. (1999) claim that centripetal (network effects) and centrifugal (e.g. congestion) forces are the main source of international allocation. Centripetal forces promote economic clusters, while centrifugal forces leads to a spatial allocation of economic clusters. A factor that cause, but also can prevent, undesirable disturbances of the metabolism of economies is technology (Grübler, 1998). Technology oriented trade theories like Vernon (1966) claim that new products are first produced in the most advanced economies. Subsequently, demand spreads abroad, leading to trade, and finally it becomes more attractive for the importing countries to start its own production. A similar pattern is predicted by the demand oriented trade theory of Linder (1961). He states that the demand for the most advanced products is generated in the high-income countries, and that low-income countries accept lower quality. This can explain the relative larger use of recycled products in developing countries compared to developed countries (Beukering and Bouman, 2000).

An analysis of the international material product chain requires a dynamic trade model in which technological development and supply and demand dynamics are incorporated. Adding a physical dimension of the economic system will subsequently give rise to a model suitable to study spatial and international patterns of material flows. A first version of such a model is described in the next section.

3. A 2-region model of industrial metabolism

The model describes an economic system of 2 regions. In line with the discussion in the previous section, a chain of activities is considered. Materials are extracted from a renewable resource. They can, together with recycled materials, be used to produce consumer goods. The latter are consumed and generate utility. Consumer goods are depreciated and the resulting waste material can be either recycled or dumped into the environment. Materials dumped into the environment reduce the carrying capacity of the renewable resources. Trade between the region consists of consumer goods, and primary and secondary materials (Figure 1). A trade balance in monetary terms exists. The overall social objective is to maximise the sum of discounted utility of consumption in each region. This can be realised by appropriate choices of investments in capital stocks of material extraction, production of consumer goods, use of material inputs and recycling.

The model is formulised as a dynamic optimisation model that combines standard economic growth model with a model of material cycles. The model also includes elements of models on climate change (Nordhaus 1994, Nordhaus and Yang, 1995), spatial models for sustainability (van den Bergh and Nijkamp, 1994, 1995) and economic models of materials flows (Kandelaars, 1999).

The novelty of this model is the integration of material flows in a multi-regional product chain with economic production, consumption and trade relationships. The model is presented in more detail below.

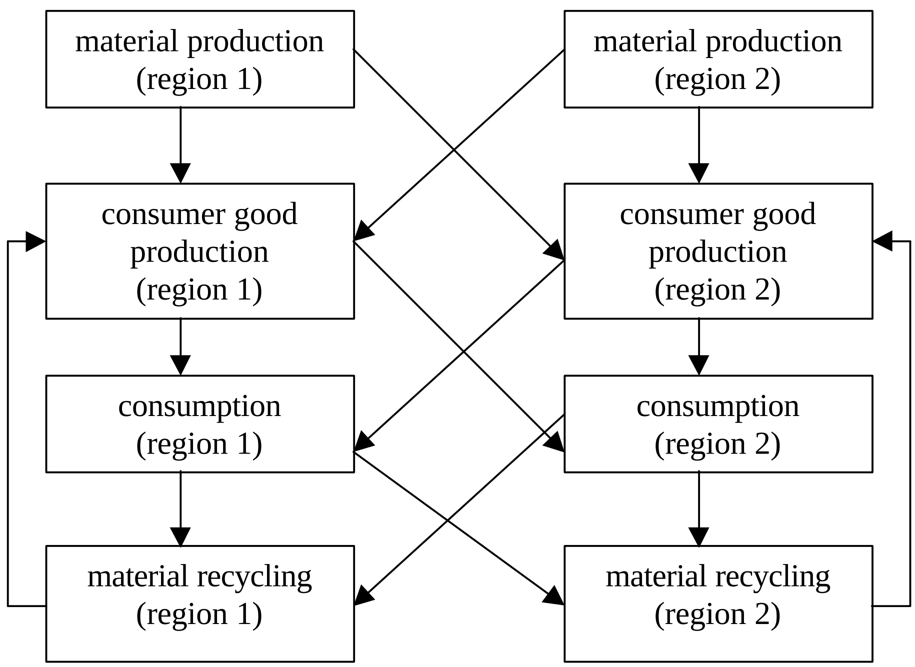

Figure 1: Trade flows and the international material product chain

Objective function

The model is designed to derive a situation in which the discounted sum of the general level of consumption achieves a maximum. The objective is:[1]

$$\max \quad \Sigma_{r=1,2} \int_0^{th} U_r/(1+\rho)^{-t}\, dt \tag{1}$$

[1] We omit time subscripts to economize on notation.

which expresses the sum of utilities, U_r, discounted by ρ and summed over the relevant time horizon (from 0 till t_h).
The yearly level of utility of social well-being in region r is expressed as C_r^{η} where C_r describes the level of consumption goods of region r. The parameter η determines the influence of the consumer good on the utility level. The yearly, discounted, level of utility of consumer can be formulated as

$$U_r = C_r^{\eta} \tag{2}$$

Consumption
Consumption is based on durable goods. The increase in the level of consumer goods C_r equals new consumption goods, $C_{n,r}$, minus depreciation of consumer goods. The depreciation rate of consumer goods, δ_{cr}, is assumed to be a certain percentage per annum, reflecting an average lifetime of consumer goods equal to $1/\delta_{cr}$ years.

$$dC_r/dt = C_{n,r} - \delta_{cr} * C_r \tag{3}$$

New consumer goods are defined as domestically produced, plus imported goods, $C_{M,r}$, minus exported consumer goods, $C_{X,r}$. The levels of imports and exports are determined by the trade balance.

$$C_{n,r} = C_{Pr} + C_{M,r} - C_{X,r} \tag{4}$$

Production of Consumption Goods
The sectoral output $Y_{C,r}$ is given by a standard constant-returns-to-scale Cobb-Douglas production function using production factors capital $K_{C,r}$, and materials M_r. The production function contains parameters for the scale of technology $a_{C,r}$, technological change, $\tau_{C,r}$, and elasticity of output with respect to the inputs, $\gamma_{C,r}$.

$$Y_{C,r} = (a_{C,r} /(\tau_{C,r})^t)\, K_{C,r}^{\gamma C,r}\, M_r^{\,1-\gamma C,r} \tag{5}$$

The capital level depends on yearly investments, $I_{C,r}$, and depreciation of capital at rate δ_{kr}.

$$dK_{Cr}^{\gamma,r}/dt = I_{C,r} - \delta_{kr} * K_{C,r,t-1} \tag{6}$$

Extraction of Materials
The production of materials, $M_{P,r}$ is directly related to the production of goods or commodities $Y_{M,r}$. Extraction of materials depends on the production factor $K_{M,r}$.
The economic output depends on parameters representing the level of technology, $a_{M,r}$, technological change, $\tau_{M,r}$, elasticity parameter $\gamma_{M,r}$ and a depletion factor $\pi_{M,r}$. This depletion factor, formulated in Eq. (8), includes the fact that more capital is needed to extract the same amount of material when the resource size is decreased. The capital stock, $K_{M,r,}$ is defined in line with Eq. (6).

$$Y_{M,r} = (\pi_{M,r}\, a_{M,r}/(\tau_{M,r})^t)(K_{M,r})^{\gamma M,r} \tag{7}$$

We assume that the highest quality of the resource is depleted first. Thus the concentration of material to be extracted from the resource declines leading to more efforts for extraction.

When there is no depletion $\tau_{M,r}$ is equal to one. This number declines with the relative depletion of the resource.

$$\pi_{M,r} = (M_{R,r} / M_{R,r}(0))^{p\pi,r} \quad (8)$$

where $p_{\pi,r}$ represent the sensitivity of the rate in which the depletion factor declines when the resource declines.

The price of materials can be defined as proportional to the ratio of capital inputs to output:

$$p_{M,r} = a_{M,r} * K_{M,r} / M_{P,r} \quad (9)$$

where $a_{M,r}$ is an annuity factor, which is defined as

$$a_{M,r} = i/(1-(1+i))^{-(1/\delta M,r)} \quad (10)$$

where i is the interest rate, and $1/\delta_{M,r}$ the capital life time.

Recycling

The physical amount of recycling, $M_{R,r}$, is directly linked to the economic output $Y_{R,r}$. Output of recycling of materials is a function of capital $K_{R,r}$. The production function is dependent of the level of technology, $a_{R,r}$, technological change, $\tau_{R,r}$, elasticity parameter $\gamma_{R,r}$ and a recycling factor $\pi_{R,r}$. The capital stock, $K_{R,r}$, is defined line with Eq. (6).

$$Y_{R,r} = (\pi_{R,r}\, a_{R,r} / (\tau_{R,r})^{t})(K_{R,r})^{\gamma R,r} \quad (11)$$

The scaling factor for recycling captures the insight that increasing levels of recycling leads to increasing amount of inputs. The variable $x_{R,r}$ is a decision variable representing the level of recycling.

$$\pi_{R,r} = (1-x_{R,r})^2 \quad (12)$$

The price of recycled materials $p_{R,r}$ is defined in line with Eq. (9) and (10).

Budget Constraint

Each region obtains income from production Y in four sectors. This is either invested, I, or spent on two types of consumer goods, C.

$$Y_{C,r}+Y_{M,r}+Y_{R,r} = I_{C,r}+ I_{M,r}+I_{R,r}+C_{P,r} \quad (13)$$

Material Stocks and Flows

The physical dimension of the economic system consist of material stocks, and flows between those stocks (Figure 2). The production of materials ($M_{P,r}$) results from a net demand of material use from both regions. Net demand is equal to demand for material (M_r) minus utilised recycled materials ($M_{U,r}$). Furthermore, we assume that a fraction, $w_{p,r}$, of the material is lost as waste during the production process. This leads to the following mass balance condition for primary materials:

$$\Sigma_{r=1,2}\, (1-w_{p,r})*M_{P,r} = \Sigma_{r=1,2}\, M_r-M_{U,r} \quad (14)$$

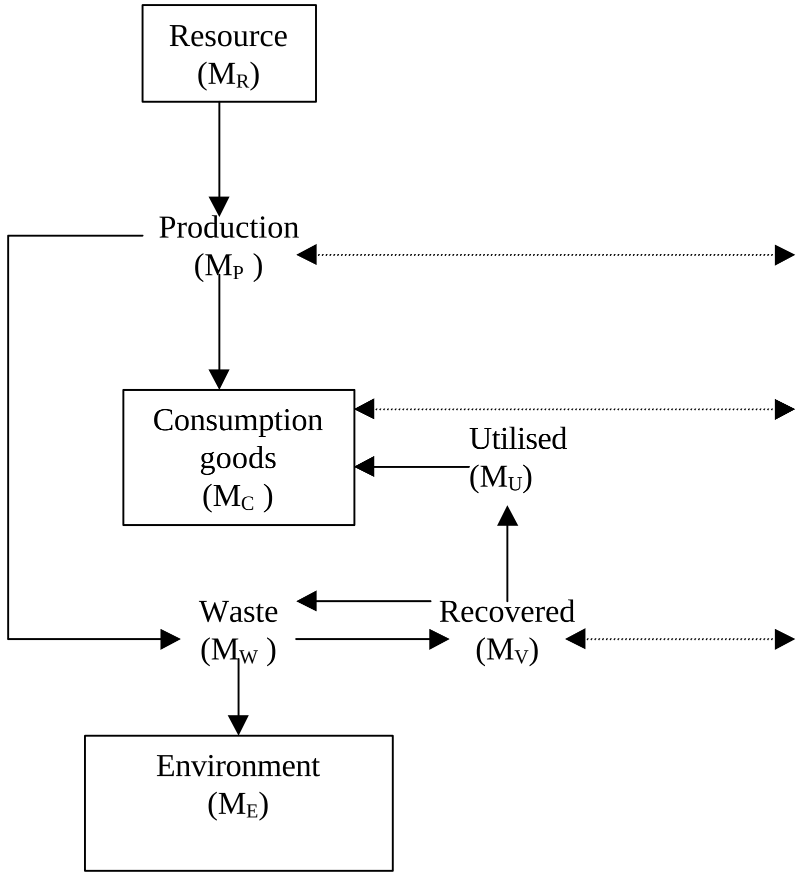

Figure 2: Material stocks and flows within one region. The dashed lines represent interregional flows.

In similar terms we can define the mass balance condition for secondary materials. Materials are recovered in both regions, $M_{V,r}$, and a fraction $(1-w_{s,r})$ of recovered materials is utilised in both regions, $M_{U,r}$.

$$\Sigma_{r=1,2}\ (1-w_{s,r})*M_{V,r} = \Sigma_{r=1,2}\ M_{U,r} \tag{15}$$

Our aim is to analyse whether trade stimulates sustainable economic growth when we include explicitly physical constraints. A simple material resource is formulated. This resource is assumed to be renewable and follows the standard logistic formulation.[2] The renewal rate is equal to λ_r and the maximum resource size is equal to the carrying capacity $M_{RK,r}$. The resource declines due to extraction of materials.

$$dM_{R,r}/dt = \lambda_r * M_{R,r} *(Z_{M,r} - M_{R,r})/Z_{M,r} - M_{P,r} \tag{16}$$

Materials incorporated in both types of consumer goods are denoted by $M_{C,r}$. It increases through the use of materials for new consumer goods, and declines through the depreciation of the stock of consumer goods. The parameter φ transforms the amount of consumer goods into materials. The δ_{cr} is the depreciation rate as defined for Eq. (3).

[2] Standard logistic equation is formulated as $dX/dt=\lambda*X*(1-X/Z)$, with λ the growth rate, X the stock size and Z the carrying capacity.

$$dM^{i}_{C,i,r}/dt = \varphi * C_{n,r} - \delta_{cr} * M_{C,r} \qquad (17)$$

The total amount of waste that is yearly produced, $M_{W,r}$, is equal to the depreciation of consumer goods plus the waste generated by the production of primary and secondary materials

$$M_{W,r} = \delta_{cr} * M_{C,r} + \Sigma_{r=1,2} (w_{p,r}*M_{P,r}+w_{s,r}*M_{R,r}) \qquad (18)$$

From the material waste, a share $x_{R,r}$ is recycled, resulting in a yearly amount of recovered material $M_{V,r}$

$$M_{V,r} = x_{R,r} * M_{W,r} \qquad (19)$$

The other part $(1-x_{R,r})$ accumulates in the environment, $M_{E,r}$.

$$dM_{E,r}/dt = (1-x_{Rr})*M_{W,r} \qquad (20)$$

Trade balance
Markets are assumed to clear resulting in equal amounts of import and export in monetary terms. Consumer goods, and primary and secondary materials are allowed to be traded. The allocation of imports and exports is derived by optimisation. Trade is subject to the following trade balance equations. For region 1 the value of imports ($Q_{M,1}$) is equal to imports of consumer goods and the value of imported virgin and secondary goods.

$$Q_{M,1} = C_{M,1} + p_{M,2} * M_{P,1,2} + p_{V,2} * M_{V,1,2} \qquad (21)$$

The same holds for region 2

$$Q_{M,2} = C_{M,2} + p_{M,1} * M_{P,2,1} + p_{V,1} * M_{V,2,1} \qquad (22)$$

Where $M_{i,j,2} + M_{i,j,1}$ is equal to $M_{i,j}$ for i=P and V, and j=1,2.

Imports of both regions are equal in value:

$$Q_{M,1} = Q_{M,2} \qquad (23)$$

The amount of material that accumulates in the economic system (A_i) in each region i can now be derived i (and j is the other region), and is equal to

$$A_i = \varphi * (C_{M,i} – C_{X,i})+(M_{P,i,j} –M_{P,j,i})+(M_{V,i,j} – M_{V,j,i})-(1-x_{R,i})*M_{W,i} +M_{P,i} \qquad (24)$$

Environmental Feedback
Environmental degradation caused by the accumulation of materials in the environment is assumed to affect the carrying capacity of the resources, $M_{RK,r}$. Different types of environmental feedbacks can be considered. Here local and global feedbacks are distinguished, where the first one only includes pollution generated by the own region, and the latter includes transboundary effects of pollution. Given a pollution impact coefficient κ_{mr} the change in carrying capacity can be formulated as below:

Local feedback

$$Z_{M,r}(t)= EXP(-\Sigma_{T=0}^{t} (\kappa_r*M_{E,r}(T)))*EXP(-\Sigma_{T=0}^{t} (\kappa_r*M_{E,r}(T))) \quad (25)$$

Global feedback

$$Z_{M,r}(t)= EXP(-\Sigma_{r=1,2}\Sigma_{T=0}^{t} (\kappa_r*M_{E,r}(T)))*EXP(-\Sigma_{r=1,2}\Sigma_{T=0}^{t} (\kappa_r*M_{E,r}(T))) \quad (26)$$

4. Optimisation Results

In the numerical optimisation the 2 regions are identical except for the carrying capacity of the material resource. In region 1 the carrying capacity of the materials resource is high, while the carrying capacity of region 2 is small.

In the optimisation formulation each region has 5 decision variables. Each decision variable is held constant for the whole period to allow solutions to the numerical optimisation problem. The decision how much to investment in the various capital stock is formulated by $I_{C,r}(t) = x_{C,r} * Y_{C,r}(t)$. The same holds for decision variables $x_{E,r}$, material extraction, and $x_{V,r}$, material recycling. The degree of recycling $x_{R,r}$ was already defined in Eq. (10), and decision variable x_M, which determines the level of material inputs is formulated as $M_r(t) = x_{M,r} * Y_{C,r}$

In this section we will investigate the implications of assumptions with particular assumptions about trade, technological development, resource dynamics and sensitivity of the resource for environmental pollution. The results are compared with those obtained for a reference scenario. The latter is constructed in such a way that economic activities yield a long term growth rate of the global economy (the two regions) (100 years) equal to 3 percent. The parameter values for the reference case are given in the Annex. The time horizon of optimisation is 200 years, as we are not interested in end-of-time-horizon effects, the results are depicted for 100 years.

We consider five alternative cases:

1. *No trade*. The regions cannot trade ($Q_{M,i}$=0).
2. *Technology of material production*. Technological development determines against which costs material can be extracted and recycled improves (τ_R =0.99; τ_M =0.99).
3. *Non-renewable resource*. The growth rate of the resource is zero in each region (λ_r=0).
4. *Local feedback*. Materials accumulated in the environment of each region reduce the carrying capacity of the material resource (κ_r = 0.001).
5. *Global feedback*. Materials accumulated in the global environment reduce the carrying capacity of the material resource (κ_r =0.001).

Reference case

Maximising the sum of discounted utility of consumption implies that each region specialises in one specific economic activity in the product chain. The economic output of the resource rich region, region 1, is mainly determined by extraction of materials, while the economic output of the resource poor region, region 2, is determined by the production of consumer goods and material recycling (Figures 3 and 4). The economic growth rate is lower in region 1 than in the region 2, although the discounted utility of consumption is somewhat higher in region 1 compared to region 2. One explanation for this is the relatively high reinvestment fraction of economic output in region 2. Production of consumer goods is more capital intensive than material extraction or recycling. There is some empirical evidence that economies with large natural resources exports have low growth rates. Sachs and Warner (1995) found that economies with a high ratio of natural resource exports to GDP in 1971 (the base year in their analysis) tended to have low growth rates during the subsequent period 1971-89. However, they did not explain this observed relationship.

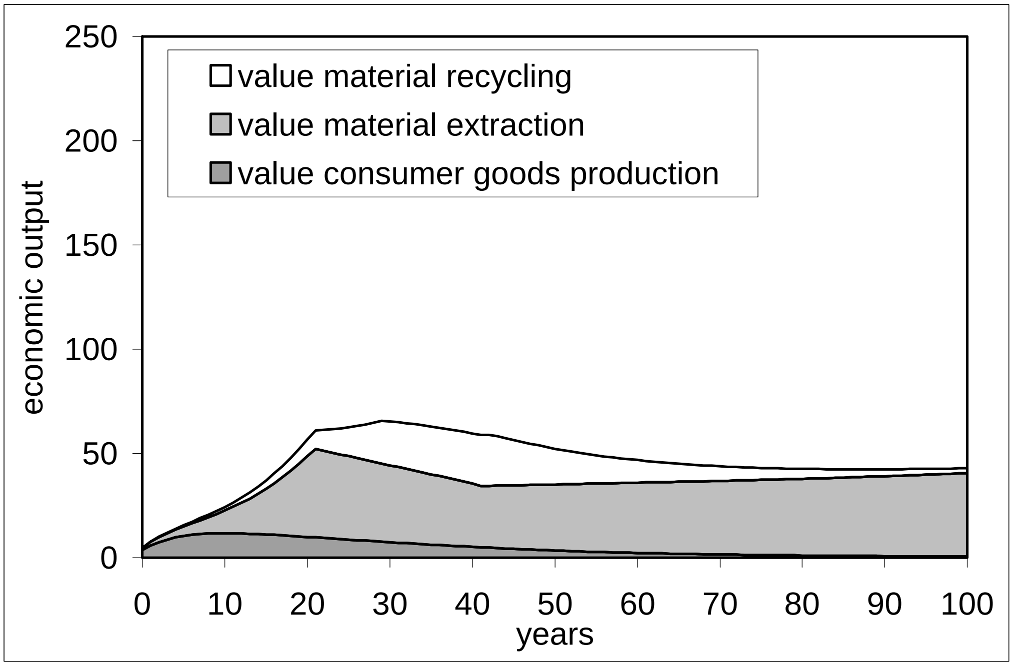

Figure 3: Sources of economic output in region 1 in the base case scenario.

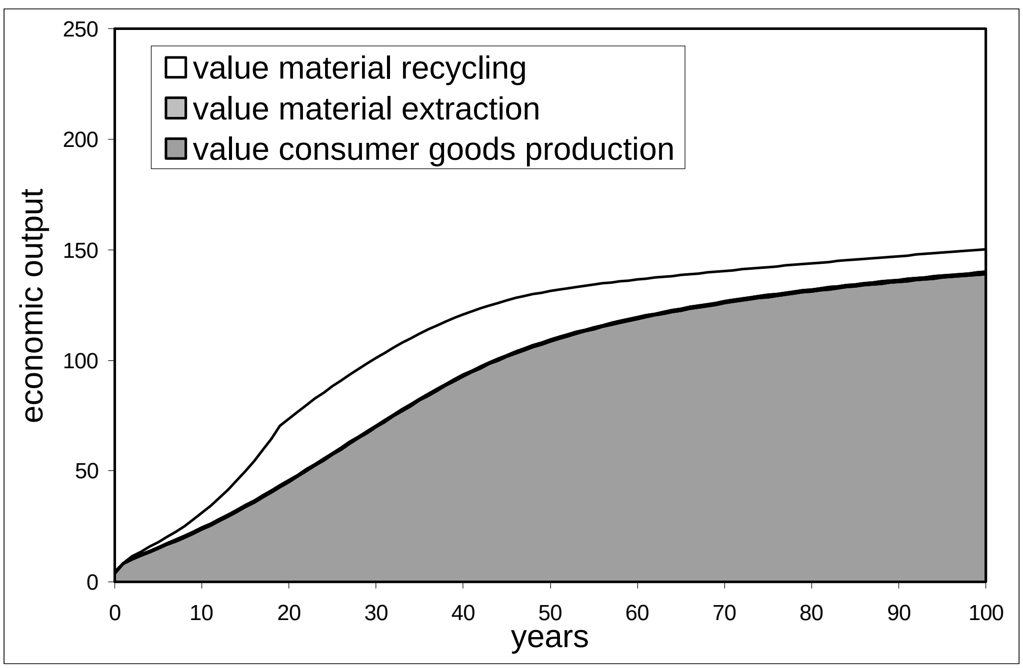

Figure 4: Sources of economic output in region 2 in the base case scenario.

The resource is depleted mostly in region 1 (Figures 5 and 6). The extracted material from the resource in region 1 is for a large degree exported to region 2, where consumer goods are produced. The stock of materials encapsulated in consumer goods increases first due to increased consumption. After 30 years, the stock declines because of dematerialization, stimulated by depletion of the resources. Materials accumulate in the environment of both regions, but mostly in region 2.

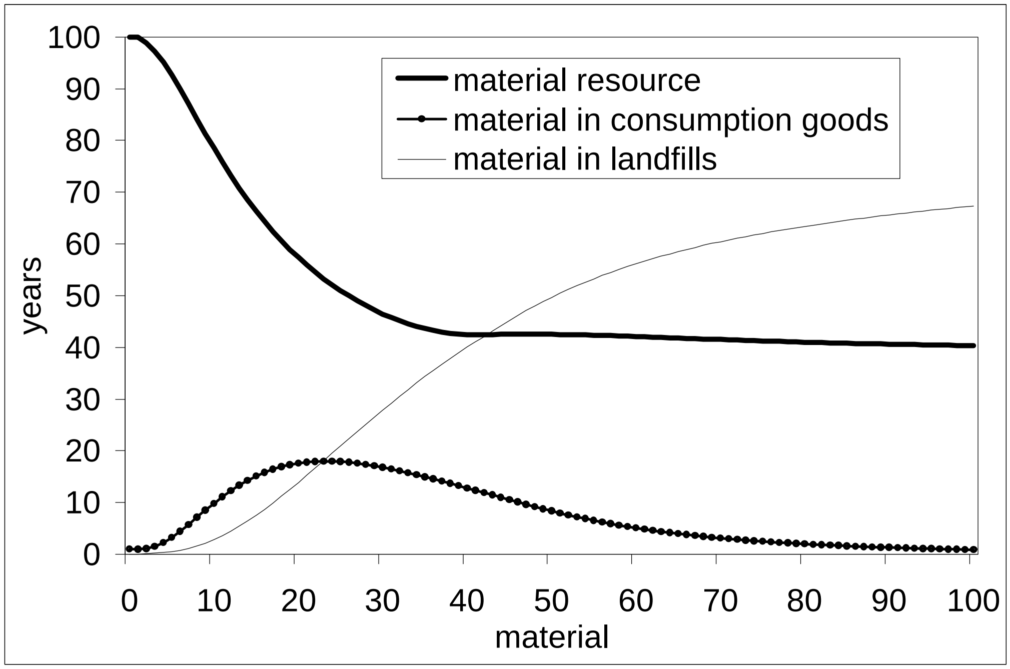

Figure 5: Material stocks in region 1 in the base case scenario.

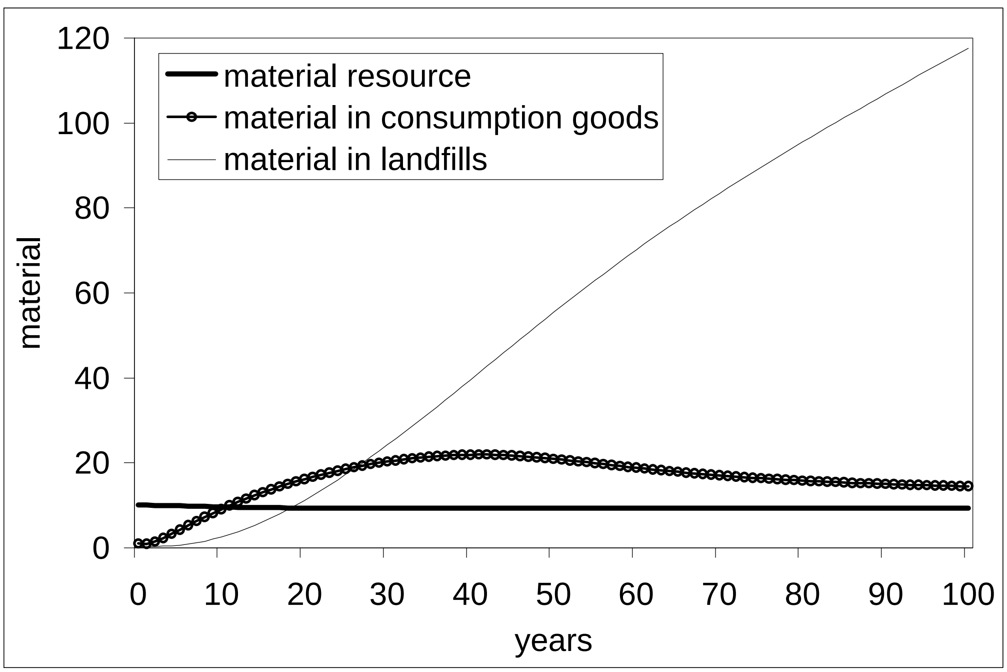

Figure 6: Material stocks in region 2 in the base case scenario.

The material inputs originate from resource extraction as well as from recycling (Figures 7 and 8). Nevertheless, region 1, which has a lower long run consumption level than region 2, only uses recycled material in the second half of the period. Note that we have assumed that recyclable and virgin materials are perfect substitutes.

Figure 7: Material inputs in region 1 in the base case scenario.

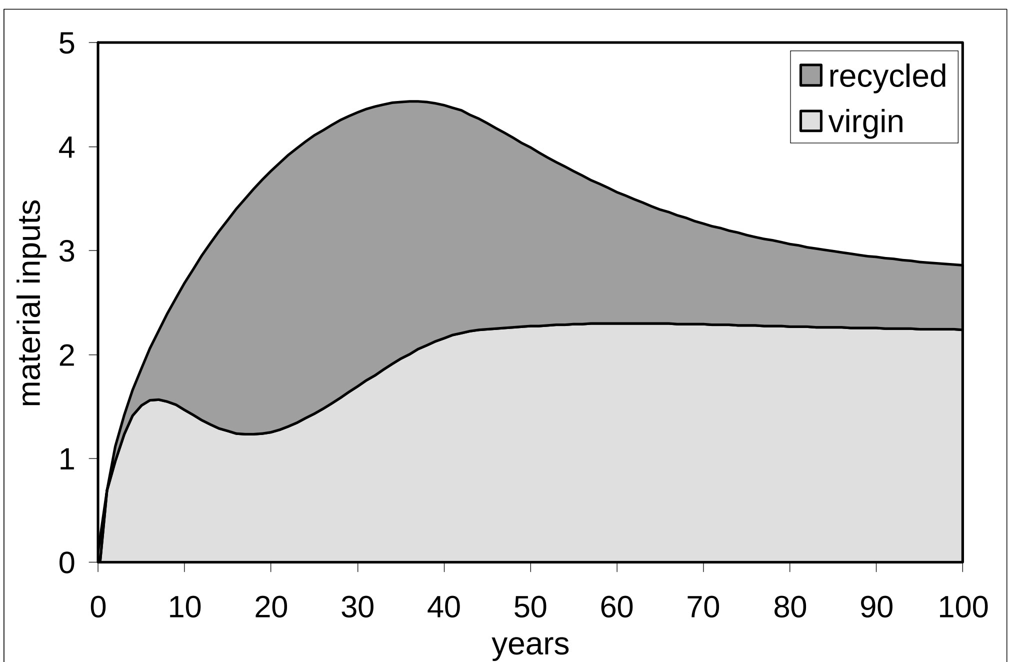

Figure 8: Material inputs of region 2 in the base case scenario.

The amount of new materials for production of consumer goods is chosen as an indicator of pressure of economic activities on the environment. The relation between this indicators and economic output is depicted for each region as well as the total of regions in Figure 9-11. These Figures show curves similar to the “Environmental Kuznets Curve”, namely when the extraction of new materials is taken as a measure for the environmental pressure. Figure 10 resembles a N shaped curve hypothesized by de Bruyn and Opschoor (1997).
Looking at the relationships for each region separate gives a different picture. Region 1 first consumes a large amount of materials before it turns to recycled materials, and therefore a zero amount of new material inputs. Region 2 requires an increasing amount of input of materials due to the larger economic growth rate. This demand can not be supplied by recycled materials

at low costs. Consequently, the amount of inputs of new materials increases. The N-shaped relationship in region 2 is caused by the large domestic consumption of virgin materials in region 1, reducing the availability of importing virgin materials from region 1 by region 2. An increase of waste material in region 1 reduces the demand for virgin materials. The import of virgin materials from region 1 increases again. Therefore, the N-shape relationship between environmental pressure and economic development of a country might also be explained from a spatial perspective.

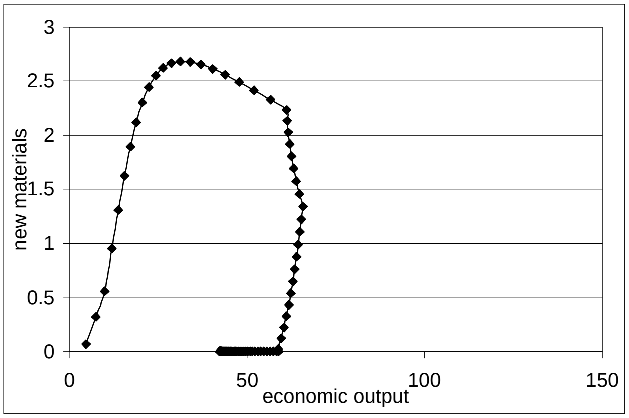

Figure 9: Relation between inputs from new materials and economic output in region 1 in the base case.

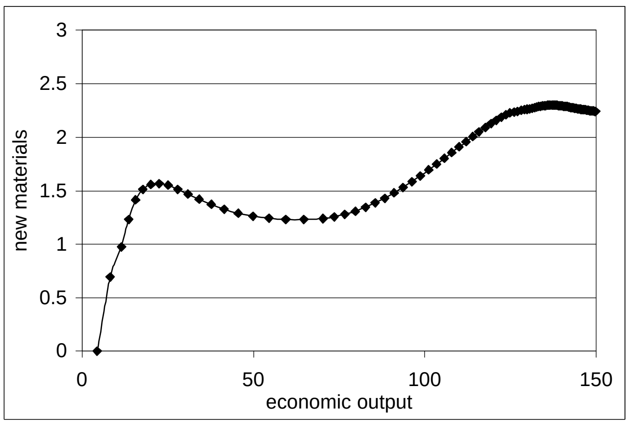

Figure 10: Relation between inputs from new materials and economic output in region 2 in the base case.

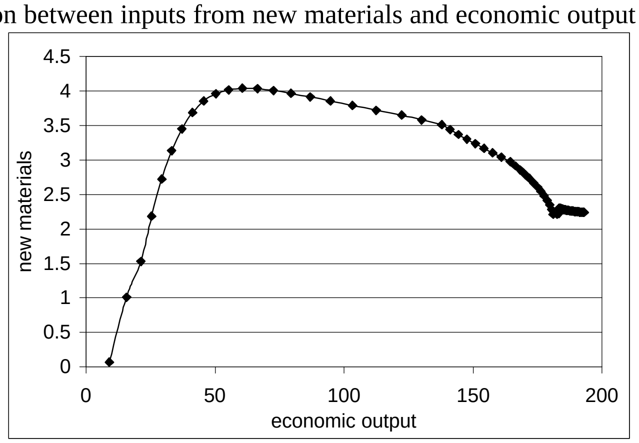

Figure 11: Relation between inputs from new materials and economic output in both regions in the base case.

No trade

If the regions are not allowed to trade, economic growth of each of them is evidently much lower. The discounted sum of utility of consumption is about 27% lower than the reference case in both regions (Table 1). Region 2 is obviously constrained by the lack of resources that are needed to reach the economic development level obtained under the reference case. Although region 1 has a large amount of resources, it does not have the ability to export materials to allow for import of consumer goods. As shown in Figures 12 and 13, the consumption level grows at a lower rate compared to the reference case. The “EKC” stabilises at a lower level and shows a N-shape (Figure 14). This N shape is caused by the scarcity of virgin material relative to secondary material. After a fast growth of virgin material use, depreciation of consumer goods result in a large supply of secondary materials, reducing the demand for virgin materials during a short period. After this short period, the consumption of virgin material increases again, but at a slower rate. It is clear from this case, that trade increases both the carrying capacities and the sustainable and maximum growth rates.

Technology of material production

In this case the amount of capital needed to extract materials, or to recycle materials, decreases at an exogenous rate. Because of the improved options to use the available material resources, the discounted utility of consumption increases in both regions compared to the reference case (Table 1). The increase in region 2 is higher because it has fewer resources. The “EKC” found is similar to the one under the reference case (Figure 15). This illustrates that the increased welfare is mainly due to increased possibilities to recycle materials (Figures 12 and 13).

Non-renewable resource

In the reference case each resource has a growth rate of 10%. In this case we assume that the growth rate is equal to zero, such that the resource is a non-renewable resource. This constraint has a severe impact on both regions. The discounted sum of utility is decreased by 30% in the resource rich region 1 and 25% in region 2. The levels of consumer goods peak halfway the 100 year period, and declines afterwards (Figures 13 and 14). The “EKC” peaks at a high level at a low economic development of 60 (Figure 17). The economic development levels off during the second part of the 100-year period.

Local feedback

The accumulation of materials in the environment leads to a decrease of the carrying capacity of the own resource. Therefore, one expects that an increased amount of materials will be recycled, to avoid its accumulation in the environment. As depicted in Figure 18, not only does the amount of new materials peak at a lower level, but also does the economic development level off. The consumption of goods increases at a low rate in region 1, while in region 2 the amount of consumer goods decreases during the second half of the 100-year period. Explanations for this phenomena are the reduction of materials extraction, leading to a reduction of trade, and a reduction of economic growth. Especially the resource poor region will suffer the most in the long term from a restriction on using virgin resources.

Global feedback

Instead of a feedback from accumulated materials to their own resource, the global feedback assumes a reduction in the carrying capacity of both resources. This means that waste generated by region i affects the resource in region j. This extra constraint leads to a lower optimal use of new materials compared to the local feedback situation (Figure 18). Moreover, the economic output decreases at the end of the time horizon. The utility of consumption decreases compared with the local feedback case (Table 1). Similar to the local feedback case, the resource poor region will suffer the most from the feedback of environmental degradation.

Table 1: The discounted sum of utility of consumption in both regions, $U(C_i)$, in absolute and relative terms for the six experiments. The changes as denoted in the right columns are differences compared with the reference

case.

	Total discounted utility region 1	Total discounted utility region 2	% Change	% Change
Reference	413.0	394.1	0	0
No trade	300.2	286.0	-27.3	-27.4
Technology resources	425.3	469.2	+3.0	+19.1
Nonrenewable resource	291.0	294.3	-29.5	-25.3
Local feedback	381.6	329.6	-7.6	-16.4
Global feedback	369.3	334.7	-10.6	-15.1

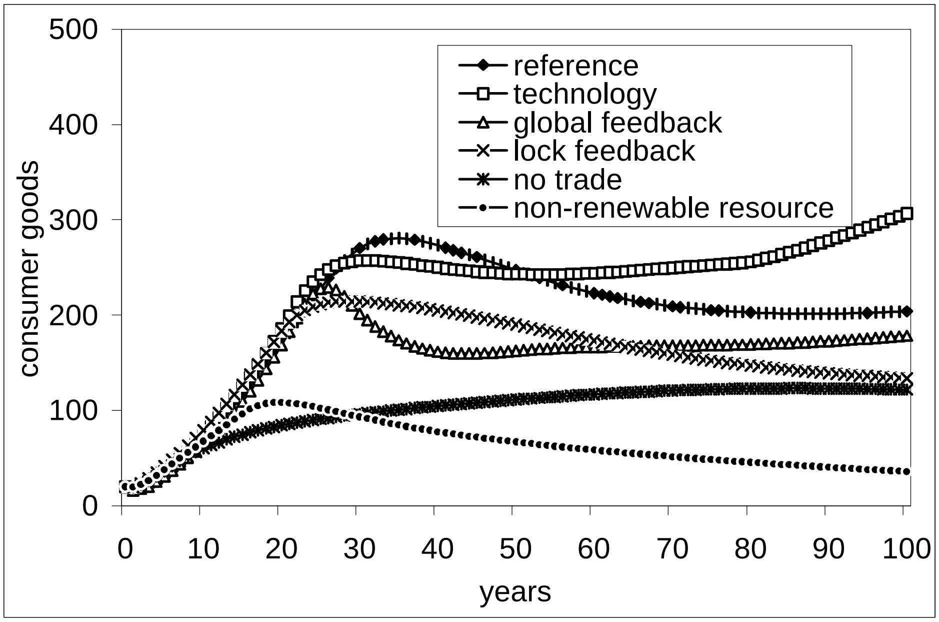

Figure 12: Stock of consumer goods in region 1.

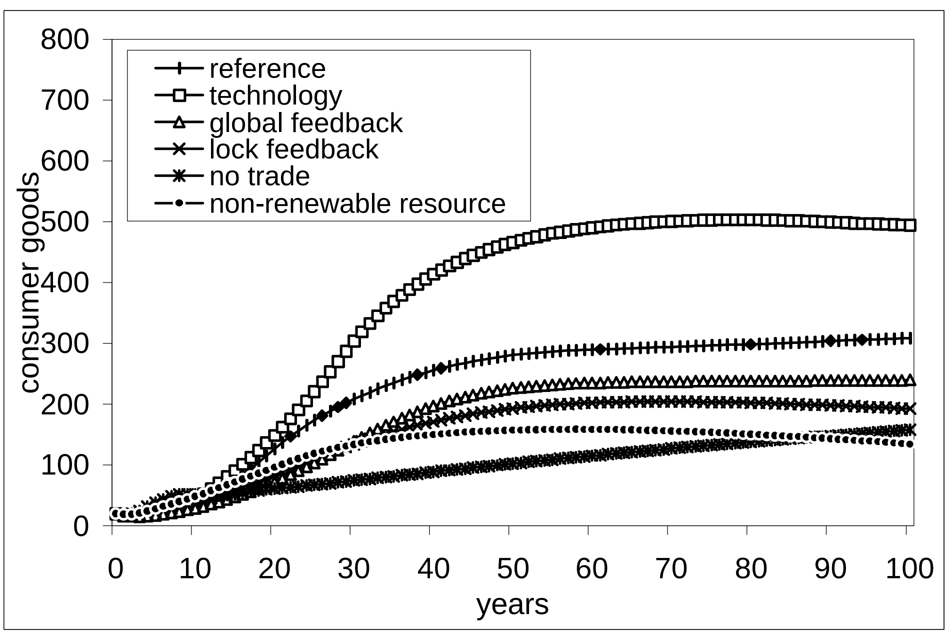

Figure 13: Stock of consumer goods in region 2.

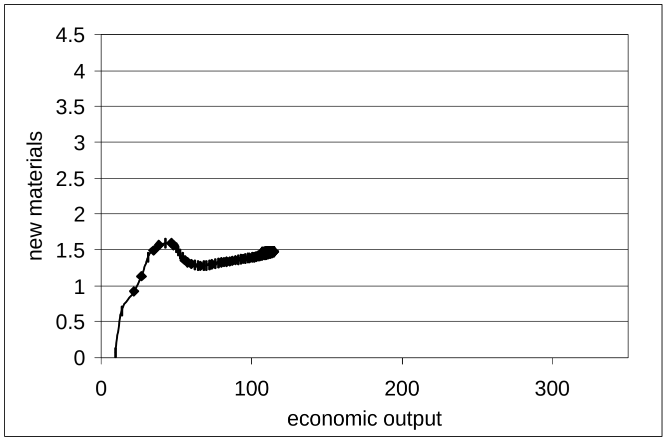

Figure 14: Relation between inputs from new materials and economic output in both regions for the no trade case.

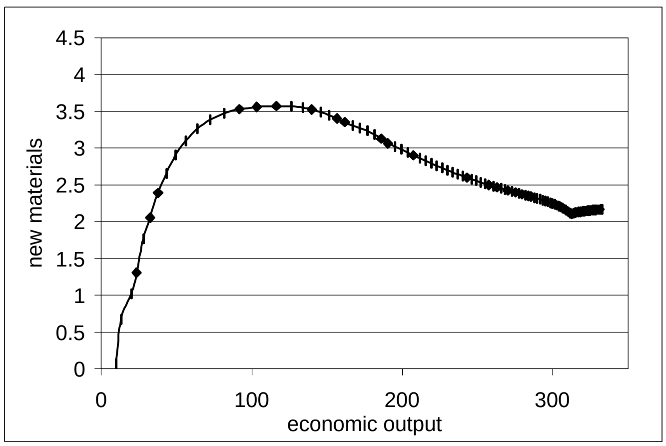

Figure 15: Relation between inputs from new materials and economic output in both regions for the technology of resources case.

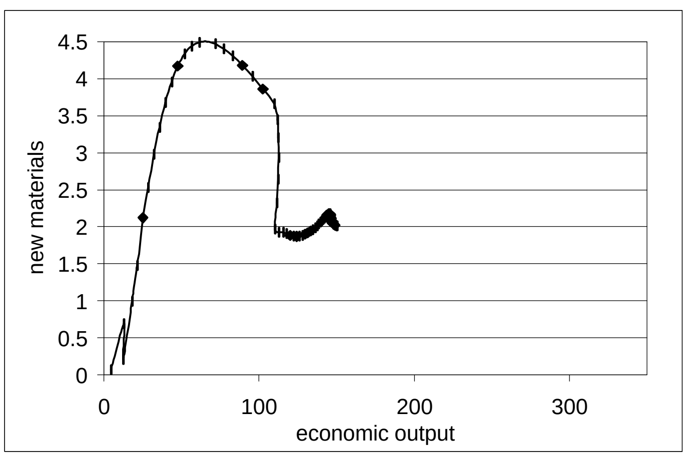

Figure 16: Relation between inputs from new materials and economic output in both regions for the non-renewable resources case.

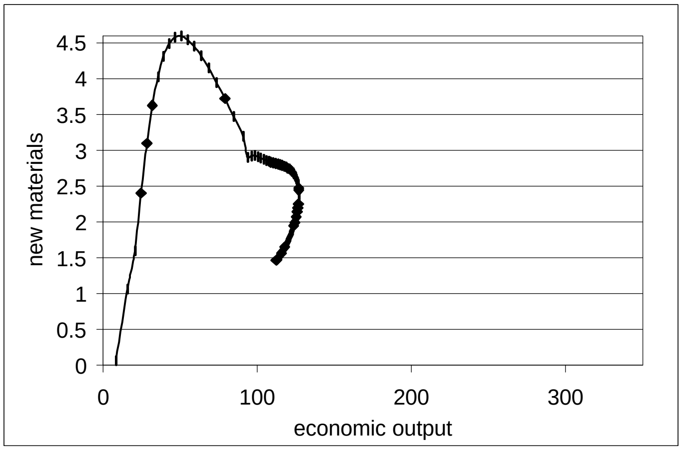

Figure 17: Relation between inputs from new materials and economic output in both regions for the local feedback case.

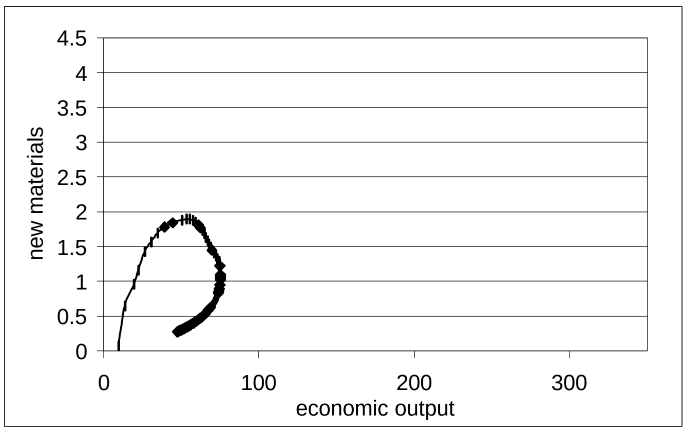

Figure 18: Relation between inputs from new materials and economic output in both regions for the global feedback case.

5. Conclusions

A model has been presented that focuses the attention on spatial flows of materials. The model describes product chains in two economies. Materials are extracted from a renewable resource, used as inputs for the production of consumer goods, and recovered and recycled. The possibility of the regions to trade increases their carrying capacity and maximum and sustainable growth. When the regions differ with regard to the carrying capacity of the resource, welfare optimisation requires that regions will specialise. The region with the largest carrying capacity will specialise in resource extraction, while the other region will specialise in the production of consumer goods. Numerical optimisation experiments show that both regions are sensitive to alternative assumption of technology and resource dynamics. All experiments generate global relationships between environmental pressure and income that support the relinking hypothesis of de Bruyn and Opschoor (1997) except when environmental feedback stimulate a collapse of the economic systems. N-shaped relationships between environmental pressure and income can be explained by temporary technological and institutional changes due to exhaustion of easy solutions. This paper shows the existence of a N-shaped curve due to trade of materials between countries, and substitution of virgin and secondary materials due to relative scarcity.

Model experiments show that it is unlikely that delinking environmental pressure and economic development is possible over a longer period of time. The current model is not appropriate to address all issues relevant to re- and delinking. Possible future steps in developing models for spatial industrial metabolism are the inclusion of endogenous technological change (both learning-by-doing and learning-by-using dynamics), of sectoral interactions, and of increasing returns to scale dynamics to generate spatial clusters of economic activities. The current framework serves as a starting point to include such elements.

Acknowledgements
This research was done in the context of the research programme "Materials Use and Spatial Scales in Industrial Metabolism" (MUSSIM), funded by the Netherlands Organisation for Scientific Research (NWO). For information see: www.econ.vu.nl/re/MUSSIM/mussim.htm.

Annex. List of Variables (r denotes region, r=1,2)

Stocks (The values between brackets are the initial values)
C_r = level of consumption goods (200,300)
$K_{C,r}$ = level of capital goods production consumption goods (40,40)
$K_{R,r}$ = level of capital goods recycling materials (100,10)
$K_{M,r}$ = level of capital goods material production (2, 0.05)
$M_{R,r}$ = material in the environmental resource (100,10)
$M_{C,r}$ = material of consumption goods (1,5)
$M_{E,r}$ = material accumulated in the environment (0,0)

Flows
$C_{n,r}$ = new consumption goods
$C_{P,r}$ = production of consumption goods
$C_{M,r}$ = import of consumption goods
$C_{X,r}$ = export of consumption goods
$Y_{K,r}$ = sectoral output consumer goods production
$Y_{M,r}$ = sectoral output material production
$Y_{R,r}$ = sectoral output recycling
$M_{D,r}$ = input of materials
$M_{P,r}$ = material production
$M_{R,r}$ = material recycling
$M_{V,r}$ = recovered materials
$M_{U,r}$ = utilised recovered materials
$I_{C,r}$ = investments in production consumer goods
$I_{M,r}$ = investments in production materials
$I_{R,r}$ = investments in material recycling
$p_{M,r}$ = price of virgin materials
$p_{R,r}$ = price of recycled materials
$Q_{M,r}$ = total imports
$\pi_{M,r}$ = resource depletion
$\pi_{R,r}$ = recycling factor

Parameters (The values between brackets are the parameter values in the reference case)
η=elasticity consumption (0.5)
ρ=discount rate (0.03)
δ_{cr} = depreciation rate consumer goods (0.2)
$\delta_{kc,r}$ = depreciation rate capital goods consumption production (0.04)
$\delta_{km,r}$ = depreciation rate capital goods material production (0.04)
$\delta_{kr,r}$ = depreciation rate capital goods recycling materials (0.1)

a_C = technology level (2)
a_M = technology level (1)
a_R = technology level (10)
γ_r = elasticity of output (0.6)
τ_C = technology improvement production consumer goods (1)
τ_M= technology improvement production materials (0.995)
τ_R = technology improvement recycling materials (0.995)
$p_{\pi,r}$= exponent of depletion function (0.25)
i = interest rate (0.03)
$w_{p,r}$ = loss rate materials, consumption goods production (0.1)
$w_{s,r}$ = loss rate materials, recycling materials (0.1)
λ_r = growth rate material resource (0.1,0.1)
$Z_{M,r}$ = carrying capacity of the material resource (100,10)
κ_r = impact coefficient material resource (0)
φ = transformation parameter (1)

Decision variables
$x_{E,r}$ = degree of investments in material extraction
$x_{C,r}$ = degree of investments in producing consumer goods
$x_{V,r}$ = degree of investment in recycling
$x_{M,r}$ = level of material inputs
$x_{V,r}$ = % of recovering waste materials

References

Ayres, R.U. and U.E. Simonis (eds.) 1994. Industrial metabolism, restructuring for sustainable development. United Nations University Press. Tokyo, Japan

van den Bergh, J.C.J.M. and P. Nijkamp 1994. Dynamic macro modelling and materials balance: Economic-environmental integration for sustainable development. Economic Modelling.11 (3) 283-307.

van den Bergh, J.M.J.M. and P. Nijkamp 1995. Growth, trade and sustainability in the spatial economy. Stud. Reg. Sci. 25, 67-87.

Beukering, P van and M. Bouman 2000. Empirical Evidence in International Trade and Recycling of Secondary Materials. World Bank Working Paper. Environment Department, The World Bank. Washington, DC.

Beukering, P. van, J.C.J.M. van den Bergh, M.A. Janssen and H. Verbruggen 2000. The international material product chain: an alternative perspective on international trade and trade theories. submitted.

Bruyn, S.M. de and J.B. Opschoor 1997. Developments in the thoughput-income relationship: theoretical and empirical observations. Ecological Economics. 20:255-268.

Bruyn, S.M. de, en R.J. Heintz 1999. The environmental Kuznets curve hypothesis. In: J.C.J.M. van den Bergh (ed.), Handbook of Environmental and Resource Economics. Edward Elgar. Cheltenham, UK, pp/ 656-677.

Fuijta, M. and P. Krugman and A.J. Venables 1999. The Spatial Economy: Cities, regions and international trade. The MIT Press, Cambridge/London.

Grübler, A. 1998. Technology and Global Change. MIT Press. Cambridge/London.

Janssen, M.A. and J.M.J.M. van den Bergh 1999. SIMBIOSES: Modelling Industrial Metabolism in a Multi-Regional Economic System. discussion paper TI-99-060/3. Tinbergen Institute, Amsterdam/Rotterdam.

Kandelaars, P.P.A.A.H. 1999. Economic Models of Material-Product Chains for Environmental Policy Analysis. Kluwer Academic Publishers, Dordrecht, the Netherlands.
Leach, M.A., A. Bauen and N.J.D. 1997. A Systems Approach to Materials Flows in Sustainable Cities: A Case Study of Paper. Journal of Environmental Planning and Management. 40(6), 705-723.
Linder, S.B. 1961. An Essay on Trade and Transformation. Almquist & Wiksell. Upsala.
Nordhaus, W.D. 1994. Managing the Global Commons: The Economics of Climate Change. MIT Press. Cambridge, MA, USA.
Nordhaus W.D. and Z. Yang 1995. RICE: A Regional Dynamic General Equilibrium Model of Optimizal Climate-Change Policy. American Economic Review. Vol. 86 (4) 741-765
Sachs, J.D. and A.M. Warner 1995. Natural Resource Abundance and Economic Growth, Development Discussion Paper. No. 517a. Harvard Institute for International Development, Harvard University.
Suri, V., and D. Chapman 1998. Economic growth, trade and energy implication for the environmental Kuznets curve. Ecological Economics. 25 (2). 195-208.
Vernon, R. 1966. International Investment and Trade in the Product Cycle. Quarterly Journal of Economics. May.