Dematerialization, growth theory and the environment

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VERY PROVISIONAL VERSION,
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Abstract

This paper aims at providing a unifying reading to the mainstream economic literature on the environmental limits to growth since the 70s. The different analytical structures are described, first the neoclassical growth theory framework (Dasgupta-Solow-Stiglitz, 1974), then the endogenous growth archetypal models.
The general requirement for unlimited growth turns out to be a progressive de-linking of income from its material basis. In particular, in a renewable resource context, material throughput has to be bounded from above. Rich countries still show increasing trends in total material use. Whether the whole world economy will be able to invert this trend is an open question.

Keywords: environmental limits to growth, dematerialization, growth theory

1. Introduction

It is sometimes useful to start by asking why questions are asked. In this respect, the question of the limits to growth is a very “natural” one. Our everyday experience is that growth eventually ceases in any process, at least as concerns natural processes. This has a correspondence at a more abstract level, research, where growth processes are modelled or thought as exhibiting logistic (or similar) trends. Examples ranges from biology e.g. cell cultures, to business analyses, e.g. the life-curve of products.

Two mechanisms that end growth in natural processes are easily acknowledged. One is due to the lack of nutrients/inputs or other external factors feeding the process. The other one is internal, the inhibition that occurs due to (by) products of the process, a “poisoning”. A nice example comes from the process of wine making. [example to be added]

As concern environmental limits to economic growth we can find both type of limits. Scarcity of resources might leave production without its material basis, while wastes and pollution might “poison” the environment within which the economic process takes place and make undesirable further economic growth.

The classical economists perceived the constraints on (exogenous) inputs[1] - times were not mature to think of a “self-poisoning economy”. What is relevant here, however, is that the question of “the limits to growth” was central in their research agenda. Their analyses of the increasing size (and structural changes) of their economies also included the causes that would have stopped it. That growth would have stopped was not in dispute. Ricardo, for example,

> “disliked the idea of the stationary state […] and saw two factors that might, at least temporarily in his view, delay the stationary state. The first was international trade […]. The other […] was technical change […]. However, Ricardo, like contemporary theorists of limited economic growth, viewed both free trade and technical change as only temporary stopgaps delaying, but not preventing, the arrival of the stationary state.”
> (Foley and Michael 1997, p. 161)

Industrial revolution - its deep specialisation, its strong urbanisation and its opulence, made the western man progressively dissociated from its environment and from nature in general. This affected many economists too, as, since the neoclassical revolution, most economic theory[2] disregarded the question of the material basis of the economic process. After a century man looked so powerful that economists had an almost unanimous reaction when “The Limits to Growth” (Meadows et al. 1972) appeared. They regarded such a question as not to be put on the research agenda, as, consistently with their experience, they were perceiving unlimited growth as obvious. A U-turn with respect to classical economists.

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[1] Smith is included if the expansion of the market is interpreted as an external input to the process of division of labour, the engine of growth.

Forced to tackle the question, mainstream economics gave its answer shortly after the publication of the mentioned report. The analytical framework was the well-established neoclassical growth theory while the focus, consistently with the ongoing debate, was on exhaustible resources. The new growth theory has tackled again the question since the 90s. However, in a world where wastes and pollution are leading actors, the analysis has become more cautious. The existence of environmental limits is considered at least as possible. The limits themselves are thought as deriving from the deterioration of the environment, which is now modelled mainly as a renewable resource.

Does the mentioned literature get its target, to show that "there might actually be no environmental limits to economic growth"? The present paper aims to answer this question.

2. The first reaction to "Limits to Growth"

It is well known that the report "Limits to Growth" (Meadows et al., 1972) provoked strong adverse reactions from many economists, some of them considering it as a real non-sense (see, for example, Beckerman, 1972). If they did not show methodological consistency[3], it is also true that much criticism was forcefully argued. At the same time it was mainly based on the narrow interpretation of the report that prevailed in the general debate. In particular the focus remained on its quantitative predictions (interpreted as actual rather than ceteribus paribus predictions) and on the problem of scarcity of resources (the first oil shock was around!). Both the qualitative mechanisms outlined in the analysis and its attention towards the issue of pollution and of the general interdependence between economic processes and ecosystems did not received much attention (Common).

Consequently, the problem was initially thought and modelled by economists as mainly one of economic growth with exhaustible resources.

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[2] See Martinez Alier (1989) for the exceptions.

[3] As was emphasised by Georgescu-Roegen, 1976, p. , much of what they said could also have been applied against their analysis.

Such a problem fitted perfectly within the mainstream economics, devoted to the study of the allocation of scarce resources. The obvious answer was "substitution of scarce inputs via changes in relative prices". Limits to growth would have not been binding if, in the long run, a (strong) substitution of exhaustible inputs occurred. In a market economy (possibly helped by the State in the presence of externalities), the occurrence of such a process was seen as highly probable. Any increasing scarcity of particular materials would have lead progressive increase in relative prices. Due to this pressure technology and science would have found better extraction techniques, new inputs, and new productive processes. At the same time, the progress in abatement techniques would have reduced the problem of pollution.

Technological progress actually occurred, materials reservoirs were shown to be bigger than expected, new materials and processes are continuously introduced, production is often cleaner. However, the argument of technological progress still looks weak. Who guarantees that the progress will be strong and quick enough to avoid the resource limits to become binding? This is not to say our economy will "run out its fuel" tomorrow. The key point is the nature of the argument, based on *static expectations*. To believe that "salvation" will come from advancement in technology is an a priori extrapolation of what occurred in the recent past, resembling more to an act of faith in human power than to a scientific argument.

Doubts in that faith emerge in particular because of two reasons. One is the simplistic view of the environment as a mere input to production. Environment and ecological systems provide many functions to humans and life in general, in a setting where irreversibility, thresholds and catastrophe risks are relevant. Thus, technological progress needs not merely to find out substitutes for resources, rather also to offset the general damages that feedback from a highly disturbed environment on human society. A "poisoning" halt might then become actual.

The other reason concerns the lack of realism of the conditions that are founded to be necessary for unlimited growth. As we will see, this applies not only to the literature of the 70s, but also to the analyses developed in the 90s within the New Growth Theory. The first strand of literature is well represented by three seminal papers, Dasgupta and Heal (1974), Solow (1974), and Stiglitz (1974), published in a special issue of the Review of Economic Studies. They develop one-sector models of neoclassical growth with exogenous technical progress where, along with capital and labour, also a depletable resource is included in the production function. A central planner maximises the present value of the utility function of the representative agent, whose argument is consumption, while production is specialised with CES functions. The results depend crucially on the elasticity of substitution between capital services and the resource. For elasticity bigger than one production is possible even without the resource. The depletable resource does not constitute a limit since it can be progressively substituted by capital. For elasticity less or equal than one these models allow sustained utility or even optimal growth only in the presence of a strong enough ever-increasing resource augmenting technical progress (see Stiglitz 1974).

Both ways to avoid depletable resource limits do not look very realistic. With Toman et al. (1996, p.146) one can doubt “whether it is realistic to make such a conception of technical progress that squeezes a constant flow of [...] services out of an evershrinking flow of resource service inputs.” At the same time, an elasticity of substitution bigger or equal to one “[...] seems to be inconsistent with physical laws. Since the first law of thermodynamics requires conservation of mass and energy, the implication that [...] the economy could run on zero or a vanishingly small quantity of energy is problematic” (ibid., p.143). In both cases the issue is whether it is realistic for the amount of used resources to tend to zero, which also entails a ratio of “exhaustible resource to Income” that tends to zero. The basic requirement for unlimited growth in this class of models is therefore a very simple one, a progressive de-linking of income from its material basis.

3. A better representation of the environment

Since the 70s, economics gradually broadened its view about the relation between the environment and the economy. First, pollution started to be included into the models (e.g. 1980). More importantly, the general interdependence between ecosystems and economies became widely accepted. A new discipline was born towards the end of the 80s, Ecological Economics, in order to take explicitly into account this interdependence (see Costanza, 1989). In general terms, it was acknowledged that for man the environment is not merely a source of resources. Environment provides waste absorption and general ecosystem maintenance, enters directly the utility function both because of its amenity value and because effects on health, it affects production. Moreover, abatement is a relevant economic activity.

At the same time, confidence in the non-existence of environmental limits to growth started to decline. The progressive deterioration of the environment, the appearance of the idea of sustainable development (WCED, 1987), and, maybe, the collapse of real communism, let enter the discussion the issue of the possible environmental bankruptcy of the market economy. Environmental degradation was more and more evident, global, and harmful, the market economy was not anymore under discussion, the notion of sustainable development explicitly admitted the possibility of conjugating market growth and natural environment. “No limits to growth” was not warranted anymore, while being a goal within the realm of possibility. In this new atmosphere, the report of a joint group of economists and ecologists (Arrow et al. 1995) did not provoked such adverse reactions as the report of Meadows et al. (1972), although it admitted there are “limits to the carrying capacity of the planet” (ibid. p. 521) and came “very close to endorsing the essential message of The Limits to Growth” (Common p.).

4. New Growth Theory and the environment

According to Aghion and Howitt endogenous growth theory “is also inherently more suitable for addressing the problems of sustainable development than is the neoclassical theory, because whether or not growth can be sustained is the central question to which endogenous growth theory is addressed” (Aghion and Howitt, 1998, p. 151). Nonetheless a quick look both at reference databases and at textbooks reveals that the environmental question is not that central in the research agenda of new growth theory. Most recent surveys include the quoted chapter in Aghion and Howitt textbook and Smulders (1999).

The latter develops a useful archetypal model that is briefly synthesised here.

- The environmental quality, N, is modelled as a renewable resource. As usual, its dynamic follows a spontaneous logistic growth trend[4] that is altered by “extraction” of resource, R, for production purposes.

  $$\dot{N} = E(N)-R \tag{1}$$

  with $E(0)\leq 0$, $E_{NN} <0$

- (Intertemporal) utility depends positively both by consumption, C, and by environmental quality.

  $$W = \int U(C, N)\,^{-r\,t}\ \mathrm{dt} \tag{2}$$

  with $U(C,0)=U(0,N)= -\infty$ and $U_c >0$, $U_N \geq 0$

- Capital, H includes both physical and human capital. Production, Y, which as usual goes partly to consumption and partly to accumulation of new capital/knowledge, is a positive function of extracted resources, state of the environment, and capital. All inputs are essential. The long-run marginal productivity of capital does not go zero.

  $$\dot{H} = Y(N, R, H) - C \tag{3}$$

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[4] As E is continuos and $E(0)\leq 0$, it is admitted the existence of a threshold below which the renewable resource enters a process of progressive deterioration.

with $Y(0,R,H)=Y(N,0,H)=Y(N,R,0)=-\infty$ and $Y_N \geq 0$, $Y_R>0$, $Y_H>0$

Given this setting, unlimited growth with non-deteriorating environment can be optimal (in the standard representative agent framework and depending on the utility function) if the economy lives out of a constant level of "extraction" which is consistent with ecological stability, $R=E(N)$ (see eq 1). Constant levels of both environmental quality and resources enter the production. Thus, the economy can be optimally fuelled by levels of man-made capital, which are increasing in virtue of the absence of decreasing returns. Smulders (*ibid.*, 613-14) illustrates this through a simple example where constant returns to human capital are assumed. In this case the production function becomes $Y(N,R,H)=y(N,R)H$ so that the whole model end up as being an AK model. If, for simplicity, a constant saving propensity is assumed, s, equation (3) becomes $H=sy(N,R)H$. Dividing by H, the long-run growth rate of a balanced growth path is obtained.

To our purposes it is interesting to analyse also a different setting, set forth by Stokey (1998) and followed by Aghion and Howitt (1998, 151-171). Stokey (*ibid.*) aims at providing an analytical foundation of the Environmental Kuznets Curve, a supposed hump-shaped empirical relationship between income and pollution U, a relationship that, despite claims by the author, is far from being proved (see, for example, Stern, 1997; de Bruyn and Heintz, 1999; de Bruyn 2000). As concern growth, two contexts are analysed; one characterised by an AK production function, another by exogenous technical progress. Pollution, treated as a flow or as a stock, links the environment to the economy. Pollution negatively affects utility[5] while being at the same time a joint product of production. Increasing production will increase consumption

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[5] The utility was assumed as additively separable in consumption and pollution.

but also pollution.[6] The way out that Stokey suggests is the possibility of choosing a cleaner technology, this, however, is assumed to be costly in terms of reduction of output. The resulting reduced form of the model is one with capital and pollution entering as factors of a Cobb-Douglas production function. Obviously, growth can be optimal only in the presence of technical progress.

With a slightly modified notation, the basic structure is the following:

- Actual income, Y, is given by the product of potential income and a coefficient, z, indicating the dirtiness of the chosen technology, with $0\leq z$£1. , Potential income is given by a standard production function $f(\cdot)$.

  $$Y= f(\cdot)z \tag{4}$$

- Pollution (or the increase in pollution when pollution is modelled as a stock), X, is an increasing and convex function of actual output, given potential output.

  $$X= f(\cdot)\,f(z) \tag{5}$$

  specialised as

  $$X= f(\cdot)z^{b} \quad (b>1) \tag{5'}$$

By combining equations 4 and 5' actual output is obtained as

$$Y = f(\cdot)\exp(1\text{-}1/b)\ \ X\exp(1/b) \tag{6}$$

To have an intuition of the behaviour of such a model it has to be noticed, firstly, that the marginal product of capital is MPK = $B\ Y/K$ (from equation 6), where B is a constant that depends on the specialisation of $f(\cdot)$, secondly, that optimal z is decreasing in potential outcome, $f(\cdot)$. Stokey analyses two cases.

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[6] For the moment, note that pollution has a similar role of “extraction” in Smulders’ setting. What is omitted in Stokey, but this does not seem relevant, is the possible positive influence on production of the environmental quality, that is, in Stokey $Y_N=0$ instead of Y_N³$0$.

a) If $f(\cdot) = AK$, then actual income (eq. 4) is $Y = AKz$, which implies average capital product equal to Az and MPK= $(1-1/b)Az$. As optimal z exhibits a decreasing path, the MPK will fall below the rate of time preference and make investment not attractive anymore. Growth, while being technologically feasible (it is possible to choose a rate of change of z such that output grows and pollution declines), is not optimal.

b) In the presence of exogenous technical progress ($f(\cdot)=AK^{a}e^{gt}$ with $0<a<1$) the outcome is unbounded growth. This is because the average product of capital (MPK= $a(1-1/b)Y/K$) is constant along the balanced growth path . Similar conclusions are obtained within the endogenous growth Schumpeterian framework described by Aghion and Howitt (*ibid.* p. 151-171).

A distinctive feature of Stokey's paper is that pollution can increase without bound. On the contrary, it seems reasonable to assume the existence of critical ecological thresholds "below which environmental quality cannot fall without starting in motion an irreversible and cumulative deterioration entailing a prohibitive cost" (Aghion and Howitt p. 157). Such an assumption entails the need of a non-increasing rate of pollution so that, for income to be free to grow exponentially, optimal pollution intensity, z, must tend to zero (see eqs. 4 and 5) fast enough. With a CES utility function additively separable in consumption and income, this occurs only if the elasticity of the marginal utility of consumption is bigger than one. The same holds for the Schumpeterian model (Aghion and Howitt p. 161).

When comparing the two approaches described above, one can find a strict formal resemblance.

- Utility depends on consumption and either on environmental quality or on pollution, two variables than can be thought as reciprocal/complement/... [7]

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[7] A difference is that the second framework, as already said, assumed utility as additively separable.

- The environment is modelled as renewable resources[8], so that, after the needed transformation of pollution stock into environmental quality, both structures have an equation similar to (1). In particular for the second approach one can write:

  $$\dot{N} = E(N)-X(Y, z) \qquad (7)$$

  where the rate of pollution, X, replaces the extraction rate, R, of eq. 1.[9]

- The difference in the results are due to different production functions. For simplicity, these functions can be written as follows:

  $$Y = Ky(R) \qquad (8)'$$

  $$Y = (AK)\exp(1\text{-}1/\boldsymbol{b})\ X \exp(1/\boldsymbol{b}) \qquad (8)''$$

  $$Y = (AK^{a}e^{gt})\exp(1\text{-}1/\boldsymbol{b})\ X \exp(1/\boldsymbol{b}) \qquad (8)'''$$

  As was already noticed, equation 8' is actually an AK production function, as ecological stability imposes to stabilise extraction at a constant rate, R. In this way production can increase indefinitely without affecting the environment.

When looking at the mechanisms behind the two different approaches, the second one seems less appealing. First, one can raise doubts that technology, at the level of the whole economy, can be considered as a choice variable, as a control. This is not only because the production of new technology needs time and is the outcome of an evolutionary process, but also because cleaner techniques need not to entail an extra cost both at the individual level, and in terms of aggregate output. A production process that is less polluting because it saves on materials is cheaper. Abatement costs enter GNP contributing to a positive relationship between cleaner technology and higher income. If a cleaner technology does not necessarily entail an aggregate cost, at least in static terms, then equation (4) does not hold. Second, the mentioned condition on the elasticity of marginal utility of consumption (>1)

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[8] Aghion and Howitt analyse also the case of non-renewable resources.

[9] *E*( ) has different formal properties in each authors.

is problematic in many macro-economic models (see. Aghion and Howitt p. 162). Finally, the model seems inconsistent, as neoclassical growth theory (see § 2), with physical laws as pollution intensity for the whole economy is not bounded from below. This allows the growth path of the model to be such that the whole economy is run by processes whose interference with the environment is vanishingly small.

However, when looking at the reasons why the structure in Smulders looks less problematic, one finds that the "trick" is at the very beginning. Production, on the contrary to the second approach, does not necessarily entails pollution as a joint product. Given a minimum requirement of natural resource, R, production can be increased indefinitely by increases in (human) capital, H, that do not affect the environment.

The following conclusion can then be made. Although endogenous growth models avoid simplistic representations of the links between the economy and the environment, the proofs of the possibility of unbounded growth are built on attempts to break exactly those links, that is, on attempts to push matter away from the economy. This is obtained in one case, Stokey and Aghion-Howitt, by assuming that technology can, at the end, make production non-polluting[10], in the other, Smulders, by directly assuming that production need not to affect the environment. Thus, the conditions they get for unlimited growth can be summarised in the idea that production needs to become increasingly dematerialised. Material inflows must be bounded from above and, independently of any possible "greening" of the technology, a growing income will make the ratio "Material Inflows" over "Income" to fall asymptotically to zero. As we will see these requirements (which are similar to those that holds for the analysis of depletable resources in the neoclassical growth theory, see section 2), can be obtained within a very simple alternative framework.

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[10] More precisely, in Stokey matter does not matter also in another way, as, depending on the utility, pollution can grow without bound without consequences for ecological systems, an assumption that is difficult to accept.

5. *Dematerialization as a necessary condition for unbounded economic growth*

As was already said, a multifaceted relationship links the economy to the system within which the economy takes place, that is, the natural environment. However, at a basic physical level we know, particularly thanks to the work of Georgescu-Roegen, that the economic process consists of dissipating matter and energy, that is, of production of waste. Thus, material inputs matters not as much as basis for production, but as they start becoming waste since the very beginning of their birth. Material inputs are to be considered, as it is particularly emphasised by research on dematerialization started in the 90s at the Wuppertal Institute for Climate and the Environment (see. e.g. Schmidt-Bleck), key indicators of the interference provoked by man on natural processes.

Having this in mind, it is easy to understand how growth can occur. Material inputs, after remaining for a while within the economy, go back to nature as waste (output). This affects natural environment in ways that can be harmful to human welfare both directly and indirectly via reduced productive efficiency:

$$\xrightarrow{a}\text{INPUT}\xrightarrow{b}\text{ OUTPUT(waste)}\xrightarrow{c}\text{ HARMFULNESS}$$

Three strategies can be followed to reduce the negative consequences on welfare. First, one can break the link "*c*", between waste and its harmfulness by improving the "quality" of waste, thanks to "end of the pipe" tools, such as treatment of toxic waste, emission abatement, and so on. Second, there is some space to increase the permanence of throughput within economic system (arrow *b*), by promoting, for example, product durability and repairing. Third, less material can be used (arrow *a*) thanks, for example, to increases in material efficiency or increased durability (*b*).

If material waste is left to follow the growth of income, given the limits in the possibility of avoiding goods to deteriorate to waste, and the limits in the "regenerative" capacity of nature, the improvement in "end of the pipe" technologies that has to occur must make the impact per unit of waste to tend to zero. The lack of plausibility of an economy running on a “non-polluting” technology has been already discussed in the previous section. Consequently, if income has to grow indefinitely (and as long as our environment remains our planet) material (and energy) throughput of the economy must be bounded from above (not differently from what suggested by Daly, 1973). In other words, income has to be de-linked from its material basis and the ratio between material input and income has to tend to zero.

The upper limit to material throughput is also seen in a much simpler way. Let H be the “harmfulness” (impact) of the human system. H is bounded from above, $H \leq H^{M}$, due to limited ecosystems regenerative capacity. d is the “dirtiness” of the technology, bounded to be strictly positive for the reasons seen in the previous section, $d \geq d^{m} > 0$. M is total material use. As in the debate during the 70s, let the impact to be given by the product of some measure of the material scale, M, and the state of the technology:

$$H=Md \tag{9}$$

Then, the following inequalities hold:

$$H^{M} \geq H = Md \geq Md^{m} \tag{10}$$

which imply an upper bound to M, $M \leq H^{M} / d^{m}$. M could be unbounded only if one assumes there is no upper bound in H, or if d^{m} tend to zero, hypotheses used in Stokey and Aghion-Howitt approach.

Whether it is possible for income indefinitely to grow over a bounded from above material basis is much a matter of personal opinion, involving also deep issues such as the theory of value. However, economists can make some considerations on what is occurring now and its perception. For this purpose, it is illustrative to look again at Smulders (1999 p. 610) to read, in the introduction, that

> “environmental and natural resource constraints did not turn the historical growth process into stagnation. Instead, accumulation of human knowledge […] allowed the economy to expand within the fixed physical system of the earth. […] (man) continually creates new knowledge to derive more value from *a given amount of physical resources*” (emphasis added).

Such a position reveals firstly a sort of “linear thinking”; in so far it seems to suggest the prediction of perpetual growth merely based on the (relatively recent) past. More importantly, the available amount of physical resource is not distinguished by the amount of resources actually used. This is not to deny that knowledge can be considered as the engine of growth, the fuel, however, during the past two centuries has been a growing amount of materials, particularly fossil energy. Then, more value has been created from a *growing*, rather than a *given*, amount of physical resources.

However, Smulders, whose paper remains highly valuable, cannot be blamed for these sentences as they constitute a shared perception[11], the perception that the economy has started to de-link. This feeling must be at the basis, for example, of that empirical research that is “desperately seeking the environmental Kuznets Curve”[12]. The illusion we are entering what Quah () calls “the weightless economy” was due perhaps both to the progress in pollution abatement techniques and the look of many new products of the “knowledge economy”, where high value is embedded in few bits or in some lines of code.

This being an illusion is easily understood by examining the literature on the EKC (see references mentioned in the previous section) or by looking at the increasing trends in material requirements of the developed economies (see, e.g., Adriansee et al., 1997). The reasons for this illusion are manifold. For example, if it is true that some new products are almost immaterial, it cannot to be forgotten that their consumption need complements which are highly material. Software alone is useless, we need hardware, whose production requires high quantity of material inflows, and that becomes soon obsolete due to progress in software itself. Another reason is the small size of many final products, which is often betraying as a small size does not necessarily entails low material inflows. To produce a gold ring of the weight of 5g 5 metric tons

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[11] The same confusion between available and actually used resources is also in Aghion Howitt, 1998, p. 151: “If it had not been for resource-saving innovations it is unlikely that our *finite* planet could have supported the expansion in material welfare” (emphasis added)

[12] This is the title of a recent paper by REFERENCE TO BE ADDED

of matter are used (ref to be added). More in general, the wrong perception seems to be arising from a mistake in passing from a hierarchical level to another, as small improvements visible at the individual level are believed to hold also at level of the whole economy (see, for example, Giampietro and Mayumi 2000).

Future trends of total throughput are uncertain. Actually, there might be a reduction in the throughput of developed countries, although such a reduction would be easily more than offset by the increase in the throughput of the rest of the world in case it starts growing.

6. Conclusion

Aghion and Howitt claim that "… endogenous growth theory […] does imply that with enough innovations, and the right direction of innovations, such an outcome (sustainable development) is at least *within the realm of possibility*" (Aghion Howitt, p.151, emphasis added), while Stokey (1988) is even more optimistic about environmental limits to growth. However, for the reasons seen above, the conditions that growth theory finds as necessary for unbounded growth do not look very much "within the realm of possibility". This is not a novelty in economics, as both rationalisation rather than explanation is often the theoretical outcome and the realism of the hypotheses is seldom an issue.

Moreover, there is a problem of methodological consistency. The principle of Occam's razors, often invoked by economists, would condemn most literature surveyed here. Actually, the main outcome of its elegant formal models and optimisation techniques could be obtained in a much more simple way. The obvious necessary condition for unlimited growth is "de-linking", "dematerialization", that is, to make the economy ultimately grow out of a constant material throughput. Whether this can occur or not is an open question. For the moment, recent trends on material requirements do not seem to show a halt in the growth of the economy throughput.

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