ON THE ECONOMIC LOGIC OF ECO-EFFICIENCY AND RECYCLING

Mario Cogoy

Department of Economics and Statistics - University of Trieste
Piazzale Europa 1 - 34127 - Trieste - Italy
Phone: ++39040-5587041 / Fax: ++39040-567543 / email: mario.cogoy@econ.units.it

---

Abstract

This paper attempts to integrate materials balances into quantitative economic modelling by adopting a dual view of the economic process. All activities are described by two equations: an economic and a materials balance equation. Eco-efficiency defines the efficient use of materials in all processes.

The economic system is related to the environment by a flow of virgin materials into the economy, and by the diffusion of waste into the environment. The material scale of economic activities also affects the biosphere. Scale is defined as the quantity of all materials subtracted from nature and frozen within the boundaries of the economic system. It is assumed, that the diffusion of materials into the environment and the material scale of the economy negatively affect welfare.

Eco-efficiency and recycling are controlled by human capital. A higher level of eco-efficiency and a higher rate of recycling are only possible, if human capital supports technical progress.

The paper develops a framework for comparative static analysis. Optimal levels of physical and human capital, eco-efficiency and recycling are determined for a given population. Numerical simulations are performed in order to illustrate the role of parameters.

It is shown, that eco-efficiency is always optimal, whereas recycling is not. It may be sometimes advisable to keep recycling below its technologically feasible level. It is also shown, that the optimal level of physical capital may be declining for rising levels of human capital. For reasonable values of the parameters the model generates a Kuznets curve for physical capital.

Keywords: Eco-Efficiency, Recycling, Materials Balances, Human Capital

JEL Classification:

1. INTRODUCTION

The current anthropogenic pressure on the natural environment calls for an effective control of the material dimensions of human activities in advanced industrial societies (Adriaanse et al., 1997; Fischer-Kowalski, 1998; Fischer-Kowalski / Hüttler, 1998). Different possible technological responses to the task of controlling anthropogenic material flows have been discussed in the literature as e.g.: dematerialisation (Hermann et al. 1989; Bernardini / Galli, 1993; Fortis, 1994; De Bruyn, 1998; Weizsäcker, 1998; Cogoy, forthcoming), eco-efficiency (Schmidt-Bleek, 1992, 1997; Weizsäcker / Lovins / Lovins, 1997; Reijnders, 1998), recycling (Smith, 1972; Bianciardi et al. 1993, 1996; Converse, 1996, 1997; Washida, 1998; Huhtala, 1999; Ayres, 1999a; Craig, 2001; Di Vita, 2001; Eichner / Pethig, 2001; Highfill / Mc Asey, 2001; Hosoda, 2001), industrial ecology and industrial metabolism (Ayres, 1989; Ayres / Simonis, 1994; Ayres / Ayres, 1996; Erkman, 1997).

The present paper attempts to study the economics of the control of material stocks and flows. The flows considered are the flows of virgin materials from the natural environment into the economy and the discharge of waste from the economy into the environment. The stocks are the materials frozen in the shape of physical capital and the waste materials captured in the “waste basket” (Ayres, 1999a) or in the “holding tank” (Converse, 1997) out of which materials can be recycled instead of being released into the environment. These stocks determine the material scale of the economy. Scale measures the occupation of natural spaces by anthropic activities.

This paper adopts a dual approach to the economics of materials. Each process is described by two equations: a materials balance equation, and an economic equation. It is shown, that materials balance conditions impose constraints upon the economic system, the most relevant of which is probably to be seen in the fact that physical capital, being an aggregation of molecules, affects scale. There is a limit to the transfer of matter from the environment into human artefacts and for this reason also the quantity of capital an economy can reasonably wish to accumulate is limited.

An optimal material structure of the economy is determined by knowledge and technology, and the level of technological capabilities is measured in this paper by human capital. Since human capital is scarce, an optimal material state of the economy requires an optimal allocation of human capital to its different possible uses. I shall consider three uses of human capital.

First of all, human capital can be used for increasing productivity. This role of human capital has been extensively investigated in economic theory (Lucas, 1988; Romer, 1989) and will also be considered here. Increasing productivity in a dual framework implies however an increased throughput of materials which has to be accounted for, both backwards, as an increased input of virgin and/or recycled materials, and also forwards, as an increased production of waste.

The second use of human capital concerns eco-efficiency and recycling. Both eco-efficiency and recycling do not come at zero costs: human capital is a basic resource necessary for increasing the rates at which eco-efficiency and recycling can take place. Eco-efficiency is defined as the rate at which useful materials are extracted from raw materials inputs. Eco-efficiency can increase the useful portion of material throughput and reduce waste. Recycling does not reduce waste. It feeds waste back into production and reduces in this way inputs of virgin materials. At the same time the scale of the economy increases, since a larger waste-basket will be required. This leads to formulate the economic problem of recycling, since an optimal proportion between virgin and reused materials will have to be determined. It will be shown that it is mostly non-optimal to recycle materials at the highest technologically possible level. A consequence of this is that the issue of complete recycling (Converse, 1996, 1997; Washida, 1998) turns out to be of little economic relevance. Even if complete recycling were possible, it is very unlikely to be economically meaningful.

A third use of human capital is in consumption. Consumption is not only a material, but also a cultural, aesthetic and social process. Consumption is therefore fundamentally influenced by knowledge and human capital (Cogoy, 1999, *forthcoming*) and the consumptive outcome of the economic system has no value, if it is not accompanied by human and social capabilities and skills.

The past discussion on strong vs. weak sustainability (Perman et al., 1999) was too narrowly focussed on physical and natural capital. Human capital is a third and important party in the sustainability game, since human capital significantly affects the material scale of economic activities. This paper argues that human capital can, to a certain limit, substitute physical capital and relieve in this way the pressure on natural capital due to the scale of economic activities. Sustainability calls therefore for an intensive development of human capital, necessary for reducing the material scale of human activities.

Although the analysis of physical constraints on economic activities is a much debated issue (among others: Ayres and Kneese, 1969; Converse, 1971; Converse, 1996; Converse, 1997; Cleveland and Ruth, 1997; Ayres, 1998; Ayres, 1999a; Ayres, 1999b; Ruth, 1993, 1999; Craig, 2001) the development of models combining physical insights with specific tools of economic analysis is a field into which much more work will have to be invested. Existing economic-physical models make very different assumptions and focus on very different aspects of the complex interaction between economic and physical analysis.

Smith, 1972 applies the law of mass conservation to recycling, but has no physical capital and therefore no focus on scale. He develops economic conditions for complete or zero recycling. Huhtala, 1999 investigates recycling as an alternative to resource extraction. Recycling reduces pollution, but labour is the only input and physical capital does not come into the picture. Di Vita, 2001 focuses on the effects of recycling on the rate of growth. His model has technical progress, endogenously generated by research. Welfare is negatively affected by the dimension of the waste stock, but not by the scale of economic activities. Hosoda, 2001 applies the corn-guano model of the post-Sraffian school (Bidard and Erreygers, 2001) to an analysis of recycling. The residuals of a first process are used as inputs of a second process. In this way, waste is completely absorbed and unlimited growth is therefore possible, even after exhaustion of landfills. There are no physical capital, no problems of scale and no technical progress. Eichner and Pethig, 2001 present a labour-only model based on mass conservation with recycling activities and waste treatment before disposal. They extensively analyse waste markets and market failures in the waste sector. Highfill and Mc Asey, 2001 study recycling as an alternative to landfilling in the framework of a growing economy.

Economic growth is exogenous and no interrelationship between physical capital, recycling as production input and technical progress is therefore addressed. Van den Bergh, 1996 presents an experimental model based on materials balances. Waste can be emitted, recycled or stored. Environmental quality depends on the stocks of renewables and on the stock of pollutants, which is affected by emissions. Simulations are performed with exogenous scenarios. An overview on applied materials flows models is given in: Bouman et al., 2000.

The present paper attempts to combine eco-efficiency, recycling and stock-flows aspects of mass balances in a model where technology is determined by human capital. Sections 2 to 5 introduce the model, section 6 performs numerical simulations for different values of the parameters, section 7 concludes.

2. THE MACRO MODEL

The material basis of the economic process will be compared in this paper to the flow of air into and out of a bagpipe and to the air contained in it.

Figure 1

V represents the stream of air blown into the bagpipe. In the economy, these are the virgin materials extracted from the natural environment and processed by the economic system.

D is the flow of air out of the bagpipe. These are the materials diffused into the environment after having performed their role within the economy.

S is the quantity of air confined within the boundaries of the bagpipe skin. In the economy, these are the materials frozen within the economic system, and determining its material scale. I shall consider two main components of scale in this paper. The first is physical capital, and the second is the “waste basket” (Ayres, 1999a) or the “holding tank" (Converse, 1997), i.e. the stock of waste materials kept for recycling within the boundaries of the economic bagpipe instead of being released into the environment.

$$S = K + X \tag{1}$$

S is scale, K is total physical capital and X is the waste basket. At any point in time, of course, these frozen materials can melt away and disperse into the environment after crossing the border between the economy and the environment.

There is some ambiguity in the literature on the nature of the "waste-basket" (Converse, 1997; Ayres, 1999a). Is the waste-basket separated from the earth-system, or is the earth system itself the waste-basket out of which used materials can be recovered? From an economic point of view the difference is important.

First of all, if the waste-basket is isolated from the environment, economic resources, as labour, capital and technology must be provided in order to keep the waste sequestered from the environment. Isolated from the environment obviously means: temporarily isolated. Waste deposits can leak, and leakages again, as all waste, can be redirected into the waste-basket, or can diffuse into the environment.

Secondly, and more important, if the environment itself is the waste-basket, the difference between virgin materials and recycled materials disappears, since both would have to be retrieved from the environment. The ideas of virgin material inputs from the environment into the economic system, and of materials emissions from the economy into the environment would both be lost, since no inputs and outputs can exist, if the system boundaries are so broadly defined as to comprise the whole earth/ocean/atmosphere system. I shall adopt the view of a waste-basket isolated from the environment, because I assume that capturing waste materials before dissipation is economically more convenient than recovering materials after dissipation. In this case, virgin materials and recycled materials are different inputs, since the first originate in nature, while the second originate from the waste-basket.

Clearly:

$$\dot{S} = V - D \tag{2}$$

If the inflow of virgin materials exceeds the dispersion of materials into the environment, the dimension of the bagpipe, i.e. the material scale of the economy will grow.

At macro-level the material basis of the economic system can be described using five variables. V denotes the inputs of virgin materials from the environment into the economy, D are emissions, and S measures the material stocks within the economic system. S is further divided into capital K and the waste basket X.

Taking time derivatives of (1) and using (2) one gets:

$$V = D + \dot{K} + \dot{X} \tag{3}$$

This means that all virgin materials inputs must either disperse into the environment, or accumulate as physical capital or in the waste basket. Notice that recycling does not affect this fundamental relationship. Recycling can reduce the input of virgin materials, but once virgin materials enter the economic system, they must either exit again or accumulate as assets within the system.

The difference between the economy and a bagpipe is obviously related to the fact that the economy is structured within the boundaries of the skin separating it from the environment, and it is to the mass aspects of this internal structure that I now turn.

Within the bagpipe's skin materials are transformed into waste. There are three sources of waste. The first source of waste is the transformation process moulding materials into the desired shape: if some materials are "lost", while others are given a useful economic shape, these losses represent one source of waste. But even if no losses were to occur in transformation, waste would still arise out of all types of consumptive uses of output and out of capital depreciation. Consumptive uses of output and capital depreciation therefore, together with material losses in transformation, produce waste within the bagpipe's skin. <<< **Note. Consumptive uses of output do not only include personal consumption, but also, for example, the flow of final output to the research sector. I do not consider consumer durables in this paper. I assume therefore that all materials consumed are transformed into waste during the same time period.** >>>

Waste is a potential candidate for recycling. Recycling requires that waste materials are captured and sequestered within the waste basket. The waste materials escaping sequestration dissipate into the environment and are lost for recycling.

Therefore:

$$W = D + F \tag{4}$$

where W is the flow of total waste and F is the flow of materials into the waste basket. I assume that society can choose how to divide waste between D and F. Such a choice is a choice under technological constraint, since society can only direct a flow of given magnitude into the waste basket if a technology is available for doing so. I shall later give more details concerning this technological constraint.

I define the rate of recycling J as:

$$J = \frac{F}{W} \tag{5}$$

The purpose of a waste basket is to serve as a source of materials for recycling. I model recycling as a flow R out of the waste basket:

$$R = \frac{1}{r} X \qquad\qquad r \geq 1 \tag{6}$$

r is a technological parameter reflecting the idea that materials cannot be directly recycled out of the flow of waste, but necessitate storage in a larger stock, out of which they can be recovered (Ayres, 1999a). For this reason, a realistic value for r will be greater than unity. $r = 1$ would imply immediate recycling out of non-dissipated waste. The larger r, the bigger the waste basket required to sustain a given flow of recycling.

Clearly:

$$\dot{X} = F - R \tag{7}$$

which means that the waste basket will grow, if the flow of materials into the basket exceeds recycling.

From (3), (4) and (7):

$$V + R = W + \dot{K} \qquad (8)$$

This means that all material inputs, whether virgin or recycled, must end up into waste or accumulate as physical capital.

3. THE MICRO MODEL. A DUAL APROACH

3.1. Materials balances

I consider four processes within the bagpipe skin: extraction of virgin materials, recycling, production of final output and research (production of knowledge). <<<**Note. I neglect end-of-the-pipe waste treatment and storage, although waste treatment can improve environmental conditions in the short run.** >>> Each process is seen from a dual point of view: the materials balance aspect and the economic aspect, and is described therefore by two equations. In a dual framework all economic entities appear both in a set of materials balance equations and in a set of economic equations. In order to make these two sets comparable, all economic entities must be measured in the same unit, which is a mass unit, e.g. tons. Tons of capital or of consumption goods make sense in materials balance equations. They make little sense however in economic equations, if they are not qualified by an index, measuring the quality, or the "shape" given to materials, so that they may perform their role as capital or consumption goods within the economic system. I shall now continue with the description of the economic system in terms of "mass" and later give a more detailed account of "shape", when I shall introduce the economic part of the model.

Consider extraction first. From the materials balance point of view, the input of virgin materials must be equal to the sum of useful materials, shaped, refined and processed, and waste, which are materials "lost" during processing and refining:

$$V = M_V + W_V \qquad (9)$$

where M_V are useful materials transformed from virgin materials inputs and W_V is waste from extractive processes. I define an eco-efficiency coefficient h as:

$$h = \frac{M_V}{V} \qquad 0 \le h \le 1 \qquad (10)$$

h evaluates the extractive process under the point of view of materials efficiency. If h is equal to one, the process is perfectly efficient and no materials are lost in transformation. If h is equal to zero, the process is perfectly inefficient, no output comes out of the process, and all inputs are transformed into waste. h is a complex measure of eco-efficiency, since it evaluates more than one aspect of materials efficiency with one variable only. If fewer materials are lost in transformation (and therefore, if less waste is produced) h will rise. But also if process waste is directly channelled as input to other processes h will rise. In other words, h measures both materials efficiency at plant level and also efficiency in the design of interconnected plants (industrial ecology). If waste is directly channelled from a production plant to another, it appears as useful material in this paper. The definition of waste is therefore confined to those materials requiring containment in a waste basket before further processing. If industrial ecology were perfectly successful, process waste would be reduced to zero and h would be equal to one. Depreciated capital and consumption would then be the only sources of waste.

(9) and (10) are equivalent to:

$$M_V = h\,V \qquad (11)$$

$$W_V = (1 - h)\,V \qquad (12)$$

Recycling and production can be analysed along similar lines:

$$M_R = h\,R \qquad (13)$$

$$W_R = (1 - h)\,R \qquad (14)$$

where M_R are useful “shaped” materials coming out of the recycling process, and W_R is waste from the recycling process. I assume that the eco-efficiency coefficient h is the same in all processes.

Similar equations also describe final output production:

$$Y = h\left(M_V + M_R\right) \tag{15}$$

$$W_P = (1-h)\left(M_V + M_R\right) \tag{16}$$

where Y is final output, and W_P is waste from final output production.

Aggregating sectors, from (11), (13) and (15) one obtains:

$$Y = h^2 (V + R) \tag{17}$$

Equation (17) represents the aggregate materials requirements (virgin or recycled) of final output, and these requirements will have to be higher, if eco-efficiency is lower.

3.2. The economic equations

From the economic point of view, the same processes are described by production functions. I consider two factors: physical capital, measured in tons and labour, measured in time-units. Clearly, one ton of physical capital can be more or less productive, and in economic equations physical capital is therefore multiplied by a productivity factor p, measuring the quality of the "shape" given to materials, so that they can serve as capital. Constant returns to scale production functions and the productivity factor p are the same in all sectors.

I assume an exogenously given population of N identical individuals. One unit of labour is inelastically supplied by each individual, so that total labour supply is equal to N.

The production function for virgin materials can be written as:

$$M_V = \left(pK_V\right)^p L_V^{\,1-p} \tag{18}$$

where K_V is physical capital (in tons), applied to the extraction of virgin materials, L_v is the fraction of total labour employed in virgin materials extraction, and p is a Cobb-Douglas exponent. The production function plays the role of a flow-regulator: the greater the values of pK_V and L_v, the more refined virgin material will flow out of the extraction process and, given an eco-efficiency coefficient h, the more virgin materials inputs will be absorbed by the process.

The production functions for recycling and final output are:

$$M_R = (pK_R)^p L_R^{1-p} \tag{19}$$

$$Y = (pK_P)^p L_P^{1-p} \tag{20}$$

K_R , K_P, L_R and L_P are capital and labour in the recycling and final output sectors respectively.

3.3. Personal consumption

One possible use of final output is personal consumption. C is total social personal consumption. $\frac{C}{N}$ is per capita personal consumption. Consumption is measured in tons. In the same way as one physical unit of capital can be more or less productive, depending on a productivity index, so can a physical unit of consumption deliver a higher contribution to welfare if consumption goods are more conveniently “shaped”. In this way the effects of physical consumption are enhanced by higher quality:

$$z = q\frac{C}{N} \tag{21}$$

q is a quality index measuring the consumptive “shape” of consumption goods and z is qualified per capita personal consumption.

Consumption goods are finally transformed into waste:

$$W_C = C \tag{22}$$

(22) is the materials balance equation for consumption, where W_C is waste from consumption.

3.4. Human capital

I assume that the technological coefficients p , h and q are determined by human capital (measured in some appropriate unit of knowledge, e.g. meters of bookshelves in a library of blueprints). Therefore:

$$p = p(H_K) \tag{23}$$

where H_K represents accumulated production knowledge. The idea is simply that knowledge H_K can give a better “shape” to the materials contained in all types of capital, so as to increase their productivity.

Eco-efficiency is also determined by human capital, applied to the knowledge of materials and their metabolism in human activities. I call this type of knowledge metabolic human capital (H_M).

$$h = h(H_M) \tag{24}$$

I assume that recycling is constrained by the same technological knowledge constraining eco-efficiency:

$$J \leq h \tag{25}$$

There is no reason why recycling should necessarily be at its technological maximum of $J = h$. The rate of recycling only affects the proportion between virgin materials and recycled materials and the optimal proportion will depend on preferences, as will be seen later.

The quality index of consumption depends on knowledge applied to consumptive processes:

$$q = q(H_C) \tag{26}$$

H_C is human capital applied to the improvement of consumption quality.

Since all types of human capital are measured in the same unit (meters of bookshelves), H measures the size of the social library:

$$H = H_K + H_M + H_C \tag{27}$$

h has a logical upper bound of one, if perfect eco-efficiency is considered to be possible. Otherwise, the upper bound of eco-efficiency $\bar{h}$ will be lower than one. p and q may have empirical upper bounds. I shall assume that such upper bounds, if they exist, are beyond the level of human capital accumulation reached by the system, so that they may be neglected.

I assume that knowledge can be produced making use of capital, labour, knowledge and final output. Knowledge can also be partially lost as time elapses. Human capital depreciates therefore in a similar way as physical capital does. Additional knowledge can be produced according to:

$$\dot{H} = y\left(pK_H\right)^p L_H{}^{1-p} H^e - jH \qquad 0 < e < 1 \tag{28}$$

where K_H and L_H are capital and labour requirements in research and j is the rate of human capital depreciation. y is a coefficient relating body (output in tons) to soul (immaterial units of knowledge). $\left(pK_H\right)^p L_H{}^{1-p}$ is potential physical output forsaken in order to produce $\dot{H} + jH$ units of knowledge. $\frac{1}{yH^e}$ are therefore opportunity costs of a unit of knowledge in terms of forsaken output.

The production of knowledge further requires a flow of final output (e.g.: paper):

$$C_H = \frac{x}{h}\left(\dot{H} + jH\right) \tag{29}$$

C_H is final output used in the research sector and $\frac{x}{h}$ are final output requirements per unit of research output. Final output requirements decline as overall eco-efficiency rises.

Final output requirements of research, after fulfilling their function, are transformed into waste:

$$W_H = C_H \tag{30}$$

W_H is waste from the research sector.

There are in the above model four types of physical capital and labour in extraction, recycling, final output and research.

Total capital is equal to:

$$K = K_V + K_R + K_P + K_H \tag{31}$$

Total labour is equal to:

$$N = L_V + L_R + L_P + L_H \tag{32}$$

There are three types of human capital: knowledge applied to the increase of productivity, knowledge applied to the increase of eco-efficiency and recycling, and knowledge applied to the improvement of consumption quality. All types of knowledge are utilized in the research sector in order to produce new knowledge, and operate therefore as externalities in research. These three types of knowledge are rival to each other and no externalities exist between the realms of production, optimisation of materials use and consumption.

3.5. Investment in physical capital

Net investment in physical capital is:

$$\dot{K} = Y - C - C_H - d\ K \tag{33}$$

dK is capital depreciation.

Although (33) has an economic flavour, it is here a materials balance equation, stating that an increase in mass capital is equal to mass output, minus mass personal consumption, minus consumption in the research sector, minus mass capital depreciation.

Also:

$$W_K = \mathbf{d}\ K \tag{34}$$

W_K is waste from capital.

Total waste is therefore:

$$W = W_V + W_R + W_P + W_C + W_K + W_H \tag{35}$$

The flow of materials just described can be also represented with following diagram:

Figure 2

3.6. Mass and shape

At this place some additional remarks on “mass” and “shape” may be useful. Of the three technology parameters: p, h, and q, two (p and q) are related to shape, and one (h) is related to mass. p qualifies the shape of capital and q the shape of consumption goods. p measures the contribution of the shape of capital to productivity. In this way, the quality index p, although measuring shape, has effects on mass, since a higher value of p increases the materials throughput per unit of capital. q evaluates the shape of consumption goods and has therefore a direct effect on welfare. This does not mean however, that productive and consumptive knowledge are only operative at production and consumption level. Productive and consumptive knowledge begin to shape materials already at extraction and recycling level, since production and consumption knowledge select materials to be extracted and recycled and shapes them in such a way, as they can best serve as inputs to the production of final output. Knowledge thus permeates all stages of the economic process, although its results are only measurable when output reaches its final destination as capital or consumption good.

h is a mass-related index, since it only compares output and input mass without considering the fact that the shape of inputs and outputs is different.

(23), (24), (26) and (27) imply that p, h, and q are dependent on different types of human capital, are unrelated among each other and no side-effects or spillovers between them exist. This is obviously a strong assumption, since joint effects are very likely to occur in the real world. A shaped piece of marble (i.e. a statue) for example is more likely to produce aesthetic pleasure on the beholder than an unshaped piece of the same matter. Sculptured marble will “loose” however more matter in transformation than unsculptured one, and eco-efficiency will be lower as a consequence of an improved aesthetic quality of marble, so that eco-efficiency is negatively affected by quality. Also, at individual process level, eco-efficiency will be less dependent on technology and more on the aesthetic ideals of the sculptor: a baroque Pietà is likely to be less eco-efficient than a sculpture by Henry Moore. Assuming independence of eco-efficiency and quality means that, in the aggregate, for a given level of eco-efficiency, the proportion of materials finding any kind of useful employment (either as statue or as marble dust) compared to waste is determined. The assumption of independence at aggregate level is therefore less unrealistic than it may seem for individual processes, and has the advantage of allowing to model productivity, eco-efficiency and quality as controlled by three different types of knowledge. This allows to formulate a social choice problem concerning the type of knowledge society would like to acquire.

4. STEADY STATES

In this paper I shall not perform any dynamic analysis, but only compare steady states. For this reason I shall assume:

$$\dot{S} = \dot{K} = \dot{X} = \dot{H} = 0 \qquad (36)$$

which implies:

$$V = D \qquad (37)$$

$$F = R \qquad (38)$$

$$jH = y\,(pK_H)^p\, L_H{}^{1-p}\, H^e \qquad (39)$$

$$C_H = \frac{x}{h} jH \qquad (40)$$

$$Y = C + C_H + d\,K \qquad (41)$$

$$W = V + R \qquad (42)$$

In steady state the rate of recycling J is:

$$J = \frac{R}{V + R} \qquad (43)$$

The assumption of a steady state requires at this point some qualification. A steady state, as defined in this paper, implies a constant flow of virgin materials into the system, a constant flow of emissions, and a constant scale of the economy. The limit case, where material flows are zero, is not given particular relevance in the following analysis. For this reason, a steady state does not by itself imply sustainability, but only permanence for a time period which is long enough as to justify detailed analysis. The duration of this time period depends on the quality of the steady state, and in particular on resources and the energy system. It is not unrealistic to assume abundant resources in an aggregate model, although individual resources may face exhaustion in a shorter time period. Obviously, society may be interested in reducing flows, in order to prolong the steady state, and this is reflected in social preferences, which will be discussed later.

In the present paper aggregate material flows are modelled, but not energy. Obviously, a source of energy is necessary in order to set flows in motion. If some of the materials here described are fossil fuels, they may provide the necessary source of energy. Alternatively, some of the capital goods of this paper may be thought of as consisting of appliances able to capture solar energy. A steady state based on fossil fuels is however completely different from a steady state based on solar energy. In a fossil fuel system carbon is extracted from below the earth crust and is emitted into the atmosphere. In the terminology of this paper eco-efficiency is very low in such a system, since it is based on carbon dispersion. A fossil system will be capable of producing a steady state of some duration, if an adequate technology for carbon recovery from the atmosphere becomes available (Holloway, 2001). Low eco-efficiency and storage of waste is therefore a characteristic feature of such a system. In a solar system waste production is low, since it is basically reduced to the wear and tear of solar capital stock. For this reason, eco-efficiency is high. In the numerical simulations of section 6, high eco-efficiency is assumed for high levels of human capital. This pattern corresponds rather to a solar, than to a fossil fuel system. The energy system of this model may be best thought of therefore as being based on solar energy.

If society chooses to recycle, waste of different quality will flow into the waste basket. It is certainly not meaningful to mix all sorts of waste and have a uniform mixture of materials in the waste basket. It will be probably more reasonable to have separate storage facilities for different types of materials (Craig, 2001). Bent nails will have to be straightened, and not ground and mixed with sand before extracting iron out of the mixture. A fundamental equilibrium condition must be satisfied however in steady state: the chemical elements entering the system as virgin materials must exit the system in the same proportions; otherwise the economic bagpipe would work as a filter, increasing the concentration of some chemical elements at the expense of others. It is not necessary that outputs and inputs are of the same chemical composition. They must only be in the same elemental proportion: water as input and hydrogen and oxygen as output would not violate the non-concentration condition.

The recycling sector, as it is modelled in the present paper, uses capital in order to collect waste of different types in different drawers of the waste basket and to reprocess this waste. It is assumed that these operations deliver to the final sector processed materials of the same quality as the output of the virgin materials sector, so that processed virgin materials and processed waste are perfect substitutes. It is also assumed, that capital and labour costs are the same in both sectors. Under these circumstances, the only reason to prefer recycling to virgin materials extraction is a social choice to reduce flows at the cost of increasing scale. Although the assumptions of perfect substitutability between virgin and recycled materials and of equal production costs are admittedly strong assumptions, they could be easily relaxed without changing the basic framework here adopted.

5. THE ECONOMIC PROBLEM

5.1. Preferences

Preferences of individuals are defined over qualified per capita consumption and the state of the environment, which is described by V and S.

$$U = U(z, V, S) \qquad U_z > 0, \quad U_V < 0, \quad U_S < 0, \quad U_{zz} < 0, \quad U_{VV} < 0, \quad U_{zz} < 0 \qquad (44)$$

The reasons why materials exchange and scale affect welfare are straightforward: the higher the quantity of materials discharged into the environment after anthropic processing and the larger the occupation of natural space through human artefacts, the more will be the environment, and therefore welfare, negatively affected.

From the discussion above, it follows that physical capital plays a double positive and negative role for society. On the one hand, capital enhances human productivity and this role has been extensively analysed in economic theory. On the other hand however, physical capital occupies space, spoils landscapes, destroys biotopes, and for this reason has also negative effects on welfare. Physical capital is, in other words, a necessity, not a pleasure. **<<< Note: I am only concerned with productive capital in this paper. Matters are obviously different for architectural capital, architectured landscapes, gardens, etc. as an expression of aesthetic and cultural values.>>>** This suggests the idea of an optimal level of physical capital which will be determined by a compromise between its positive contribution to production and its negative effects on scale. The same thing is true of the waste basket. A bigger waste basket allows more recycling, but occupies more space and intrudes into the environment. This means, that an optimal size of the waste basket will have to be determined.

For similar reasons, also optimal human capital will have to be endogenously determined. Human capital maintenance requires capital, labour, knowledge and a flow of commodities detracted from final output. When marginal costs of human capital maintenance become equal to the marginal benefits of a larger stock of knowledge, an increase in human capital is no longer desirable.

5.*2. Aggregation*

Given the same production technologies in all sectors, efficient capital and labour allocation require:

$$\frac{K_V}{L_V} = \frac{K_R}{L_R} \tag{45}$$

$$\frac{K_V}{L_V} = \frac{K_P}{L_P} \tag{46}$$

$$\frac{K_V}{L_V} = \frac{K_H}{L_H} \tag{47}$$

(45) to (47), together with (11), (13), (18) to (20), (31), (32) and (39) yield:

$$(pK)^p N^{1-p} = \frac{1+h}{h} Y + \frac{j H^{1-e}}{y} \tag{48}$$

Equation (48) is the aggregate production function of the economy. It states that aggregate capital and labour produce a composite output of physical commodities and knowledge. The immaterial component (knowledge) is expressed in terms of forsaken output and is measured therefore in the same unit as physical production (tons). For given aggregate capital and labour, commodity production is less, if a larger share of factors are employed in research. Notice that productivity in the aggregate is different from productivity in individual processes. In individual processes the eco-efficiency index h does not appear, whereas it plays an important role in the aggregate. The reason for the dependence of aggregate output on eco-efficiency is that if eco-efficiency is low, a greater portion of total capital will have to be invested in material processing sectors, and a smaller portion will be left for final output. Economic efficiency implies therefore eco-efficiency. For this reason, eco-efficiency plays an important role at aggregate level, since, given aggregate capital and labour, the system will be more productive if a greater portion of aggregate capital is employed in final output production.

5.3. The donor and the planner

In the following analysis I shall assume that a generous donor offers society whatever quantity of physical and human capital it wishes, and a waste basket of any size. The social planner would be badly advised to ask for the greatest possible quantity of physical and human capital, since this would negatively affect society through the effects of scale and through the maintenance costs of human capital. I shall therefore consider physical and human capital as choice variables in the maximization exercise of the next section. The same thing applies to the waste basket: the planner will also have to determine the optimal size of the waste basket, which will be related to the optimal rate of recycling.

The donor is obviously a metaphor for history. In the real world, molecules can be transferred from the environment to human artefacts and knowledge can be accumulated only in the course of time, and not instantaneously by the touch of a magic wand. The donor transfers molecules into physical capital and into the waste basket and fills the social library with books in a single donation. Society is placed in this way with a single jump into the optimal state which would have to be achieved in an historical process.

The planner's solution represents the best possible state of society, since it internalises all environmental externalities. It is the task of politics to set market rules in such a way, as to approach the planner's solution as much as possible in a decentralized world. (For an analysis of markets and market failures in waste treatment, cf. Eichner and Pethig, 2001).

5.4. The planner's problem

Imagine the donor offers society any desired quantity of physical and human capital with a free choice of type (the content of the books) and a waste basket of any size. I assume that upper bounds for p, h and q are beyond the optimal endogenous level of human capital. For this reason explicit constraints on these variables are not necessary. Matters are different however with recycling. According to (25) recycling is constrained by eco-efficiency. A specific non-negativity constraint on recycling must also be added in order to avoid negative recycling:

$$J \geq 0 \tag{49}$$

The social planner maximizes the welfare of each society's member: $U = U(z, V, S)$ subject to (1), (6), (17), (21), (23), (24), (26), (27), (40), (41), (43), (48), the inequality constraint (25) and the non-negativity constraint (49).

Kuhn-Tucker conditions for this problem are given in the Appendix.

6. NUMERICAL SIMULATIONS

6.1. Content and scope of the simulations

I shall focus in the numerical simulations of this section on how knowledge and the population size affect the material structure of the economy. A solution to the optimising problem of section 5 determines the optimal values of material stocks and flows and optimal human capital. In the simulations of this section I shall consider human capital as exogenous, and study how the material structure of the economy adapts, as knowledge approaches its optimal endogenous level.

I shall briefly discuss functional specifications for the welfare function and for the technological functions first, and then perform numerical simulations for different values of the relevant parameters.

6.2. Preferences

I shall model preferences as:

$$U = u_1 \frac{1}{s} Q^s - \frac{1}{l}\left(u_2 V^l + u_3 S^l\right) \qquad s < 1;\ l > 1 \qquad u_1 + u_2 + u_3 = 1 \qquad (50)$$

The second element of the welfare function: $\frac{1}{l}\left(u_2 V^l + u_3 S^l\right)$ is a damage function where marginal damage is increasing in materials emissions and scale. In what follows I shall assume $l = 2$.

The value of s determines the elasticity of substitution between qualified consumption and environmental quality.

For $s = 0$ the utility function transforms to:

$$U = u_1 \log Q - \frac{1}{l}\left(u_2 V^l + u_3 S^l\right) \qquad (51)$$

For $s > 0$ qualified consumption and environmental quality are good substitutes: individuals can be compensated for environmental damage by increasing consumption, and consumption will rise to the detriment of environmental quality. In the simulations I shall assume $s = .5$.

For $s < 0$ qualified consumption and environmental quality are bad substitutes. The consequence is, that society will use improvements in knowledge in order to increase qualified consumption and reduce emissions and scale at the same time. In the simulations I shall assume $s = -.5$.

6.3. Technological functions

I shall model productivity, eco-efficiency and consumption quality as logistic functions, implying that gains due to an exogenous increase in human capital are more intensive around the flexure, and slower everywhere else.

$$p = \bar{p}\frac{e^{aH_K}-1}{e^{aH_K}+e^{aA}} \qquad \bar{p} > 0 \qquad (52)$$

$$h = \bar{h}\frac{e^{bH_M}-1}{e^{bH_M}+e^{bB}} \qquad 1 \geq \bar{h} > 0 \qquad (53)$$

$$q = \bar{q}\frac{e^{gH_C}-1}{e^{gH_C}+e^{gG}} \qquad \bar{q} > 0 \qquad (54)$$

where a , b and g are coefficients, and A, B and G determine the flexures of the logistic functions.

Because of the logistic specification, actual values of p, h and q will never exceed upper bounds $\bar{p}$, $\bar{h}$ and $\bar{q}$.

6.4. Parameters and scenarios

In what follows I shall not focus on technology, but rather on preferences. All simulations in this section are based on the same parameters for $p(H_K)$, $h(H_M)$ and $q(H_C)$, which are:

$a = .02 \quad b = .1 \quad g = .1 \quad \bar{p} = 10 \quad \bar{h} = .9 \quad \bar{q} = 10 \quad A = 20 \quad B = 30 \quad G = 60$

With these parameters functions (52), (53) and (54) will assume following shape, the same for all simulations:

Figure 3

The increase in productivity is smooth, whereas eco-efficiency and consumption quality require a certain amount of knowledge accumulation, before reaching the period of more intensive harvesting. I have assumed a delay for consumption quality, implying that consumption quality is more difficult to improve than eco-efficiency and requires more shelves of the social library before producing significant results.

The other parameters are:

$p = .6 \quad r = 2 \quad d = .01 \quad j = .01 \quad y = 1 \quad e = .5 \quad x = .01$

$l = 2 \quad u_1 = .5 \quad u_2 = .4 \quad u_3 = .1$

I shall study the intermediate logarithmic case ($s = 0$) first and then describe the effects of a change in the population size on the material structure of the economy. The good ($s > 0$) and bad ($s < 0$) substitutability cases will be then computed and compared with the basic logarithmic case. All diagrams are drawn for exogenous values of human capital. The right hand end in the diagrams represents the optimal endogenous level of human capital. If read from left to right the diagrams describe the adaptation of the material structure of the economy as human capital approaches its optimal level. Numerical solutions are calculated using GAMS/SNOPT software.

6.5. Logarithmic case

In the logarithmic case, and for $N = 1$ the diagrams representing the optimal material structure are:

Figure 4

In the logarithmic case the optimal state of the environment is roughly constant for different levels of knowledge. This means that knowledge accumulation is focussed on increasing per capita qualified consumption in a basically constant environment.

At low levels of eco-efficiency the largest share of total capital and of total labour are employed in the extractive sector, since materials efficiency is very low and lack of knowledge imposes severe constraints on recycling. A rather small fraction of total capital and labour are left for final output production, and therefore output and consumption are low. Materials, in other words, are mostly transformed into waste before reaching the stage of consumption, and the overall performance of the economy is therefore low. For this reason, efforts are concentrated on increasing eco-efficiency.

This relieves the pressure on virgin materials extraction, so that capital and labour may be shifted to final output production.

Optimal capital increases as improving eco-efficiency relieves pressure on the materials requirements of the economy. Due to the rapid increase in materials efficiency, capital and output can grow, although total material requirements ($V+R$) decline (section 50-100 in the diagram). There is no strong demand for recycling, since improving materials efficiency significantly lowers material requirements per unit of output.

As improvements in eco-efficiency taper off (section 100-450 in the diagram), further human capital accumulation contributes to significantly augmenting capital productivity. This allows to reduce total capital without impairing output. Physical capital is in other words substituted by knowledge. Since eco-efficiency no longer improves, a growth in capital requires an increase in material requirements, and the demand for recycled materials therefore grows. A decline of physical capital opens up spaces for the growth of the waste basket. A Kuznets curve for total capital is thus generated.

At the final point, where human capital has attained its optimal endogenous level, physical capital has been substituted to a large extent by human capital. Although recycling is highest at the final point, it is markedly below its technological potential. Optimal recycling is less than maximum recycling.

6.6. The role of population

Assume an increase in population by 100%. The social library and the stocks and flows diagrams are modified as follows:

Figure 5

Dotted lines represent the case $N = 2$ (solid lines: $N = 1$).

Optimal scale and optimal virgin materials extraction remain relatively unaffected. Aggregate consumption increases, but given the double size of the population, per capita consumption declines, although this decline is compensated by a rise in the quality of consumption. The increase in output is due to the rise in labour supply, and this in turn requires a higher input of materials. Recycling is therefore higher and optimal capital lower.

An increase in population shifts the focus of the economy towards qualitative aspects of consumption, and leads to a higher rate of recycling, necessary to keep virgin material flows within bounds.

6.7. Good substitutability ($s = .5$).

With good substitutability the pattern of material stocks and flows changes, since society is compensated for a deterioration of the environment by increasing consumption.

Figure 6

The Kuznets curve for physical capital is also preserved in this case, since optimal capital rises in a first phase, as consumption and materials throughput increases, and later declines, substituted by human capital.

6.8. Bad substitutability ($s = -.5$).

The reverse pattern applies to the bad substitutability case, since environmental quality and consumption improve at the same time.

Figure 7

Although a Kuznets curve for physical capital is not generated by the simulations with the given values of the parameters, a decline in physical capital and an increase in recycling for higher levels of knowledge also occur in this case.

6.9. A comparison of scenarios.

The structure of the social library is basically the same for all simulations. Consumptive knowledge accumulates rather quickly, although, given the logistic specification, the results on quality are rather modest in the beginnings. Books on production technology are very rapidly increasing at a higher stage of knowledge accumulation. The main reason for this is that increases in productivity reduce the demand for capital and makes in this way more recycling possible for given physical dimensions of the economy. It must be remembered however that, because of (48), both productive and metabolic knowledge have positive effects on output, so that productive and metabolic books in the social library play similar roles, although with different means.

Physical consumption is increasing with human capital availability in all simulations, although the absolute levels of consumption may vary. In the neighbourhood of optimal knowledge consumption is highest in the good substitution case. As knowledge becomes more abundant, scale and virgin materials use increase with good substitutability and decrease with bad substitutability.

At high values of human capital, physical capital declines, and recycling raises in all simulations. This is due to the fact, that, for given scale and virgin materials use, material inputs can only increase, if recycling increases at the detriment of physical capital, and physical capital can only decline, without loss of output, if its decline is compensated by an increase in productivity. In this way, physical capital is substituted by human capital.

It is noteworthy, that this decline in physical capital at high levels of knowledge survives all changes in preference parameters made in the simulations.

7. CONCLUSIONS

This paper studies the effects of increases in knowledge on the material structure of the economic system. The system dimensions are bounded both with respect to flows and with respect to scale. Increasing marginal environmental damage prevents the economy from physically growing without bounds. Recycling is not a solution to this basic problem, since recycling reduces flows of materials to the environment, but achieves this at the expenses of the economy's scale. Nevertheless, recycling is very useful at high levels of knowledge: when increasing productivity makes a substitution of physical with human capital possible, recycling can increase without increasing scale, since declining physical capital leaves space for an increase of the waste-basket. The economy can invest more into the waste basket, because it invests less in physical capital.

Although the economy is materially bounded in this paper, the growth of human capital can find adequate outlets: metabolic human capital improves eco-efficiency, productive human capital substitutes physical capital, and consumptive knowledge augments consumption quality. This suggests that the debate on weak vs. strong sustainability does not adequately reflect the effects of human capital on the trade-off between physical and natural capital. Human capital can substitute for physical capital and relieve in this way the pressure of scale on the environment. Increasing marginal environmental damage implies that human activities should not encroach upon natural capital beyond a reasonable level (Ekins, 2003; Ekins et al., 2003). Given this, substitution can and should occur between physical and human capital, since human capital may help to reduce the material scale of economic activities without reducing welfare.

The present paper has focused on a comparison between steady states for different levels of human capital. A steady state however only implies a constant scale of the economy and a constant flow of materials from and to the environment and does not warrant by itself sustainability. For sustainability it is also necessary that environmental warnings are adequately mirrored into social preferences. If this is not the case, a steady state may turn out to be environmentally disruptive in the long run, and therefore not sustainable. For this reason, a sensitivity of society for environmental warnings and a flexibility to adapt to new environmental insights remains the basic social resource, necessary to keep anthropic activities in balance with the natural environment.

REFERENCES

Adriaanse, A. / Bringezu, S. / Hammond, A. / Moriguchi, Y. / Rodenburg, E. / Rogich, D. / Schütz, H. , 1997, Resource Flows: the Material Basis of Industrial Economies, World Resources Institute

Ayres, R.U., 1989, Industrial Metabolism, in: Ausubel, J.H./Sladovich, H.E. (eds.), Technology and Environment, National Academy Press, Washington DC

Ayres, R.U.,1998, Eco-thermodynamics: Economics and the Second Law, Ecological Economics, 26, 189-209

Ayres, R.U., 1999a, The Second Law, the Fourth Law, Recycling and Limits to Growth, Ecological Economics, 29, 473-83

Ayres, R.U., 1999b, Materials, Economics and the Environment, in: van den Bergh, J. (ed.), Handbook of Environmental and Resource Economics, Edward Elgar, Aldershot, 867-894

Ayres, R.U. / Ayres, L.W., 1996, Industrial Ecology: Towards Closing the Materials Cycle, Edward Elgar

Ayres, R.U./ Kneese, A.V., 1969, Production, Consumption and Externalities, American Economic Review, 59, 282-297

Ayres, R.U. / Simonis, U.E. (eds.), 1994, Industrial Metabolism: Restructuring for Sustainable Development, Tokyo, United Nations University Press

Bernardini, O. / Galli, R., 1993, Dematerialization: Long Term Trends in the Intensity of Use of Materials and Energy, Futures, 25, 431-448

Bianciardi, C.E./ Tiezzi, E./ Ulgiati,S., 1993, Complete Recycling of Matter in the Framework of Physics, Biology and Ecological Economics, Ecological Economics 8, 1-5

Bianciardi, C./ Tiezzi, E./ Ulgiati, S., 1996, Response: The 'Recycle of Matter' Debate. Physical Principles versus Practical Impossibility, Ecological Economics, 19, 195-96

Bidard, C./ Erreygers,G., 2001, The Corn-Guano Model, Metroeconomica, 52, 243-253

Bouman, M. / Heijungs, R, / van der Voet, E. / van den Bergh, J.C.J.M. / Huppes, G., 2000, Material Flows and Economic Models: An Analytical Comparison of SFA, LCA and Partial Equilibrium Models, Ecological Economics, 32, 195-216

Cleveland, C./ Ruth, M., 1997, When, Where and by How Much Do Biophysical Limits Constrain the Economic Process? A Survey of Nicholas Georgescu-Roegen's Contribution to Ecological Economics, Ecological Economics, 22, 203-223

Cogoy, M., 1999, The Consumer as a Social and Environmental Actor, Ecological Economics, 28, 385-398

Cogoy, M., *forthcoming*, Dematerialisation, Time Allocation, and the Service Economy, Structural Change and Economic Dynamics

Converse, A.O., 1971, On the Extension of Input-output Analysis to Account for Environmental Externalities, American Economic Review, 61, 197-198

Converse, A.O., 1996, On Complete Recycling, Ecological Economics, 19, 193-194

Converse, A. O., 1997, On Complete Recycling 2, Ecological Economics, 20,1-2

Craig, P. P., 2001, Energy Limits on Recycling , Ecological Economics, 36, 373-84

De Bruyn, S., 1998, Dematerialisation and Rematerialisation, in: Vellinga, P. / Berkhout, F. / Gupta, J. (eds.), Managing a Material World. Perspectives in Industrial Ecology, Kluwer, Dordrecht/Boston/London

Di Vita, G., 2001, Technological Change, Growth and Waste Recycling, Energy Economics, 23, 549-67

Eichner, T./ Pethig, R., 2001, Product Design and Efficient Management of Recycling and Waste Treatment, Journal of Environmental Economics and Management, 41, 109-34

Ekins, P., 2003, Identifying Critical Natural Capital: Conclusions about Critical Natural Capital, Ecological Economics, 44, 277 - 292

Ekins, P. / Folke, C. / De Groot, R., 2003, Identifying Critical Natural Capital, Ecological Economics, 44, 159 - 163

Erkman, S. 1997, Industrial Ecology: An Historical View, Journal of Cleaner Production, 5, 1-10

Fischer-Kowalski, M., 1998, Society’s Metabolism. The Intellectual History of Materials Flow Analysis, Part I: 1860-1970, Journal of Industrial Ecology, 2, 61-78

Fischer-Kowalski, M. / Hüttler, W., 1998, Society's Metabolism: The Intellectual History of Materials Flow Analysis, Part II: 1970-1998, Journal of Industrial Ecology, 2

Fortis, M., 1994, Economic Growth and the Intensity Use of Industrial Materials, in: Quadrio-Curzio, A. / Fortis, M. / Zoboli, R.(eds.), Innovation, Resources and Economic Growth, Springer, New York/Heidelberg/London

Herman, R./Ardekani, S.A./Ausubel, J.H., 1989, Dematerialization, in: Ausubel, J.H./Sladovich, H.E. (eds.), Technology and Environment, National Academy Press, Washington DC

Highfill, J. / McAsey, M., 2001, Landfilling versus "Backstop" Recycling When Income Is Growing, Environmental and Resource Economics, 19, 37-52

Holloway, S., 2001, Storage of Fossil-Fuel Derived Carbon Dioxide Beneath the Surface of the Earth, Annual Review of Energy and Environment, 145-166

Hosoda, E., 2001, Recycling and Landfilling in a Dynamic Sraffian Model: Application of the Corn-Guano Model to a Waste Treatment Problem, Metroeconomica, 52, 268-81

Huhtala, A., 1999, Optimizing Production Technology Choices: Conventional Production vs. Recycling, Resource and Energy Economics, 21, 1-18

Lucas, R.E. jr., 1988, On the Mechanics of Economic Development, Journal of Monetary Economics, 22, 3-42

Perman, R. / Ma, Y. / McGilvray, J. / Common, M. 1999, Natural Resource and Environmental Economics, Pearson Education,

Reijnders, L., 1998, The Factor X Debate, Journal of Industrial Ecology, 2 , 13-22

Romer, P.M., 1989, Human Capital and Growth: Theory and Evidence, National Bureau of Economic Research, WP Nr. 3173, Cambridge

Ruth, M., 1993, Integrating Economics, Ecology and Thermodynamics, Kluwer, Dordrecht,

Ruth, M., 1999, Physical Principles and Environmental Economic Analysis, in: van den Bergh,J. (ed.), Handbook of Environmental and Resource Economics, Edward Elgar, Aldershot, 855-866

Schmidt-Bleek, F., 1992, MIPS: a Universal Ecological Measure, Fresenius Environmental Bulletin, 1

Schmidt-Bleek, F., 1997, Wieviel Umwelt braucht der Mensch? Faktor 10 – das Mass für ökologisches Wirtschaften, Birkhäuser Verlag, Basel/Berlin/Boston, Deutscher Taschenbuch Verlag, München

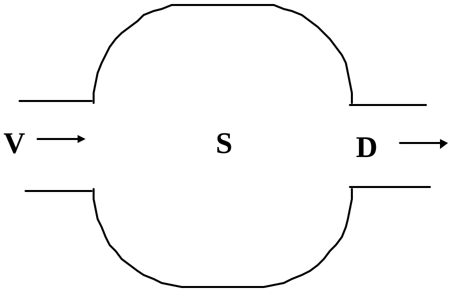
Smith,V.L., 1972, Dynamics of Waste Accumulation: Disposal versus Recycling, Quarterly Journal of Economics 86, 600-616

Van den Bergh, 1996, A Multisectoral Growth Model with Materials Flows and Economic-Ecological Interactions, in: van den Bergh, J.C.J.M., Ecological Economics and Sustainable Development. Theory, Methods, Applications, Cheltenham/Brookfields, Edward Elgar

Washida, T., 1998, Material Dissipative Conditions and the Impossibility of Complete Recycling, Structural Change and Economic Dynamics, 9, 271-88

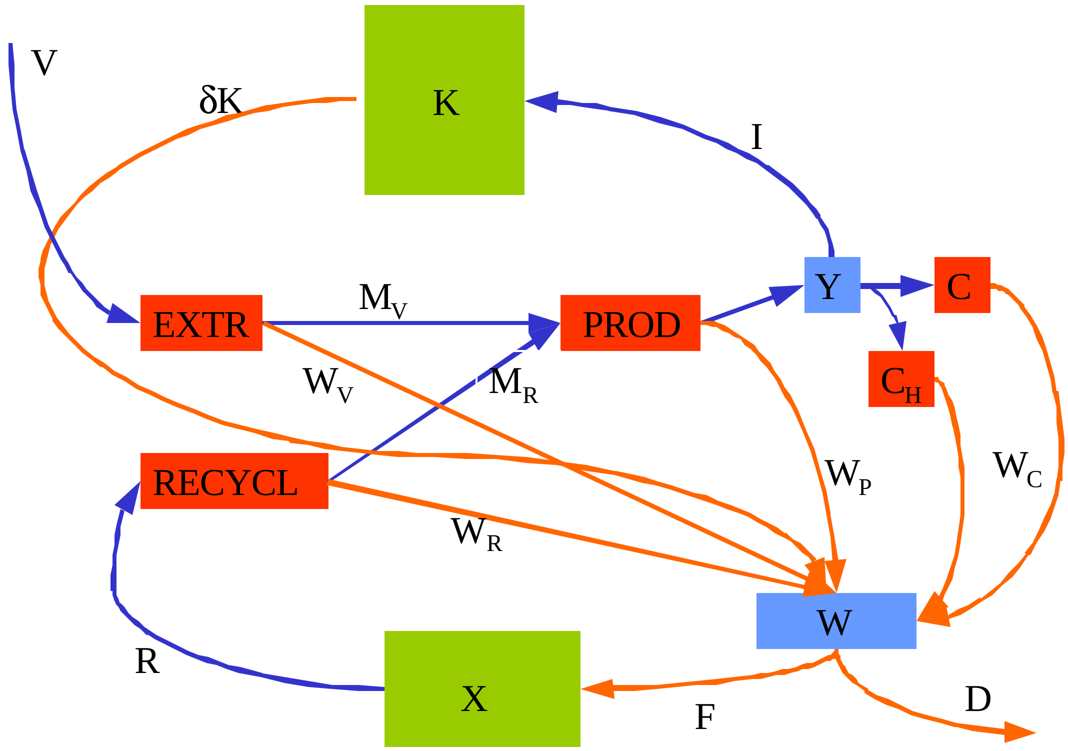
Weizsäcker, E.U. von / Lovins, A./ Lovins, L.H., 1997, Factor Four: Doubling Wealth, Halving Resource Use: The New Report to the Club of Rome, London, Earthscan Publications

Weizsäcker, E.U. von, 1998, Dematerialisation, in: Vellinga, P. / Berkhout, F. / Gupta, J.(eds.), Managing a Material World. Perspectives in Industrial Ecology, Kluwer, Dordrecht/Boston/London



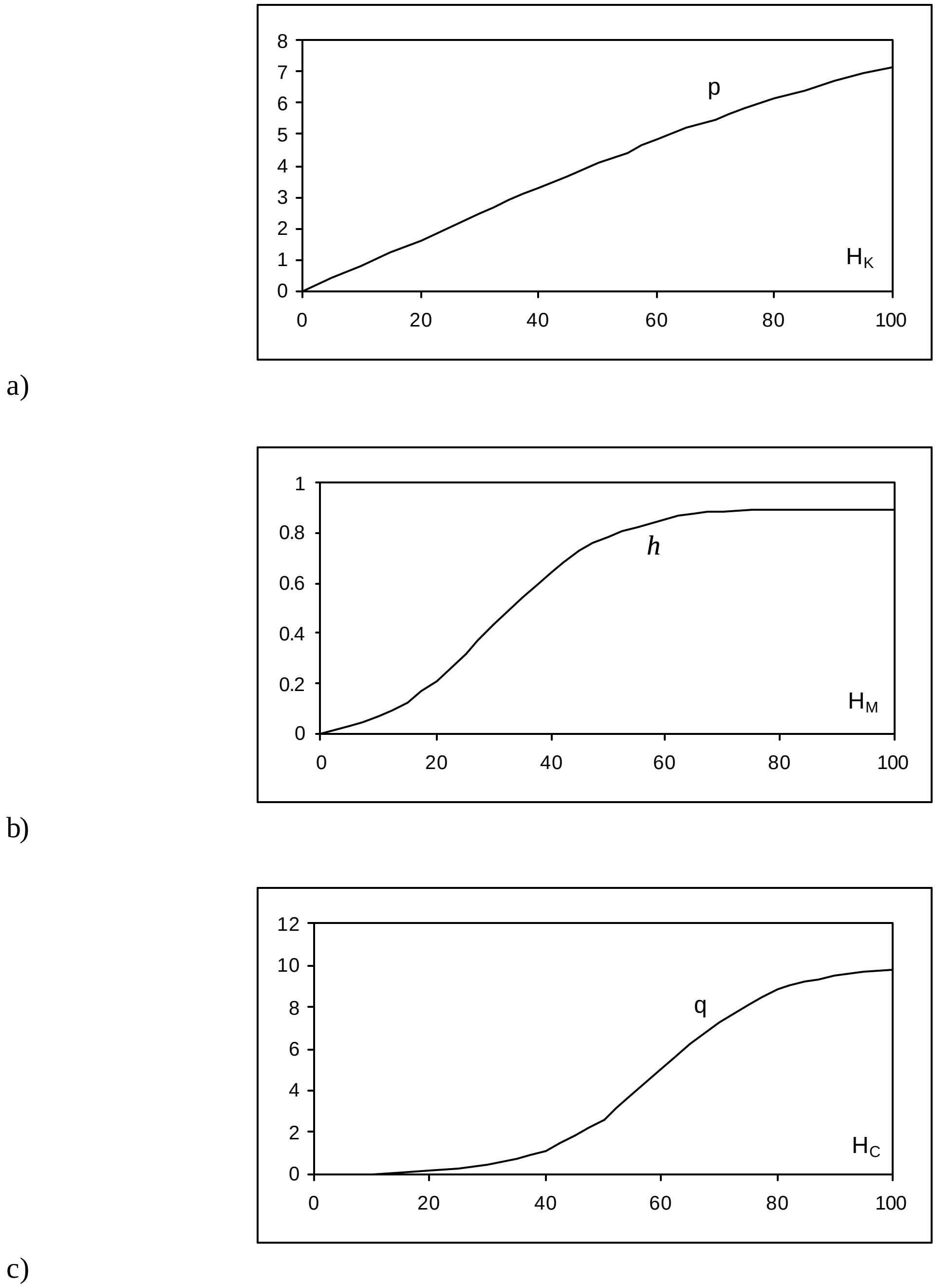
The macro-model

Figure 1



Materials flow diagram

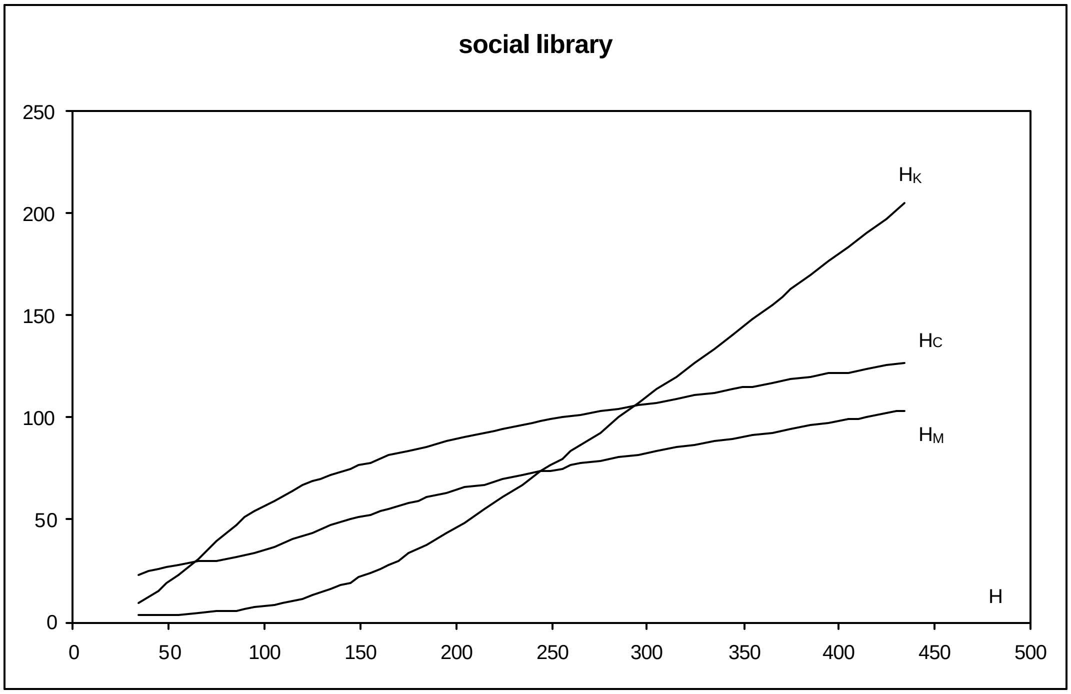
Figure 2



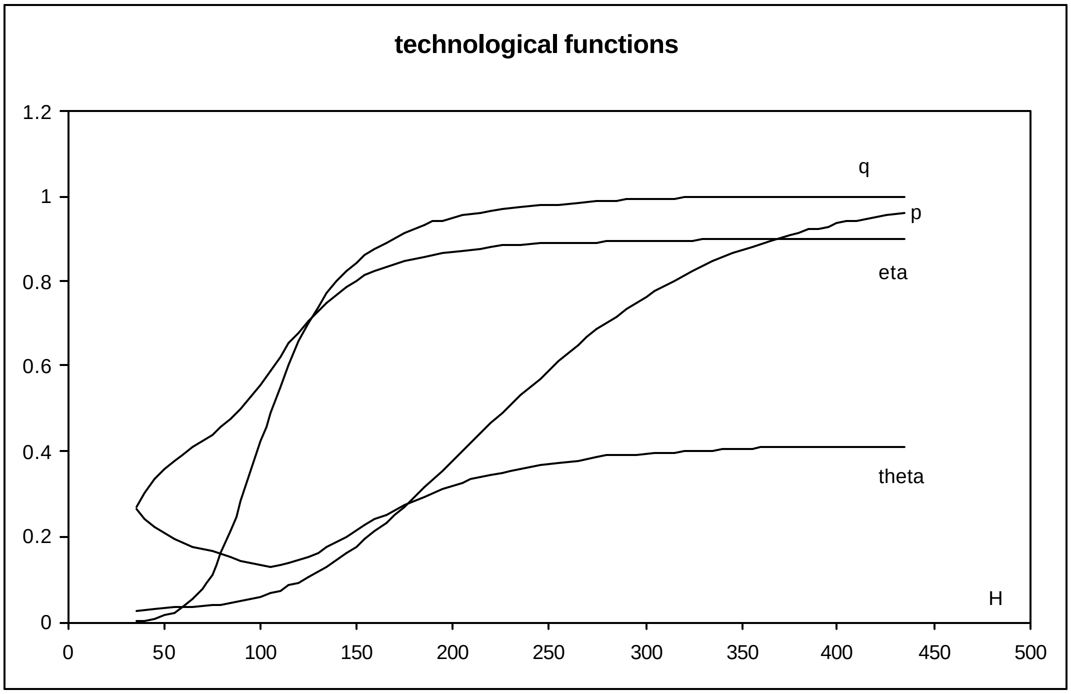
$a=.02 \quad b=.1 \quad g=.1 \quad \bar{p}=10 \quad \bar{h}=.9 \quad \bar{q}=10 \quad A=20 \quad B=30 \quad G=60$

Productivity, eco-efficiency and consumption quality

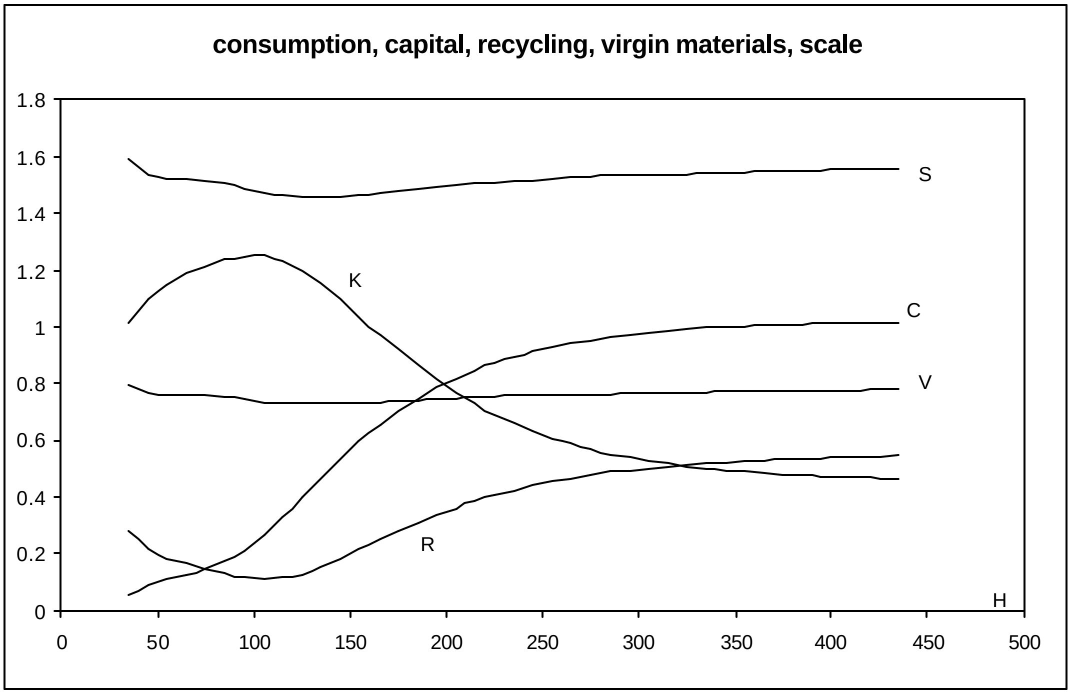
Figure 3


social library
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450
500
HK
HC
HM
H

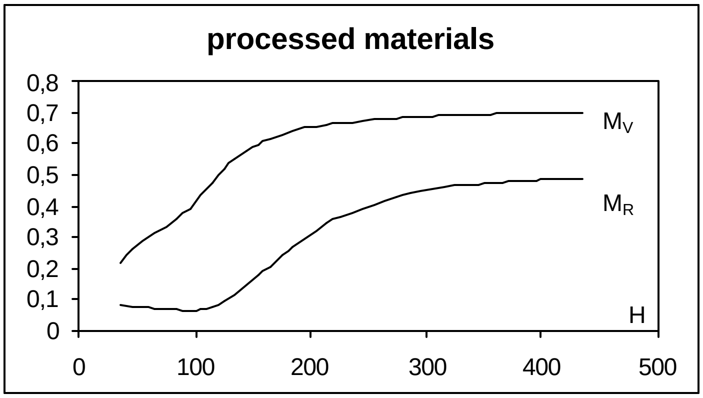
a)


technological functions
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
q
p
eta
theta
H

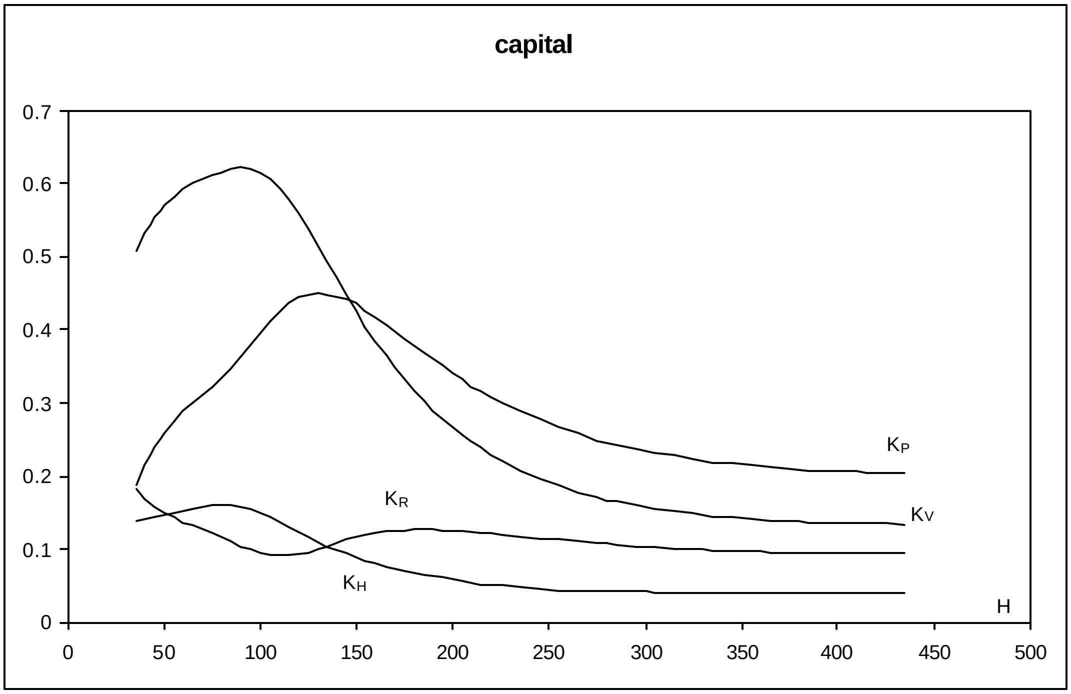
b)


consumption, capital, recycling, virgin materials, scale
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
500
S
K
C
V
R
H

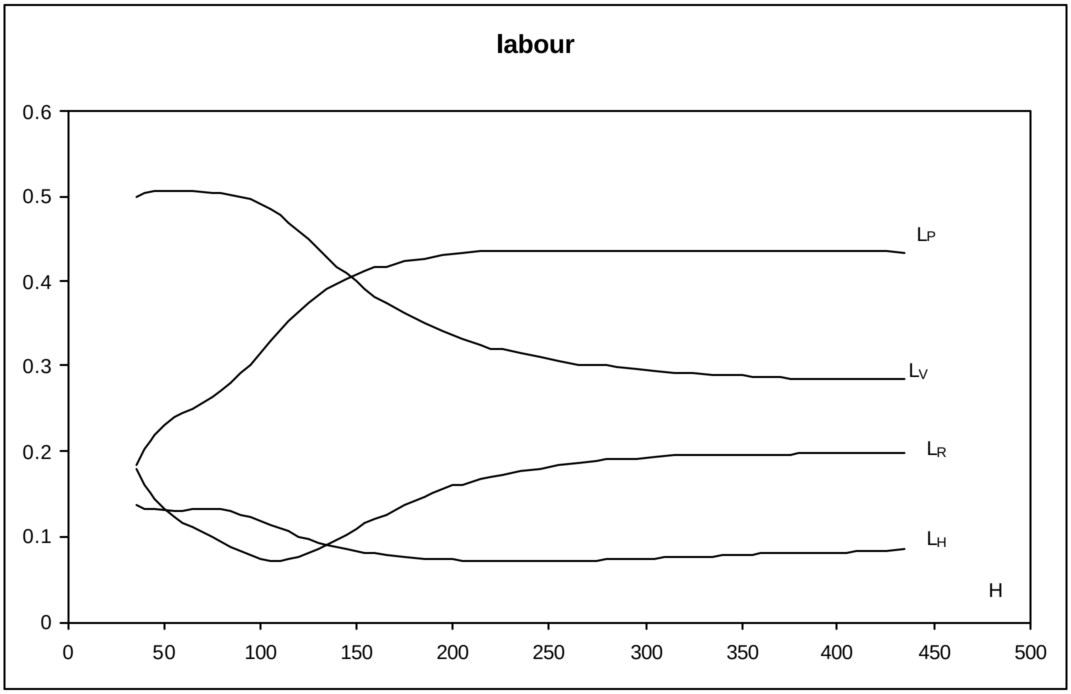
c)


processed materials
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
100
200
300
400
500
M_V
M_R
H

d)



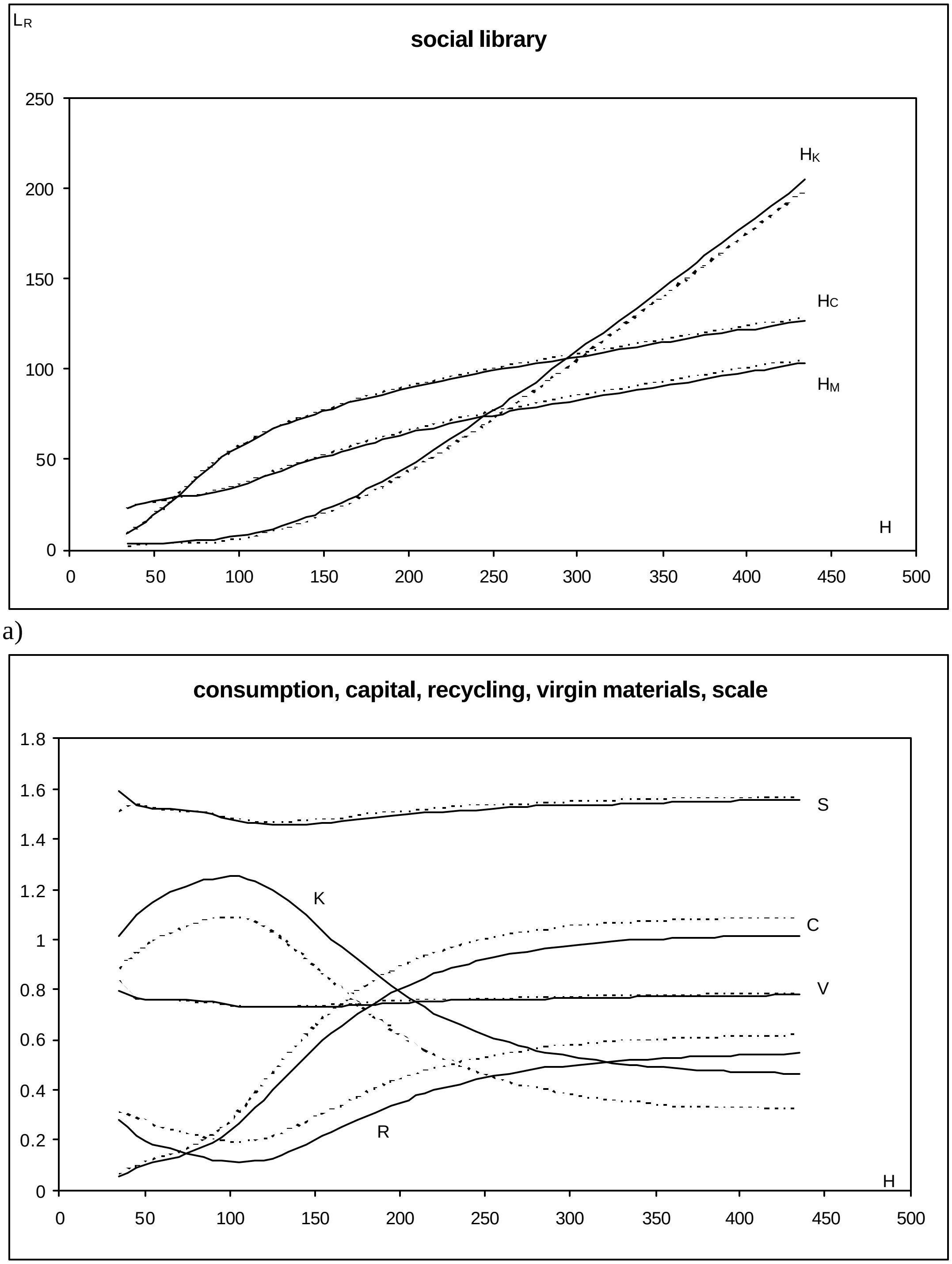
e)



f)

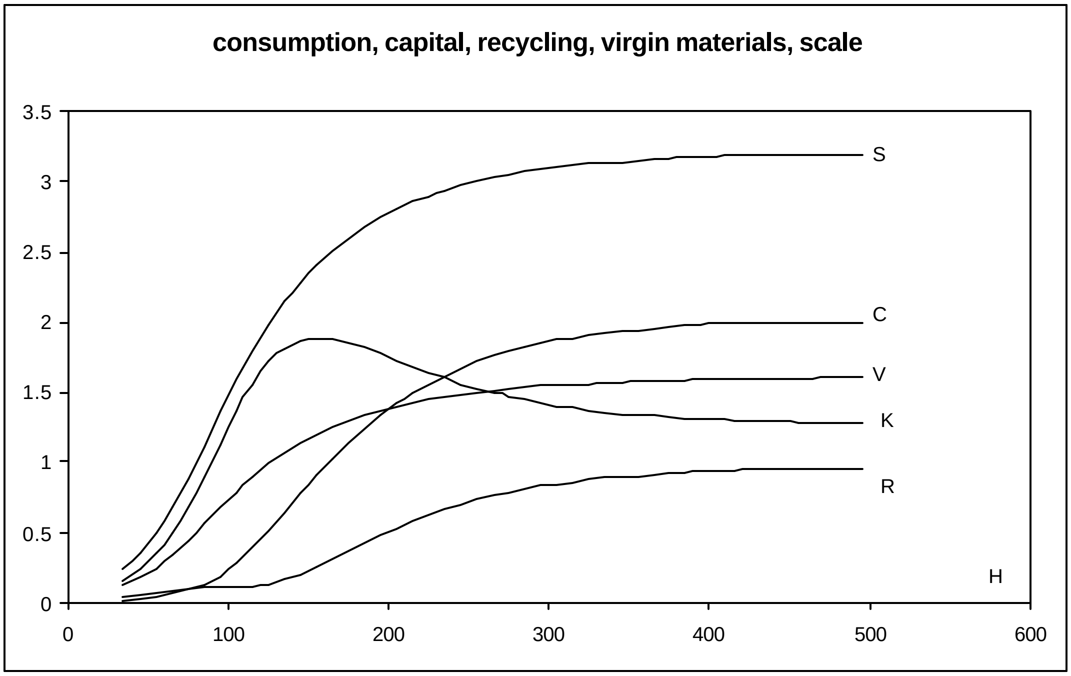
The logarithmic case

Figure 4



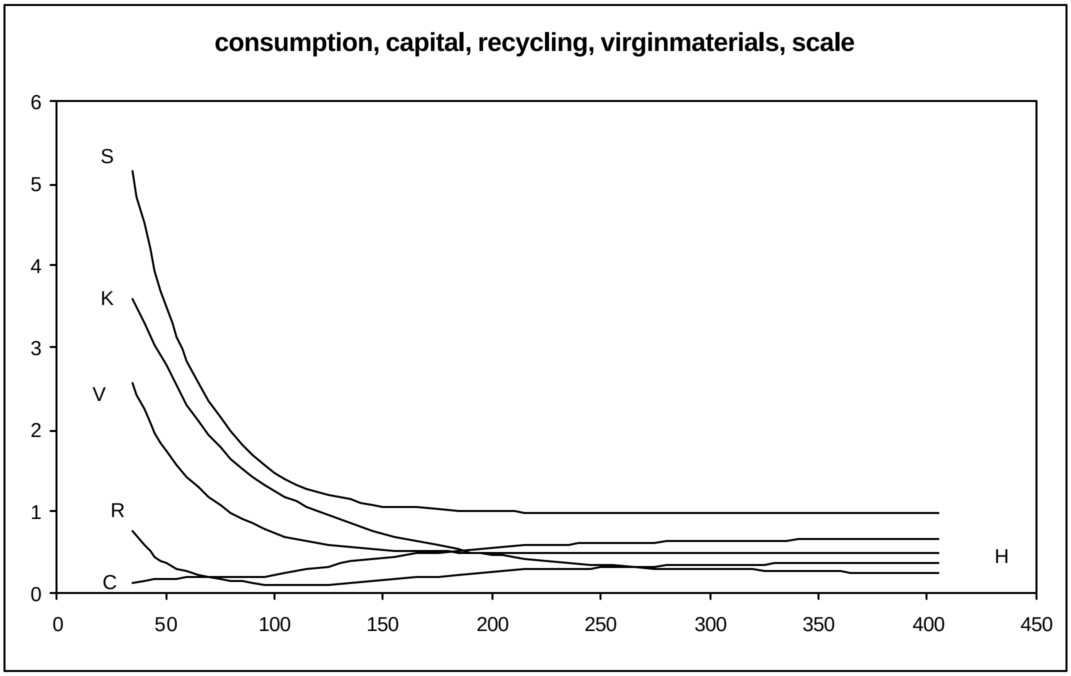
Effects of a population increase (solid line: $N = 1$; dotted line $N = 2$)

Figure 5



Good substitutability ($s = .5$)

Figure 6



Bad substitutability ($s = -.5$)

Figure 7

APPENDIX

Kuhn-Tucker conditions for the optimal material structure of the economy are:

$$H = \frac{q}{q'}\frac{C_H}{C} + \frac{1-e}{p}\frac{jH}{yH^e}\frac{1}{\Omega}\frac{p}{p'} \tag{A1}$$

$$\left[\frac{Y}{C} - \frac{dK}{C}\frac{Y}{p\Omega}\frac{1+h}{h}\right]zU_z + VU_V + \left[K\frac{Y}{p\Omega}\frac{1+h}{h} + rR\right]U_S = 0 \tag{A2}$$

$$KU_S = \left(\frac{d\ K}{C} - \frac{pq'}{qp'}\right)zU_z \tag{A3}$$

$$m_1 = \frac{1}{h}\left(\frac{Y}{p\Omega}\frac{1+2h}{h}\frac{pq'}{qp'} + \frac{hq'}{qh'} - 2\frac{Y}{C} - \frac{C_H}{C}\right)zU_z \tag{A4}$$

$$m_1 - m_2 = (V+R)(r\,U_S - U_V) \tag{A5}$$

$$\boldsymbol{m_1(h - J)} = 0 \qquad \boldsymbol{m_1} \geq 0 \tag{A6}$$

$$\boldsymbol{m_2 J} = 0 \qquad \boldsymbol{m_2} \geq 0 \tag{A7}$$

where $\boldsymbol{m_1}$ and $\boldsymbol{m_2}$ are the multipliers of the inequality and the non-negativity constraints, and:

$$\Omega = (pK)^p N^{1-p} \tag{A8}$$