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Formalising insights from ecological economics in a growth model

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Abstract

This thesis is an attempt to formalise some of the insights of ecological economics in mathematical form. It seeks to develop a model for economic growth in which natural resources are complements to labour and capital in production. The model is centred around the role of entropy in production. The model also separates between the material and the intangible dimensions of production, because they are subject to different dynamics when it comes to natural resources. The results are implications which help explain historic growth and predict future growth. Qualitative development of the intangible dimension is found to be a steady state phenomena while quantitative growth of the material dimension is found to be a transition phenomena.

Keywords: Economic growth, entropy, funds and flows, natural resources.

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1. Introduction

This thesis seeks to develop a model for economic growth which highlights the importance of low-entropy natural resources as essential complements to labour and capital in production. It builds upon a simple Solow-type model but features assumptions about the production process that can normally be found within the growing discipline of ecological economics. From these different theoretical foundations the thesis attempts a partly new take on the age old and noble question: "Why are we so rich and they so poor?".

The purpose of revisiting this question from a different angle is of course to provide some new insights into the important concept of growth. Since economic growth is one of the most revered goals of present day society, the purpose to better understand it could warrant almost any number of reviews. That there are certain oversights and misconceptions in the current body of thought, especially with respects to the environment and natural resources, further motivates this thesis. The insights that I hope to generate fall into two categories; (1) those that help explain historic growth and (2) those that indicate the prospects for future growth.

The choice to answer the question through the construction of a model for economic growth represents the novelty of the thesis. Most of the insights which the model builds upon have been expressed repeatedly by Herman Daly and Nicholas Georgescu-Roegen, but mostly in verbal form. To translate and formalize them into the form of a mathematical model is the major contribution of this thesis. In the best case scenario the thesis can contribute to these insights getting the attention they deserve.

The model created here is not in any way a complete representation of growth. The model focus on natural resources in production and treats other aspects of growth and production in a summary fashion, exemplified by that many growth rates (labour, technology etcetera) are considered exogenous. The implications for future and historic growth of a new perspective on natural resources turns out to be quite important, indicating that the narrow focus of the thesis was warranted.

1.1 Previous work and new contributions

Many have of course sought to answer this fateful research question in the past, several of them giving credit to natural resources. Two prominent ways of doing this within neoclassical economics is adding a constant factor land to a Cobb-Douglas type production function or adding a non-renewable resource factor which depletes with use (see for example Jones, 2002, p169ff). Ceteris paribus, the addition of these factors imply a lower steady state growth rate. Although these approaches have produced important insights into the contribution of the environment to growth, I find them lacking in two respects. First, they portray inputs from the environment as one production factor among others, with decreasing returns to scale and substitutability. As will be argued later in the thesis these assumptions are probably erroneous. Second, the environment should not be framed as a "growth drag", it is the base and indeed home of the economy and quite literally gives us our daily bread. It has not halted or slowed economic growth but rather made it possible. This thesis will try to move beyond these neo-classical misconceptions of the relationship between natural and man-made factors of production.

Within ecological economics, there has also been several attempts to formalize the insights of the discipline in a production function (see for example Georgescu-Roegen, 1971; Kraev, 2002; England, 2000), which could be used for explaining economic growth. The for this purpose most important of these insights are that natural and man-made factors of production are complements (Georgescu-Roegen, 1971, p230), and that there is such a thing as a fundamental resource, low entropy, which all natural inputs to the economy embody (Daly, 1992, p16). I will explore these insights at length later on. At the moment I will settle with stating that the discipline has, in my opinion, failed to model the specifics of the complementarity between natural and man-made capital. And it has too often fallen into the trap of assigning economic value directly to the low entropy embodied by natural resources and products (see for example Georgescu-Roegen, 1971, p276ff), rather than to the utility of the actual outputs of production.

Attempts to model complementarity have centred around two types of functions, so called constant elasticity of substitution (CES) and minimum functions (see for example Kraev, 2002). Minimum functions represent the most strict form of complementarity, where only the most scarce resource determines the level of output. CES functions allow for substitution at the margin but can be approximated with minimum functions if one factor of production is superabundant (ibid., p282f) (for a deeper discussion see chapter 8.1). The thrust of these models is that natural resources are quickly becoming the scarce factor which determines output. I believe that natural resources are in fact the abundant factor, reflected by their low prices and our wasteful handling of them. But that does not preclude that they do not have an important role in production and growth, as is often assumed when they are excluded from neoclassical models. The challenge is to simultaneously show that natural resources are the abundant factor in production *and* that their finitude still imposes limits to production. The solution to this challenge lies in the specifics of the complementarity between natural resources and labour and capital.

The complementarity stems from that they have different roles in production. These different roles correspond to the fund and flow type factors of production envisioned by Georgescu-Roegen (1971, p219ff). Flows are that which is transformed into products and waste, funds are the agents of transformation which are not themselves transformed. Natural resources are obviously transformed in the production process while capital and labour are predominantly left unchanged. In every production process some of the low entropy (fundamental resource) embodied by the flows is lost or used up, useable inputs are converted to unusable waste, and this imposes some limit to physical production. This insight, originally drawn from the second law of thermodynamics, can, I believe, be entered into production theory as a mathematical convergence limit. With this approach, the level of output can be determined by the productivity of the man-made factors of production (labour and capital) within the limits of natural resource flows. It allows me to avoid the pitfall of assigning productivity (which implies action or agency) to natural resources (which are clearly not agents of production) while still allowing me to model complementarity. To model the contribution of the environment as a flow rather than as a stock has other benefits as well. It makes it easy to show how that contribution has grown over time as man has appropriated ever more resources, and it has long-reaching implications for optimal resource use (Kraev, 2002, p280).

Besides the new approach to modelling the relationship between fund and flow factors of production, the model also introduces another novelty to growth theory. Following Herman Daly's work (1996, p28), the model can be used to differentiate between quantitative growth and qualitative development as sources for what is normally called economic growth. It is a way to separate the material and the intangible dimensions of production, which is desirable because they are subject to different dynamics when it comes to natural resources. Quantitative growth is limited by the finitude of our planet and resources while qualitative development is possibly boundless. Qualitative development is admittedly extremely hard to measure, just as technological improvement, but it is found to be a most important avenue for sustainable economic growth.

I mentioned in the very beginning that the model is built on and compatible with Solow-type models. This does not preclude that the model could also be compatible with say a Romer framework. The thesis focuses on the role of natural resources for growth, not technological progress. Whether technological progress is best explained as an exogenous variable or as a result of population growth or something elseis left to another debate. That Solow-type assumptions will be used in this thesis is merely a matter of seeking simplicity. If the reader has another favourite production function type, feel free to insert it in place of that used here.

1.2 Outline of the thesis

The remainder of the thesis is structured as a narrowing tunnel, it starts out with a broad overview of the economy, narrowing in on production and finally on the role of natural resources, capital and labour in production. The main theme which echoes through this tunnel is entropy, the important concept which can be said to separate ecological economics from neoclassical economics. The final result will be a discussion of historic and future growth in the context of entropy's importance to the economy.

In chapter two the relationship between economy and environment, which has so often been misinterpreted in economics, will be discussed. This relationship is essential to understanding the nature of the economy itself and certain specific limits to growth. Chapter three moves on to production. What is its purpose? How does it fulfil that purpose? And what roles do the different factors of production play in that fulfilment? Chapter four returns to the contributions of the environment in production, this time specifically in the form of natural resources. This chapter also introduces the fundamental resource embodied by natural resources, namely entropy, and discusses its importance to production theory. In chapter five, attention is turned to the more traditional factors of production, labour and capital, and their crucial role as the agents of production. Chapter six will attempt to formalize the insights from the previous chapters in a production function, the heart of any economic growth model. And growth is the subject matter of the next chapter (seven), including steady state growth as well as historic and future growth. The final chapter (eight) will discuss strengths and weaknesses of the model, future work and will hopefully leave the reader with a few new thoughts.

2. The economy and its environment

In this chapter I will challenge the standard view of the economy which underpins most models of economic growth. This view, which portrays the economy as a self-sufficient system in isolation, has become obsolete as our planet has become saturated with economic activity. With terms borrowed from Herman Daly, we have moved from empty-world economics to full-world economics and we can no longer ignore how we affect our environment or how it supports us (1999, p52).

The alternative view presented here is based on some of the fundamental principles of physics, the laws of thermodynamics. They were considered by Albert Einstein to be the least likely scientific principles to be overthrown by future discoveries (quoted in Schlipp, 1959, p33) and still remain undisputed. The first law of thermodynamics is perhaps the most known, it states that energy neither can be created nor destroyed. The second law states that entropy, a measure of disorder, always increases within a closed system. Very simply, these laws tell us that the economy cannot be a closed system, in which case disorder would be ever increasing, but rather an open system relying on external inputs of ordered energy and matter.

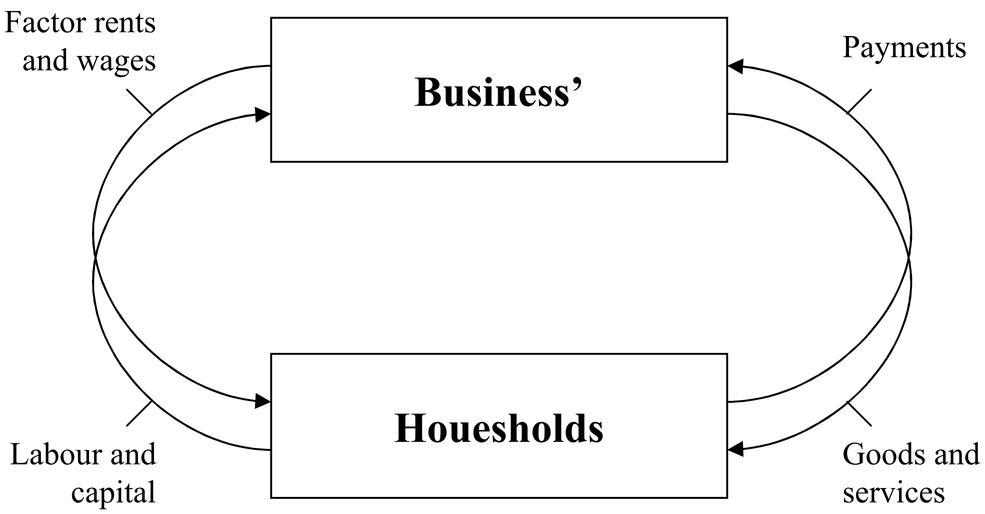


Figure 2.1: The neoclassical vision of the economy

Traditionally within our discipline the economy is modelled as a closed circular system consisting in its simplest form of households and business'. Labour and capital, the two factors of production, are owned by the households and rented to business'. These factors are employed using available technology to create goods and services. The two markets, for factors of production and for goods respectively, balance out and the activity is labelled GDP.

Although this is a useful model for understanding relations within the economy it provides us with no correct information about the relationship between the economy and the environment, which is central to economic growth. It is not reasonable to think that a closed system can grow by itself by merely running round in circles, indeed such a system should deteriorate.

The laws of thermodynamics told us that the economy cannot be a closed system; rather it can be understood as an open subsystem of the environment (Daly, 1996, p49). Three features of the relation between economy and environment prompts me to model one system as inside the other. First, the environment provides the economy with inputs of low entropy matter-energy, and *there is no other such significant source* (although the economy could possibly learn to directly harvest the potential of the solar influx, at the moment we are mainly living of those resources stored in or processed by the environment). Second, all wastes of the economy end up in the environment. Third, the environment provides ecological services such as atmospheric regulation and stable climates without which economic activity would be impossible (Barbier, 1990, 10). Indeed, the relationship can fruitfully be described as similar to that between an organism and its environment. "*Industrial economies "ingest" raw materials, which are "metabolized" to produce goods and services, and they "excrete" wastes in the form of discarded materials and pollution*." (World Resource Institute, 2000, p 1) Let us ponder this analogy briefly. To grow larger an organism must ingest more resources or metabolize them more efficiently, this probably holds true for the economy as well. This is very simply what the growth model sought in this thesis captures.

In connection with the above organismic view the World Resource Institute has created a simple model (figure 2.2) of the material interaction between economy and environment. Of special interest to this thesis are the inputs to the economic process: extraction and those flows labelled hidden flows. Hidden flows are such flows which are never sold on a market but which nonetheless are a prerequisite for economic activity, for example earth moved during mining or construction. In system terms they constitute simultaneous inputs and outputs. Worth noticing is that the presence of hidden flows (important but non-sold materials) indicates that measuring the importance of resources through pricing is flawed (a discussion which will be continued later in the thesis). So, the economic system is dependent on the environmental system for a multitude of services, one of which is the input of low entropy matter-energy. The next chapters will discuss the importance of these inputs for the production process.

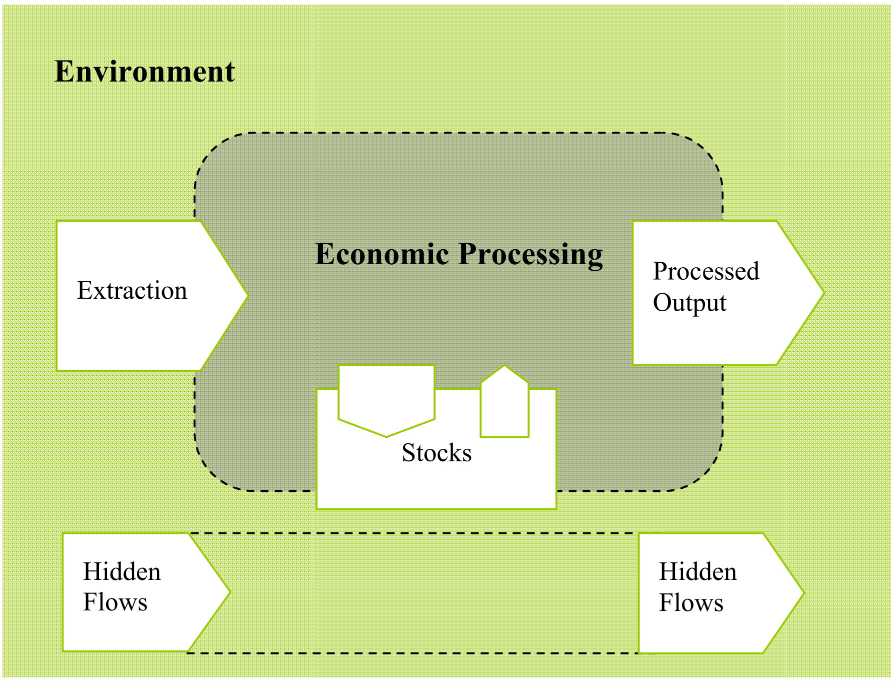


Figure 2.2: The economy as a subsystem of the environment. Source: World Resource Institute, 2000, p 5.

Before focusing on production, a few words on the other processes in the economy and why they are largely omitted from this thesis. As the organism analogy hinted at, economies actively extract resources from their environment. The extractive process is very important for determining the environmental impacts of resource throughput. It certainly matters which materials that are extracted and from where. But for the purposes of determining growth, the inner workings of the extractive process are less important. Instead, natural resources will be seen as flowing into the economy at an exogenous rate (further discussed in chapter 4.2). The labour and capital that is in reality working in the extractive industry will be ascribed to production instead.

Consumption is the second major process in the economy. It has the dual role of satisfying consumers and keeping the labour force productive. In other words, consumption tends to both the basic and the surplus needs of consumers. It is seen as a one way process, products come in and exit as wastes which are deposited to the environment. Recycling of post-consumption waste is abstracted from, partly because entropy cannot be recycled and partly because it is such a marginal process compared to production and consumption (see for example figures for Sweden in Hermele, 2002, p38). Let us now turn our focus to the most important process for economic growth, production.

3. Production and the creation of economic value

This chapter is dedicated to the act of production and the different roles that natural and man-made factors of production play in the creation of economic value.

3.1 The purpose and nature of production

Let me start with some of the most basic questions concerning production. What is the purpose of production? A fairly standard answer within economics would be that it is to satisfy the needs and wants of consumers. *How* does production satisfy the needs and wants of consumers? This natural follow-up question is much more seldom answered explicitly and the answer which I propose might have some radical implications to production theory. *Production brings satisfaction through physical alteration of reality*. The creation of products, display of entertainment or transportation of the consumer herself are for example all physical results of the efforts of men and women.

This implies that the output of the productive process in some sense always is physical or material. This assumption may be seen as heroic in the face of a growing service industry. But I would argue, following Herman Daly among others, that the difference between goods and services is one of degrees rather than absolutes (1992, p118; and 1996, p28). Even the most ethereal service must be linked to a material process to be useful, for example the storage, transmission and organisation of information in a computer. But producers do not only perform some random physical alteration of reality and sell the result, production is of course purposeful and aims to create goods and services with some specific utility to consumers. In other words production has two dimensions, one material and one intangible which involves understanding the needs and wants of consumers.

Following a standard convention, all goods and services will be simplified as a homogenous output good, GDP. From the discussion above, a unit of this output good can be understood as also having a material and an intangible component, i.e. it is a physical change which holds some value to consumers. This value corresponds to some monetary value, which is what GDP is usually measured as.

If one accepts that production has both a material component and a more intangible dimension which involves satisfying the needs and wants of consumers, then it is not shockingly strange to also structure a production function that corresponds to these different dimensions. It is perhaps unconventional to separate them but it serves to highlight the physical limits of the economy whilst stressing that the economy can improve in non-material ways. GDP can be understood as the total value added in production in a year. It depends on the amount of homogenous output units that have been created and on the value to consumers that has been added per such unit. In other words, how much output there was and how good it was. Mathematically it can easily be expressed as;

$$Y = BT, \quad \text{(Eq. 3.1)}$$

where Y signifies GDP, B stands for the value added per unit output and T for the total amount of produced units.

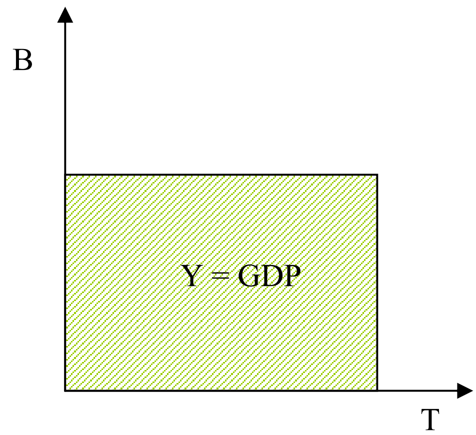


Figure 3.1: The two dimensions of GDP

3.2 The value added in production

The value added in production, B, is of course an extremely hard dimension (variable) to quantify. But then again, whoever said that something must be easy to be worthwhile. B is thought to reflect the utility of economic output to consumers. Hence, it depends both on the proficiency of producers and on the preferences and practises of consumers. In other words, the variable grows if output become better or if consumers change so that they can extract greater utility, satisfaction or pleasure from the existing output (for example by learning how to use computers). Such an increase corresponds to what Herman Daly terms qualitative development (1999, p6). In slightly more airy terms, the variable depends on our understanding of value and purpose itself, surely a to complex phenomena to be fully explained by economic theory alone.

This complexity is why I choose to regard B as a variable which is not directly influenced by the factors of production but rather as a characteristic of society as a whole, similar to how technological level is normally modelled. In mathematical terms, not as a function of labour and capital but as an independent variable with constant returns to scale. As all choices made in the construction of a scientific model, it is a simplification with drawbacks as well as benefits. The benefits are that it captures the fact that consumer satisfaction is not entirely in the hands of producers. For example, a society where fashion trends are essential renders perfectly good clothing products useless after a few months, reducing the satisfaction consumers can draw from them. It also captures that understanding of purpose is a commodity with a low degree of excludability, just like the ideas which underlie technology, and therefore best modelled as a feature of the economy as a whole. The drawbacks are simply the other side of the coin, too little of the value of economic output is explained by the behaviour of individual producers. It could definitely be argued that the purpose of services is indeed to "increase B" by intensive use of labour. But this thesis chooses the opposite view, i.e. that the quality of goods and services are determined before production and that labour and capital have only to execute the process. As it has often been said, a good model is one in which the results are not that sensitive to the assumptions. In this case, they are clearly sensitive. However, there is also a value to presenting an alternative view with clearly different results than the mainstream, especially in a fateful question such as the relation between economic growth and the environment. And, not to forget, a model based on the opposite assumption would be just as sensitive.

B, the value added to each produced unit, must be seen as an average, some production processes clearly add more value than others. A more realistic mathematical form for expressing GDP would consequently be;

$$Y = \sum_{x=a}^{x=z} B_x T_x \qquad \text{Eq. 3.2}$$

where x is a certain product and the interval a to z represent all products produced in the economy. To simplify economic output as a homogenous good is an accepted convention which allows me avoid this further complication.

Many questions still remain about the intangible dimension of production, for example: how large is B and how large can it conceivably become? First of all, the value added by production can be assumed to be unlimited, i.e. B can be any positive number (although there might be a limit to the satisfaction a single human can draw from consumption). At the very least, economists have no more insight into what the limits to B may be then do other disciplines or indeed laymen. Determining the current level is not easy as well as at least I have no thoughts on how to directly measure it. That means that it can only be calculated given values for both T and Y (see chapter 8.3). But is does not mean that B does not have value as a theoretical concept or that it is not an avenue for continued environmentfriendly growth.

3.3 The factors of production

Let us move on to the other dimension of production, namely the physical alteration of reality. The view presented here builds upon Nicholas Georgescu-Roegens fund and flow model, laid out in his seminal work "The entropy law and the economic process" (1971) which is one of the founding works of ecological economics. Georgescu-Roegen capture the fundamental complementarities between that which is transformed into products (natural resources) and that which transforms (labour and capital) (ibid., p230). The production function which Georgescu-Roegen presented based on his fund-flow model took another mathematical form than usual, namely an abstract space of functions (ibid., p232), in contrast to the point function of for example the Solow framework. He envisioned production as a conceptual black box (ibid., p 214) and his production function attempted to describe all those flows which crossed into or out of this box, including natural resources and wastes as well as output. In short, he tried to more fully describe the effects of production rather than merely explaining output in terms of inputs (Y = something). However, that limited ambition is what this thesis seeks to meet, while still relying on Georgescu-Roegens fundamental insights.

The central idea is so simple that it has already been explained in a by-the-way manner several times in this thesis, one cannot help but to explain it given a few sentences on the subject. In every production process each factor of production play one of two different roles, fund or flow. *Flows* are that which is transformed into products and waste, *funds* are the agents of transformation which are not themselves transformed.

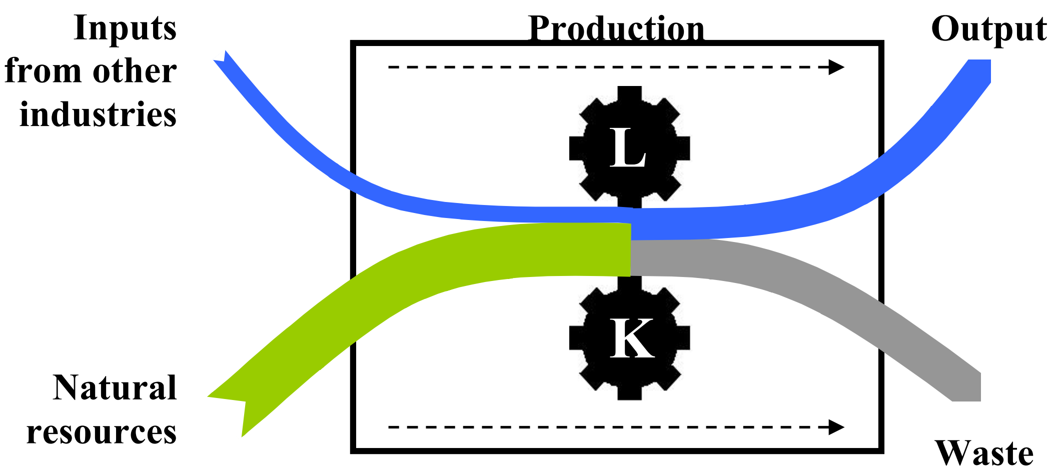


Figure 3.1: A production process featuring both funds – capital (K) and labour (L) - and flows – inputs from other industries and natural resources.

For example, consider the production of tables, it requires both a carpenter with his tools (funds) and timber and nails (flows). The carpenter and his tools remains largely unchanged by the making of the table. Sure, the carpenter becomes tired and his tools a bit worn, but they are both restored by consumption and investment respectively, outside of the production process. In contrast, the wood which becomes a table is obviously and irreversibly changed by the process. The flows are composed of indestructible matter-energy, which can only be transformed but neither created nor destroyed. In other words, the role of the traditional factors of production (the funds) in this context is not to "create" output but rather to make possible the transformation of inputs into output. The funds can be envisioned as a type of catalysts for the production process, they trigger and determine but do not take part in the changes. These insights holds true for services as well, transporting a cargo crate across town for example requires both a driver with his truck (funds) and petrol which is transformed to waste (flows).

What constitutes a fund or a flow is a question of the specific production process in question (ibid., p231). Consider the truck which constituted a fund in the last example, in the truck assembly process the truck constituted a flow. In the case of some services, it might be a bit more complex. Consider for example the repair of a personal computer, since the computer is changed by the process it is technically both an input flow and an output, even though it was never bought or sold by the repairing company. In other words, that which the service is performed upon becomes a part of the process. As can be seen in figure 3.1, man-made resources can enter production both as capital and as inputs from other industries (or in the case of the personal computer, from other parts of the economy). Natural resources can in this thesis only participate as a flow, but it is easy to imagine other non-man-made funds, for example Ricardian land. The land itself is not changed and uses an input flow of solar energy to produce agricultural output (ibid., p232).

Figure 3.1 only showed one production process in isolation, but the main interest of this thesis is aggregate production. If all production within the economy is seen as a single process, then there are no other industries from which to gather inputs and natural resources emerge as the sole contributing flow (figure 3.2). Within the "black box" of production however there is of course a web of input contributions between industries. In this aggregate view, output can be equalised with goods and services for final consumer use.

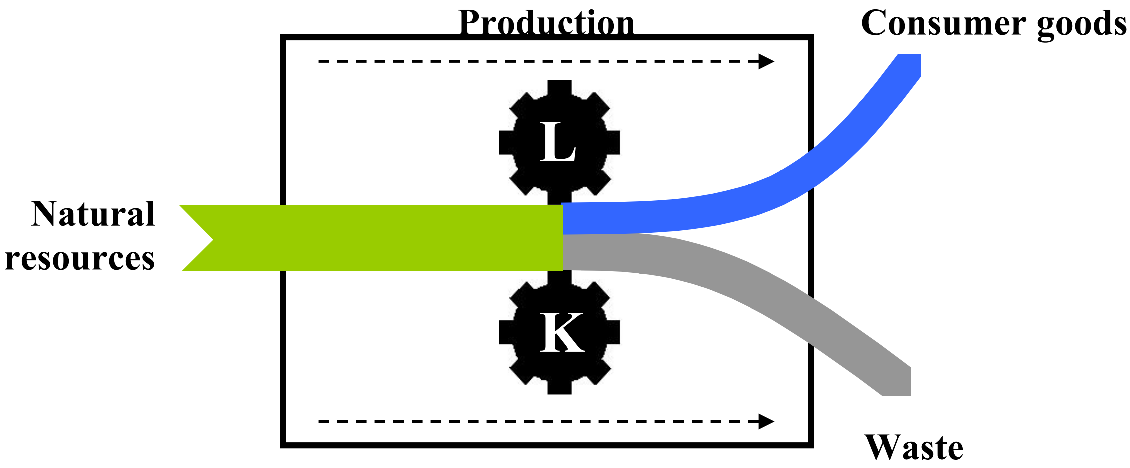


Figure 3.2: Aggregate production

Let us return to the variable T which began this foray into flows and funds. First of all, the variable is zero if either one of the funds or flows are missing. Second, funds and flows are fundamentally complements in determining the level of output, T. This implies that both flows and funds can become bottlenecks to production. Total physical production is limited by the finitude of natural resources and the low entropy they embody (further discussed in chapter four). It is also limited by the capacity of capital and labour to transform those flows. In neoclassical economics natural resources have been seen as abundant and free gifts of nature, which has resulted in ignorance concerning the first type of bottleneck in production theory (Daly, 1996, p34). And ecological economics has too often ignored the central role of the man-made funds. The production function proposed in chapter six will attempt to formalise both limits to production in a framework centred around the concept of entropy. That concept and its relation to natural resources will be the subject matter of the next chapter.

4. Natural resources and entropy

What is it about natural resources that makes them important to the human economy as flows? Herman Daly (building upon Georgescu-Roegen) has provided an interesting answer which brings us back to the second law of thermodynamics. He proposes that it is the low-entropy quality of natural resources which makes them economically valuable (Daly, 1992, p16). Entropy is a physical concept which is inversely related to the potential to do physical work stored in a system, for example as the potential in a battery. The less entropy in a system the greater the potential for physical work which can be used for production. The concept is also tied to probability, a system or state which is improbable (i.e. ordered) embodies less entropy, chaos is always the most probable state of affairs. Finally, entropy has relevance to information theory as well, the less entropy in a message the less possible meanings of the message (i.e. the clearer and unequivocal the meaning) (Nationalencyclopedin, headword: entropi).

In other words, it is not simply the content of matter or energy which makes resources important, in which case wastes would be as valuable to us as raw materials, but rather that these materials are organised into structured, concentrated units with predictable qualities (Daly, 1992, p22f). Material with this low-entropy quality has the potential to be turned into useful products and services, high-entropy wastes has a much lesser such potential. Low entropy can be created, for example through industrial processes where energy is concentrated or matter given form, but only at the expense of a greater entropy increase in another part of the system (Nationalencyclopedin, headword: entropilagen). Once again, this is the very nature of the economy, it creates useful products and services by transforming low entropy inputs from the environment.

Let us consider one of the most important natural resources of our age, oil. It is important because there are practical techniques for using it to create useful products and services. Homogenous and concentrated oil is conveniently stored in large underground reservoirs which can be accessed with machinery. This oil has predictable qualities which allow us to design engines to run on it and indeed run our entire economy on it. If oil could only be found dispersed and diluted, and if burning it was an unpredictable business, oil would never have become a cornerstone of our economy. This usefulness can be equated with the low entropy embodied by the oil. After use, the oil has been transformed into carbon dioxide, heat and other waste products which have a much lower production potential than the oil had.

But the natural resource flow envisioned here is not simply oil, coal, minerals and other such materials that have always been called natural resources. In addition to these materials this thesis also considers as natural resources plants and animals for food, the river which powers a hydropower plant, wind which powers a wind power station etcetera. These are all flows which bring low entropy into the economy.

There is a debate within ecological economics whether it is low entropy or the related concepts exergy or free energy which is the real fundamental resource of the economy (see for example Gillett, 2006 and Ayres, 1999). As an economist I am not in a position to judge which interpretation of the importance of the laws of thermodynamics that is correct. But the distinction holds little relevance to this thesis. The bottom line is that there is a non-recyclable quality to natural resources which is central to doing physical work and which is used up in the economic process. That quality is hereafter termed low entropy in this thesis (following Herman Daly's interpretation) and is equal to the potential production of a system.

4.1 Entropy in production

The great economist Alfred Marshall noted that:

"Man cannot create material things... His efforts and sacrifices result in changing the form or arrangement of matter to adapt it better for the satisfaction of his wants ... as his production of material products is really nothing more than a rearrangement of matter which gives it new utilities, so his consumption of them is nothing more than a disarrangement of matter which diminishes or destroys its utilities." (quoted in Daly, 1992, p 228)

With every such rearrangement, entropy increases (production potential is lost) in the production process on condition of the second law of thermodynamics. In the last chapter the funds were assumed to remain unchanged by the production process, this means that the entropy embodied by them does not change. The entropy increases consequently occur in the flows, when natural resources are transformed into output. If the entropy of the inputs increase to the degree that the inputs are indistinguishable from their environment, then no further production can take place without decreasing the quality (increasing the entropy) of the product itself, which would be self-defeating as it would degrade the product. This makes the finite supply of low entropy in the resource input flow an important limit to production. Or phrased in a rather more positive way, the low entropy contents of natural resources makes production possible. The total amount of low entropy (potential for production) stored in the natural resource input flow is in this thesis captured by the variable E. It is convenient if the units of this variable correspond to the units of GDP (for purposes of model construction). Remember, GDP can be understood as value per unit output times the amount of units. E, the low entropy contents of the natural resource input flow, can correspondingly be understood as the maximum number of output units that can be created with the flow (it does not relate to the quality or value of the output). This maximum can be attained only if no low entropy is lost (total entropy is constant) in the transformation of input into outputs, a purely hypothetical situation (only possible in the case of a fully reversible process)(Nationalencyclopedin, headword: entropi).

Entropy increases (loss of production potential) in the productive process come in three stylized forms in this thesis. First, the output embodies some amount of low entropy. When the output is sold for consumption, the potential to do physical work stored in it is lost for producers. The situation is similar with services if we remember the assumption that the object which the service is performed upon becomes a flow in the process and becomes enriched by low entropy, which then leave the production system. Second, the unwanted by-products of the process, industrial wastes, still contains some low entropy (production potential) when they are disposed of. Third, the combined entropy embodied by output and wastes is larger than that previously embodied by the inputs. This is a result of the irreversibility of the process, we cannot turn waste and product into inputs again (Gillett, 2006, p60). This total loss of low entropy is what necessitates the input of low entropy materials from the environment.

That low entropy leave the productive process as goods and services is in this thesis seen as the desired result, a successful positive change of a consumers' reality. It is this output that the variable T captures, the quantity of output. The two undesired types of losses can be jointly expressed as a variable W (for Wastes) which compromises the difference between E and T; Eq. 4.1

$$E = T + W \leftrightarrow T = E - W$$

An alternative way of expressing this relationship is;

$$T = E\mu \qquad \text{Eq. 4.2}$$

where μ is a number between zero and one which can be understood as the efficiency of the production process. The entropy efficiency of production (how much of the low entropy that actually exit production as useful goods and services) is the subject of the next chapter.

4.2 The size and price of the input flow

The size of E is of great importance to the economy, indeed in this thesis it represents the maximum productive potential of the economic process. At least three questions immediately arise from this statement. How large is that maximum potential? How large can it become? What is the prize of the resources which embody this potential?

The answer to the first question is; however large we want it to be. There is nothing stopping us from extracting the entire planet in one year (although this might be the limit), if we are ready to face the consequences. No one else will intervene or charge us for it, there is no one else. This places the responsibility for extraction of resources squarely on our own shoulders. So humanity must of its own accord condition resource extraction, limit it by some criteria. A reasonable criteria is intergenerational equity, i.e. that we should not let the planet deteriorate over time. In the case of non-renewable resources, that is impossible, use now precludes use at a later time. In the case of renewable resources, we have a chance. There is the possibility of extracting a constant amount of low-entropy renewable resources that is small enough to let the biosphere regenerate. The human economy currently appropriates about 40 percent of all the solar energy captured by terrestrial plants, 25 percent if we include oceanic plants (Vitousek et al, 1986). Is that small enough? In the long run, as non-renewable resources deplete, the size of E will have to converge towards some sustainable level.

But there is reason to be worried that the market might not automatically find and choose such an optimum level of E. As Herman Daly has pointed out, the market lacks the ability to rationally set the scale of the economy, although it very efficiently allocates resources between economic actors (1996, p32 and p50). The standard solution to the optimum resource extraction problem in neoclassical economics is correct pricing. If prices only reflected the full social cost of the use of natural resources, then they would be used optimally (Jones, 2002, p178). But prices deal with relative scarcity, they are used for exchanging products and in this case factors of production. Since natural resources have no substitutes, when they become scarce we face absolute scarcity, an absolute lack of productive potential. That means that the price of everything should increase. But a general increase in prices does not make resource use fall, it is simply inflation (Daly, 1992, p42) . In other words, correct pricing cannot solve this problem for us, although it can help us choose between different sources of low entropy efficiently.

Egor Kraev has further demonstrated that the scarcity of natural resource flows makes itself known only very shortly before exhaustion (with dramatic negative result for production)(2002, p281) which makes it difficult for the economy to receive and act on signals of scarcity.

All these arguments makes me assume that the size of E cannot be determined by some economic optimum or the productivity of the resource (which is equal to the productivity of the entire economy). This seems intuitively right, how much we as a society choose to extract from our surroundings probably cannot be determined by economic theory alone as it is ultimately an ethical and political question. The variable E can therefore be modelled as wholly exogenous in the sense that the model does not seek to explain its size or its growth.

5. Entropy efficiency and the production funds

All real processes suffer from unwanted entropy losses (W), i.e. conversion from input to product is imperfect ($\mu < 1$). This chapter is dedicated to discussing these losses, how they can be avoided and what role the fund factors of production and technology play in minimizing them.

5.1 Wastes and their efficient use

The last chapter outlined the losses in question. First, most production processes create some materials that have not traditionally been considered part of the product, such as chemical by-products and (remembering the hidden flows) earth moved during construction. These types of materials have too long been considered "production wastes" and been deposited to the environment in one form or another. In that case they constitute a form of entropy losses from the production process. But these materials often hold some value to other actors in the economy (due to some structure, concentration and predictable quality, i.e. remaining low entropy) and could be used as inputs in the production of another type of good. This would mean that the productive potential of the natural resource input flow could be used more fully. I.e. the low entropy contents of waste would be minimized and the low entropy contents of goods and services maximized. Note that this says nothing about the matter-energy contents of neither output nor wastes, just about the productive potential of that matter-energy.

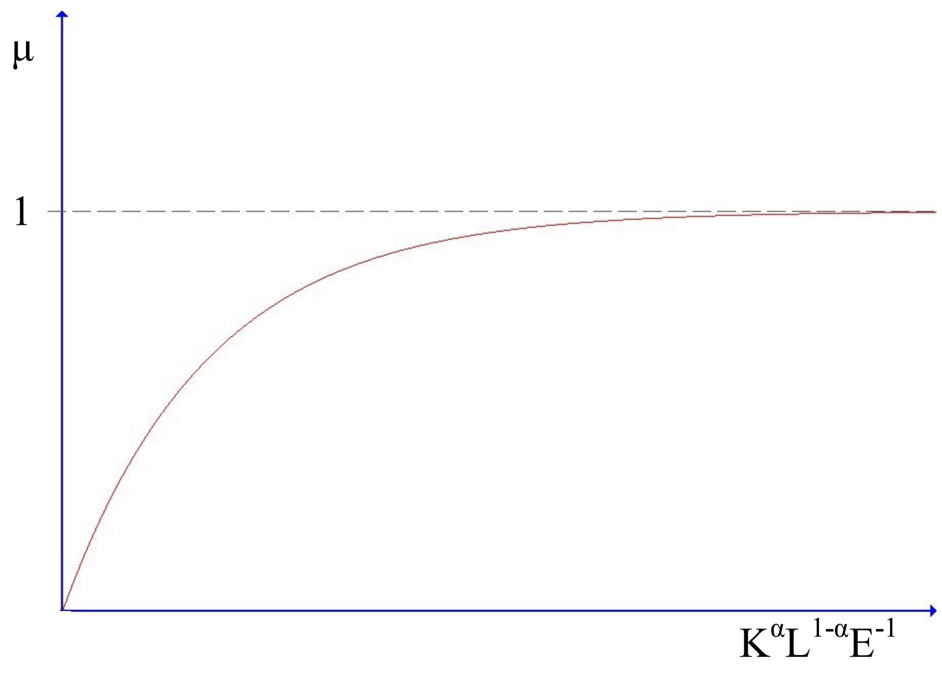
Our economy is presently a throughput economy, meaning that most substances take a fairly linear route from extraction through production of a single good and back into the environment (World Resource Institute, 2000, pXI). This is a highly inefficient use of low entropy resources. In contrast, the economy could possibly be a so called roundput economy. In such an economy, outputs from one industry match the needed inputs of another industry, mimicking natural ecosystems. If production processes were arranged in this symbiotic fashion the low entropy stored in the natural resources we extract could be used more fully, just as the biosphere maximises the life that can be sustained by solar inflow (this is a main tenant of the academic discipline of industrial ecology, see for example Korhonen & Snäkin, 2005). There is much room for improvement.

Then what is needed for this more efficient use of materials and wastes to take place? The simplest answer is that there needs to be capital and labour suited to using wastes as inputs in new production processes. Two men working for one day can make more out of a tree than one man. In other words, entropy efficiency, termed μ, rises with more capital and labour per unit natural resource input (capital and labour are assumed to be substitutes);

$$\frac{T}{E} \equiv \mu = f\left(\frac{K^{\alpha}L^{1-\alpha}}{E}\right) \qquad \text{Eq. 5.1}$$

The route to our industrial structure becoming more entropy efficient is consequently investment in waste-utilizing processes. But investment is unlikely to happen in these processes if "fresh" natural resources are available as inputs instead. If inputs grow at the same (or higher) rate as the economy, there is little incentive for business' to use the wastes of other industries. Only given a constant (or falling) level of inputs and a growing stock of capital and labour are those input flows likely to be used more efficiently. If inputs are constant, the economy will become increasingly saturated with capital and labour which will have no other choice than to utilize the waste flows of other industries, i.e. use the natural resource input flow more efficiently. Remember that funds are assumed useless for production purposes without flows (and vice versa) due to the fundamental complementarity between the two, so saturation would necessarily have this effect.

The maximum efficiency of production is one (a hundred percent). The "first" percent of efficiency is probably much easier to attain (by applying funds) than the "last" percent. It is reasonable to assume that the best resources are used first in every stage of the production process. The not so good resources, and indeed the wastes, probably require more capital and labour to be turned into valued output, leading to decreasing returns to the funds with respect to efficiency increases. A simple way to graphically demonstrate these insights is by the following diagram.



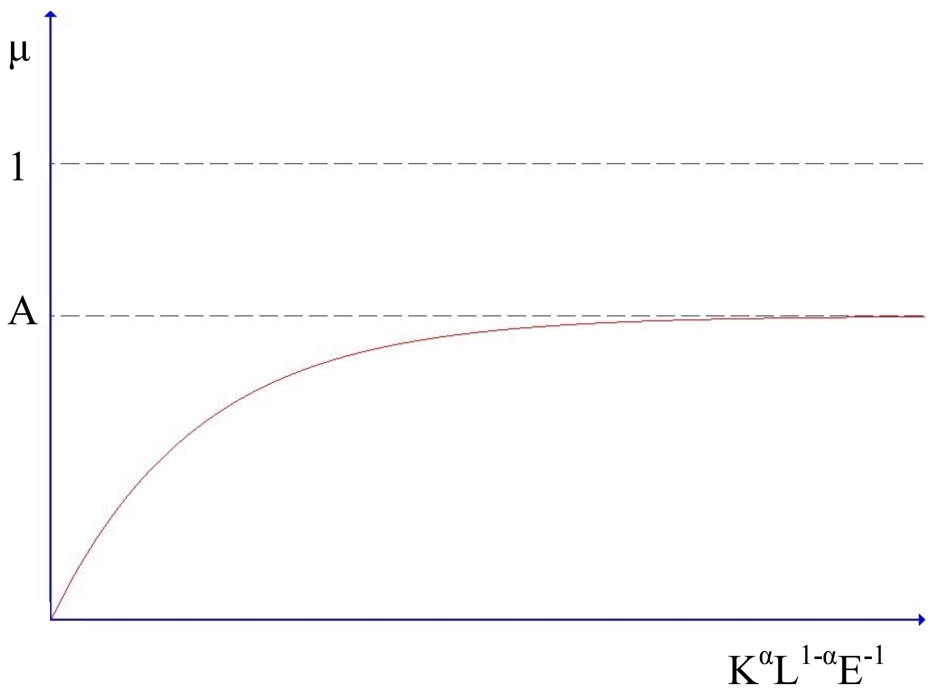
A function which corresponds to this type of relationship looks as follows;

$$\mu = 1 - e^{-K^{\alpha}L^{1-\alpha}E^{-1}} \qquad \text{Eq. 5.2}$$

5.2 Technological limits

The second type of loss outlined in the last chapter was a characteristic of the production process itself. Wastes and output together embody less low entropy than did the inputs. There are simply technical limits to the entropy efficiency of certain processes, such as the combustion of fossil fuels, which are far lower than perfect efficiency. The key to avoiding these losses is to not convert energy into low grade heat which dissipates into the environment (Gillet, 2006, p60). No matter how much capital and labour that is employed, these technological limits cannot be surpassed (without development in technology itself). Technology can therefore be entered into equation 5.2 as a variable, with a value between zero and one, which multiplied with the right hand side produces a new upper limit to the entropy efficiency of production.

$$\mu = A(1 - e^{-K^{\alpha}L^{1-\alpha}E^{-1}}) \qquad \text{Eq. 5.3}$$



But of course, neither technology nor the finite flow of low entropy inputs should be envisioned merely as limits to production. They are and have been avenues for economic growth, indeed growth in these variables are connected to increasing returns to scale. This discussion will be continued in chapter seven. To the economists eye however, which is used to seeing technology as a boundless variable that can help us outgrow any scarcity, the setup of the model might seem uncomfortable. But that A cannot grow larger than one is merely a testament that no technology, no matter how advanced, can break the laws of thermodynamics (Daly, 1992, p24).

A more familiar way to enter technology into a production function would perhaps be as a multiplicative of either or both of the funds, $AK^{\alpha}L^{1-\alpha}$. Technology could then grow forever (although output would not) and reduce the need for capital and labour in production. This is meant to capture that capital and labour become better at what they do, and that better capital is a substitute for less advanced capital and vice versa. These are important insights which are only partially shown in the alternative chosen here, in which capital and labour of different qualities are imperfect substitutes. Improving technology is a substitute to investing in additional funds, but no amount of less advanced capital can achieve the output that advanced capital could. In a sense, there is a one way substitutability between advanced and less advanced capital. I believe this to be a reasonable assumption, no amount of nineteenth century capital could effectively produce power from uranium. However, there is nothing to prevent both incarnations of technology to appear in a single model. For simplicity, that is not pursued in this thesis.

A is a variable which reflects much of the potential overall efficiency of the production process, it is dependant on the type of inputs, the type of capital, logistics and so on. In other words, it is a function of the technology *used*, not technology available in another factory or on a drawing board somewhere. As such, it does not necessarily grow just because science progresses. Use of more flow-efficient technologies clearly depend on the price of the flow, which cannot be fully explained by their usefulness in production (as seen in chapter 4.2).

To summarize, the role of fund factors of production is to transform input flows into valued output. More funds per unit flow clearly does this more efficiently, minimizing entropy losses. But no amount of capital and labour can overcome the technological limitations of the production process in question. So technology poses another limit to production and is ultimately limited itself by the laws of nature, prominently the laws of thermodynamics. The next chapter will attempt to bring this and previous chapters together in a production function.

6. The production function

In chapter three I proposed that since production has both a material and an intangible dimension a production function could be similarly divided. Equation 3.1 showed how this could be easily expressed mathematically;

$$Y = BT \qquad \text{Eq. 6.1}$$

where Y signifies GDP, the total value added in a year, B signifies the value added per unit output and T the total quantity of units. In essence, B describes the quality of output while T describes the quantity. Chapter four described how T can be expressed as a quota of the total resource input flow;

$$T = E\mu \qquad \text{Eq. 6.2}$$

where E stands for the maximum amount of output that could be created with the resource input flow, given the second law of thermodynamics. $0 < \mu < 1$ signifies the entropy efficiency of production, i.e. how much of the potential of the inputs that actually comes out as valued output. μ was further explored in chapter five and found to be a function of the fund per flow quota, $K^{\alpha}L^{1-\alpha}/E$, and technology, $0 < A < 1$;

$$\mu = A\left(1 - e^{-K^{\alpha}L^{1-\alpha}E^{-1}}\right) \qquad \text{Eq. 6.3}$$

These equations can be combined to form the final production function;

$$Y = BEA\left(1 - e^{-K^{\alpha}L^{1-\alpha}E^{-1}}\right) \qquad \text{Eq. 6.4}$$

The function is still divided into a quality and a quantity dimension. The quantity dimension has clearly received more attention and has been modelled in greater detail, which is all well and good since natural resources are the focus of the model. These natural resource inputs, E, enter the function in two capacities. First, as a convergence limit beyond which no quantitative growth is possible. Second, as a part of the fund per flow quota which helps explain entropy efficiency. This means that the returns to E depend on the relative abundance of the funds or flows in production, in other words there are decreasing returns to scale. The returns to scale for the funds, capital and labour, are also decreasing and display this type of context dependence. This is one of the strengths of the model, it simultaneously shows that funds and flows are complements but also substitutable to a degree depending on their relative abundance or scarcity.

As a whole, this production function features constant returns to scale to the material factors of production. For example, doubling both funds and flows will keep efficiency constant while doubling the scale of production. But economic growth does not only depend on growing inputs but also on advancing technology and improving the quality of output. Growth in B and A will prove very important for explaining per capita economic growth.

To form a per capita version of this model is exceedingly simple. Since B, A and $\left(1 - e^{-K^{\alpha}L^{1-\alpha}E^{-1}}\right)$ are all variables or expressions which indicate efficiencies or general characteristics of the economy, they do not change as the function is turned into per capita form. The only variable which is affected by the rewrite is the entropy input flow E which must be divided with total population.

$$\frac{E}{L} = \epsilon \qquad \text{Eq. 6.5}$$

$$Y = B\epsilon A\left(1 - e^{-K^{\alpha}L^{1-\alpha}E^{-1}}\right) \qquad \text{Eq. 6.6}$$

Because of its similarity with equation 6.4, equation 6.6 shares many of the characteristics of that function. The only difference is that the returns to labour decrease quite dramatically. Consequently, growth in the capital stock and natural resource flows stand out as more suitable venues for economic growth (once again dependent on the relative abundance and scarcity of the different factors of production). The next chapter will discuss growth within the context of the model.

7. Growth in the model

Economic growth happens over time as a result of changes in the workings and composition in the economy. Following the standard convention, I will in this chapter study the first derivative (with respects to time) of the production function to illustrate and quantify this growth in the value of total output. The main interest of growth economics is not absolute growth but rather relative growth, for example an annual two percent growth in output. If $\dot{X}$ signifies absolute growth in the variable X over time (i.e. the first derivative), then $\dot{X}/X = g_X$ signifies relative growth in X, the growth rate of X. Using these standard terms, economic growth in the model can be described as follows;

$$g_Y = g_B + g_E + g_\mu \qquad \text{Eq. 7.1}$$

Growth in B and E is easy to process mathematically, both variables grow at exogenous rates which I will discuss later in the chapter. Growth in entropy efficiency μ is however a bit tricky. μ can be seen as a function of time which contains several other functions of time;

$$\mu(t) = A(t)\left(1 - e^{-K(t)^{\alpha}L(t)^{1-\alpha}E(t)^{-1}}\right) \qquad \text{Eq. 7.2}$$

The function is easier to handle if the funds to flow ratio is expressed as a single function of time, F(t);

$$F(t) = \frac{K(t)^{\alpha}L(t)^{1-\alpha}}{E(t)} \qquad \text{Eq. 7.3}$$

$$\mu(t) = A(t)(1 - e^{-F(t)}) \qquad \text{Eq. 7.4}$$

Further it is simpler if growth in technology and entropy efficiency are handled separately;

$$\mu(t) = A(t)G(t) \qquad \text{Eq. 7.5}$$

$$G(t) = (1 - e^{-F(t)}) \qquad \text{Eq. 7.6}$$

The growth rate of F(t) is simply a function of the growth rates of capital, labour and resource input, weighted after their relative importance in production (arrived at by "taking logs and derivatives");

$$g_F = \alpha g_K + (1-\alpha)g_L - g_E. \qquad \text{Eq. 7.7}$$

But since G(t) contains a subtraction and an exponential function, the growth rate of the expression as a whole is slightly more complex. It can be arrived at by taking the derivative with respect to time of G(t).

$$\frac{dG}{dt} = \frac{dF}{dt}e^{-F(t)} \qquad \text{Eq. 7.8}$$

We do not have $\frac{dF}{dt}$ at this point but it can easily be arrived at by multiplying the growth rate g_F with the function F(t), because $g_F = \frac{\frac{dF}{dt}}{F(t)}$.

$$\frac{dG}{dt} = g_F F(t) e^{-F(t)} \qquad \text{Eq. 7.9}$$

Now there only remains to divide equation 7.9 with G(t), once again because

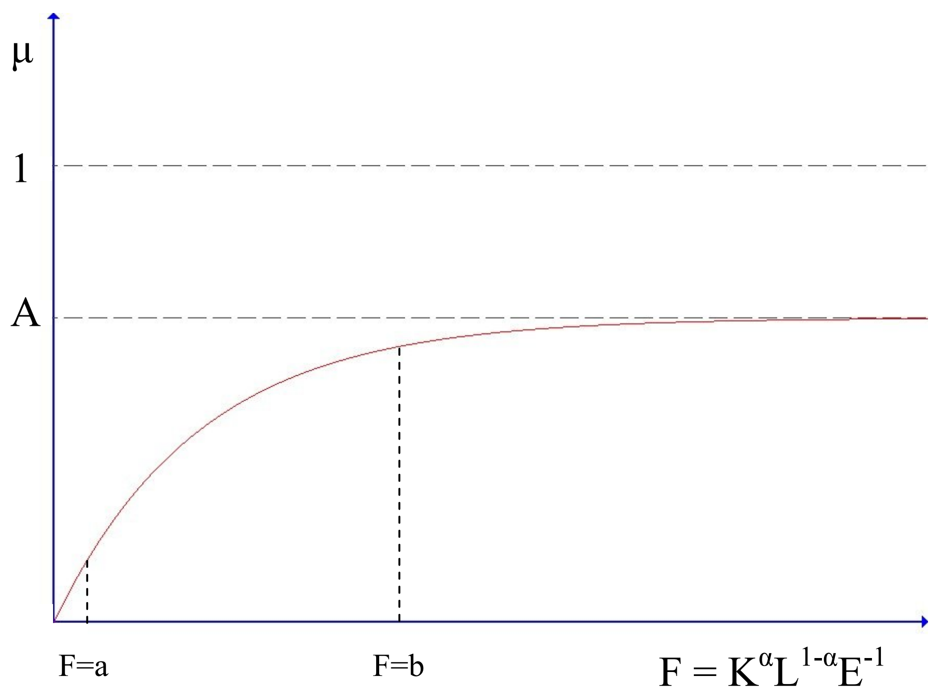
$$g_G = \frac{\frac{dG}{dt}}{G(t)} \qquad \text{Eq. 7.10}$$

$$g_G = \frac{g_F F(t) e^{-F(t)}}{1 - e^{-F(t)}} \qquad \text{Eq. 7.11}$$

Equation 7.11 can be slightly rewritten and g_F and F(t) substituted for;

$$g_G = \underbrace{(\alpha g_K + (1-\alpha) g_L - g_E)}_{\text{Part one}} \underbrace{\frac{(K^{\alpha} L^{1-\alpha} E^{-1}) e^{-K^{\alpha} L^{1-\alpha} E^{-1}}}{1 - e^{-K^{\alpha} L^{1-\alpha} E^{-1}}}}_{\text{Part two}} \qquad \text{Eq. 7.12}$$

This equation certainly looks intimidating, but the insight it conveys is quite straightforward. Part one simply tells us that efficiency growth is dependent on the growth rates of both funds (positively related) and flows (negatively related). Part two tells us that it is also dependent on the current efficiency which determines how growth in the fund to flow ratio translates into efficiency increases. This also feels intuitively correct. Consider the diagram below, if F is near a, then growth in F clearly has a larger impact on μ then if F is near b.



The growth rate of economic output can be determined by the growth of the factors in the production function;

$$g_Y = g_B + g_E + g_A + g_G \qquad \text{Eq. 7.13}$$

with the option of expanding g_G to the form of equation 7.12. The per capita growth rate can be derived as easily as the per capita production function. The growth rate for E must simply be replaced with the growth rate for E/L = ε. This growth rate is equal to the difference between the growth rates of E and L. Per capita growth in economic output can consequently be described as;

$$g_y = g_B + g_E - g_L + g_A + g_G \qquad \text{Eq. 7.14}$$

The next segment will discuss these component growth rates.

7.1 The growing variables

So far nothing has been said as to the growth of the variables featured in the production function. Economic theory is full of explanations and assumptions as to how and why such quantities as the capital stock or population grow. The most simple type of assumption is that a variable grows exogenously, i.e. that the growth is not explained by the model. In a sense, it is not a bad type of assumption. It is merely a statement that growth in that variable is outside ones area of expertise or outside the focus of the model. That is certainly the case for most of the variables in the production function of this model.

Labour growth, assumed approximately equal to population growth, is commonly seen as exogenous in these type of models. It is often modelled as growing at a constant rate (although large economic changes have often taken place in conjunction with changes in this growth rate). Population growth is clearly related to all sorts of processes in the economy, notably per capita income. But it is unlikely that any other assumption than a exogenous growth rate better could explain these intricacies.

Growth in technology (A) and the quality of output (B) have been mentioned previously in the thesis. As hinted at on those occasions it is not the purpose or focus of this thesis to explain growth in the total stock of ideas in the economy, which is why technology will be modelled as exogenous. But it is understood that if technological growth was to depend on population growth, as it does in Romer-type models, the dynamic of labour in growth would change dramatically. The reader would do well to keep this in mind when interpreting the results.

The size of E has been discussed earlier, and just as the size, the growth rate of E is also (not surprisingly) modelled as exogenous.

This brings us to the final growing variable in the production function, namely capital. The growth of capital has long been central to growth theory. In fact the capital accumulation function is seen as one of the central components of the Solow model. It generally looks like this;

$$\dot{K} = sY - dK \leftrightarrow g_K = s\frac{Y}{K} - d \qquad \text{Eq. 7.15}$$

where s represent the proportion of total income Y that is invested in the capital stock each year and d represents the depreciation rate of capital. The growth of the capital stock is consequently intimately tied to growth in economic output. That connection has been seen as a powerful tool in understanding steady state growth. The peculiarities of this model undermines this usefulness. The next segment explores this further.

7.2 Steady state growth

As we saw in the previous segments, growth in total or per capita GDP in the model result from either efficiency increases, a higher quality of output or increased input flows. The conditions of a steady state limit these avenues for economic growth. If an economy is in a steady state, the internal allocations in the economy and all parameters in the model are constants, indicating a lasting balance or equilibrium in the economy. Long run (steady state) per capita growth depend on some force which is unchecked by other forces in the model, traditionally technological progress. In other words, an economy with a positive steady state growth rate grows without sacrificing anything.

When one sees the economy as a subsystem of the environment, it is evident that growth through increasing input flows cannot continue forever. The subsystem must remain at a certain physical scale relative to the larger system if there is to be long run balance (Daly, 1992, pxiii). The variable E must therefore be a constant in the steady state. Resource extraction is only one part of the economy's relationship with the environment alongside pollution, habitat occupation and so on. But holding E constant will in this model have to approximate a balanced or unchanging relationship between the two systems. It might be the case that the economy has already overstretched the regenerative capacity of the environment, indicating that environmental health might decrease even though E was to be held constant. For simplicity, not realistics, the steady state modelled in this chapter assumes that this regenerative capacity is not overstretched. If that threshold value has been overstepped, there can be no steady state at this value for E, resource extraction (and pollution etc) would have to decrease to a scale under the regenerative capacity of the earth for long run stability.

This leaves two avenues for per capita economic growth, efficiency improvements and increasing our understanding of value (raising B). Efficiency improvements can come from two sources. Either from advancing state of the art technology (raising A) or from coming closer to fully utilizing that technology by investing in and improving the funds of the economy (raising K or L). The labour force is seen as growing exogenously at a constant rate n. In the short run this is certainly a source of economic growth, with possibly increasing returns to scale (depending on the initial fund to flow ratio). But in the long run and given a constant E, population growth will become a larger drag on flows per capita then an as a contributor to the fund to flow ratio. Consequently, for long run stability to be possible population growth must be zero.

In steady state, growth in the capital stock is equal to and a result of growth in economic output. First off, this means that capital accumulation is not a independent source of steady state growth, but rather a result of it, in steady state the capital stock is keeping pace with the rest of the economy. But more problematically, since E and L are constants capital faces decreasing returns to scale with marginal productivity converging on zero. It is highly unlikely that savings would remain a constant proportion under these conditions, who would want to invest and get nothing back? The classical statement that the capital to output ratio must remain constant for the economy to be in a steady state consequently has less relevance to this model. This gives growth in the capital stock the appearance of a transition phenomena.

The technology variable A is not similarly limited by decreasing returns to scale or per capita considerations. But it is limited by the laws of thermodynamics to the effect that it cannot grow larger than one. We might be far from one so that technological improvements for a long time may sustain per capita economic growth. But in a strict interpretation of the steady state, this is not an unlimited venue for economic growth which could sustain steady state per capita growth. Growth in technology must therefore also be considered a transition phenomena.

We are now down to only one possible source of sustainable steady state growth, namely qualitative improvements in the form of a rising value for B. Luckily, this is a dimension of the economy which (by assumption) is unlimited. Goods and services may become arbitrarily good at satisfying the needs and wants of consumers. The exogenous growth rate g_B is therefore a source of steady state growth in the model, provided of course that change in this variable is always positive which is not written in stone. I can imagine many scenarios in which a society's enjoyment of certain or all products may decrease or in which new products are no better at satisfying the needs of consumers. But in general, g_B can probably (hopefully) be assumed to be positive. Hopefully there are also things governments and societies can do to increase this growth rate.

Steady state growth is quite limited in this model, to say the least. This highlights the importance of transition dynamics over periods which might be very long, in Keynes' sense of the word. One important aspect of these transition dynamics is the semi-equilibrium growth path created by the dual role of both E and L in the per capita production function. This balanced transition growth path, as I choose to call it, occurs when L, K and E all grow at the same rate. In this case, entropy efficiency μ remains constant while growth in inputs E result in absolute economic growth. From a per capita perspective incomes are constant along this balanced growth path (barring growth in A or B) because population growth precisely offsets scale increases. In contrast to this balanced growth path, lop-sided growth in either E or L could lead to falling per capita incomes. The positive effects of raising inputs will eventually lead to larger efficiency losses. The positive effects of increasing efficiency with more labour will eventually be offset by having to split total income over more labourers. In other words, there is an optimum balance between funds and flows which does not change with the scale of the economy.

The variables discussed here can consequently be divided into three categories. First, those that can grow in the steady state and increase both absolute and per capita income, i.e. B. Second, those that can cause absolute transition growth, E and L. Third, those that can cause transition per capita economic growth, K and A. The following segments will discuss historic and future growth from this perspective.

7.3 Historic growth

Historic growth has most probably not been confined to the strictly sustainable form of growth represented by the steady state. We can easily establish that the expansion of the last centuries has not all been the result of higher quality output. Rather historic growth can be related to changing parameters and increases in those variables which should be constant in a steady state.

Population growth rates have risen dramatically during the last two centuries, causing an unprecedented population boom. And along with that increase, humanity has begun extracting incomparable amounts of resources from the environment. Just imagine the present world population of over six billion trying to survive on the food grown for one billion people. The rapid growth of the last centuries can also be connected to that man stopped living solely of the solar influx of low entropy (captured by plants) and started exploiting terrestrial sources (coal and oil etcetera) at a much faster speed and higher quantity (Daly, 1992, p23). The last century has also been a time of intense capital accumulation. That these changes have taken place simultaneously is not surprising from the perspective of this model, the economy has been growing approximately along a balanced transition growth path of the type mentioned in the last segment. The role of capital accumulation in this is central in the model. Only when man achieved the ability to accumulate capital could absolute economic growth take place without falling per capita incomes. Growth in capital is essential to maintaining a constant fund to flow ratio (because K and L are substitutes in production, growth in L alone face decreasing returns to scale). But if the capital growth rate has been higher than the population growth rate (due to a rising savings quota), capital accumulation could also lead to *rising* per capita incomes. But growth in $K/L = k$ alone has not been the sole source of per capita economic growth. These increasing returns to scale also result from those efficiency increases ascribed to technology.

A few words on the historic role of technological improvements in the light of this model. Much of that which is normally modelled as technological improvements would not fall into that category in this thesis. Often "technological progress" has merely been new techniques which allowed us to extract more resources or new types of resources. Consider for example the invention of nuclear power plants. The implementation of this idea meant both capital growth through investment, an increased throughput of uranium (and the output of a previously unseen substance on earth, plutonium) as well as certainly some efficiency improvements (the quality of the product remained the same, no different from electricity produced from for example coal). In other words, that which is normally understood as technological growth, which has been used to explain much of historic growth, can with this model be understood rather as complex changes in the economy including many if not all of the variables in the production function. But those pure technological efficiency improvements, that make use of a given resource more efficient, have certainly played an important role in rising per capita incomes.

That the growth of the past has been outside the limits of the steady state is not problematic in itself. Indeed we should be glad for the riches it has created. It is problematic that this type of growth cannot continue indefinitely.

7.4 Future growth

The concept of a steady state, when combined with the view that the economy is a subsystem of the environment, is a powerful tool for assessing sustainability. The growth which "remains" after introducing the conditions of the steady state is that which does not undermine the foundations of the economy, allowing for long term stability. In contrast, growth of inputs undermine the biosphere of which are all part and population growth entail falling per capita incomes. Improving technology has within the economic discipline been seen as a fairly unproblematic form of growth with respects to the environment, or sometimes even as the solution to all environmental problems. Technology in and by itself of course does nothing to undermine the economy. But technological advances have often been connected to increased resource throughput, "advances" are often just new ways to extract an additional resource type or increase material throughput. If technological improvement takes the form of "doing more with less", as it is modelled in this thesis, then it is wholly beneficiary and could add to prospects for future growth.

Steady state growth is the "safe way" to increasing welfare, it does not entail the risk of mounting costs. But it may of course be warranted to deviate from this route if benefits exceeds costs. But we are receiving clear signals that environmental costs are mounting fast (for example in the form of climate change) and that they may threaten long term stability. There is also the threat of depleting terrestrial sources of low entropy such as oil which means that in the long run E will have to converge on the sustainable yield from renewable resources. But there are also signs that the regenerative limit has been reached, if not overstepped, for many resources, as exemplified by overfishing of the seas. And the real limit may be environmental degradation rather than depletion of a specific resource stock which might be more unpredictable and occur before depletion (Barbier, 1990, p8). Quantitative growth in inputs is consequently becoming an increasingly unviable deviation from the steady state. If inputs are to be held stable, population growth can quickly become a downward drag on per capita incomes. This leaves two fruitful avenues for future economic growth, increasing the size and efficiency of the capital stock (raising K and A) and qualitative development (in the form of raising B). The future challenge will certainly be to decouple these variables from population and resource inputs.

8. Discussion

This chapter has three objectives. First the model is to be discussed from the angles provided by its major strengths and weaknesses. I also wish to make some suggestions based on this discussion on important areas for future work. In the last segment of the thesis I also wish to return to the research question with which it all began and hopefully leave the reader with a few new questions.

8.1 Complementarity and substitutability

I believe that one of the major strengths of the model is the way in which it incorporates that funds and flows are complements in the production process. As mentioned in the introduction, there are two other major ways of doing this, minimum functions and constant elasticity of substitution (CES) functions. Minimum functions can be illustrated with figure 8.1, using the notations from this thesis. The man made funds are the sole determinants of Y until E suddenly becomes the limiting factor. Increasing E before that happens has no value to the economy whatsoever (see for example Kraev 2002, p280). That increasing the throughput of natural resources could not be a boost to the economy, even under certain circumstances, seems unrealistic. It also feels unrealistic that growth in the economy would suddenly become constrained by something that was seen as abundant just a few moments ago. This type of function is simply to rigid.

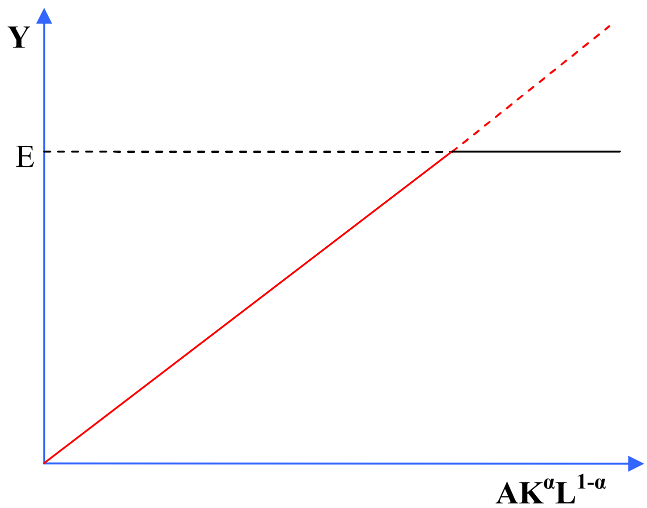


Figure 8.1: A minimum function where funds and flows are complements and the flows are abundant.

CES functions are a generalization of Cobb-Douglas functions and take the following mathematical form (Jones, 2002, p185), once again with the notations from this thesis;

$$Y = ((A_{funds}K^{\alpha}L^{1-\alpha})^{\rho} + (A_{flows}E)^{\rho})^{1/\rho} \qquad \text{Eq. 8.1}$$

If ρ is less than zero, the funds and flows are complements (ibid., p186). But this type of equation also features some substitutability at the margin between the funds and the flows which makes it more realistic than a minimum-type function. That substitutability occurs when the productivity of the funds and the flows are roughly equal (Kraev, 2002, p283). This setup is problematic in two ways which influenced the choice of another type of production function. First of all, it seems problematic to assign productivity to low entropy input flows. How can a piece of wood or a tank of oil be productive? It just sits there. It is the agents of production, labour with the help of capital, which can actively and purposely change their environment and be productive. To further confusion, this productivity which is ascribed to natural resources is often seen as rising due to technology (A_{flows}). Oil is oil, its productivity (if it has one) can at the very least not change. Second, note that the productivities of the funds and the flows are to be roughly equal for substitution to be possible. This means that the productivity of the funds can be at or *above* the productive potential stored as low entropy in the natural resources. This is simply not possible if we assume that the funds are not significantly changed by production, if they were so changed they would be considered flows. This last objection is only relevant if low entropy is in focus. CES functions might consequently be a better tool for another conception of natural resources. But if natural resources are considered primarily as carriers of low entropy, CES functions clash conceptually with other parts of the theory.

The production function proposed in this thesis takes the best elements of both minimum functions (that there is an upper limit to the productivity of funds set by the finitude of the flows) and CES functions (that there is substitutability at the margin). My conclusion is that it has been fruitful for conceptual clarity to start with the specifics of the complementarity between funds and flows and only afterwards seek a fitting function type. This fundamental strength of the model is the reason that I now recommend the model as a rewarding base for future studies into the subject of growth and natural resources.

8.2 Growth, development and sustainability

The main theoretical source in this thesis, Herman Daly, has repeatedly advocated that scholars should separate between quantitative growth and qualitative development (1999, p6). The model developed here does just that and deepens the analysis by connecting these different types of economic growth to steady state and transition phenomena respectively. Quantitative growth is in the model a transition phenomena which has mostly affected the scale of the economy but also per capita incomes through capital accumulation. Qualitative development on the other hand is a steady state phenomena which always raises per capita incomes. In other words the model allows sustainability to be formalised as the steady state (given that E is below the regenerative capacity of the biosphere). This is a powerful tool for motivating environmental policy with an economic framework and, I believe, an interesting area for future work.

8.3 Measurability and calibration

The largest flaw of the model is doubtlessly that it is almost impossible to use for practical purposes such as calculating the GDP of Sweden. It features units and quantities which have rarely seen the light of day and for which no measurements exist. In part, this is the result of the novelty of the model. Some of the variables and concepts which it introduces as important could probably be operationalised given time and research effort. If entropy was truly put in the economic spotlight I am confident it could be quantified and traced through production and become the foundation of highly usable models. It is after all a standard physical concept which must only be made accessible to economists. But other variables may be arcane beyond repair, especially B which is meant to capture the intangible dimension of production. It might be possible to triangulate if we know what we need to know about the physical dimension and GDP. But that does us little good if it is GDP we are after. A clear objective of future work based on the model must be to further investigate the operationalisation of the variables and concepts of the thesis.

This unmeasureability is the reason that I chose not to in detail model for example the steady state level of income and how that depends on different parameters. Since many of the variables are considered exogenous and the relations between the variables are very simple (with the prominent exception of μ), such an in-depth study of the steady state would not reveal much about historic and future growth that cannot be seen at first glance from the production function. But if the model is to have greater precision as a explanatory instrument an in-depth analysis is obviously needed, which is why I recommend that as an area for further study.

8.4 Concluding remarks

Why are we so rich and they so poor? What differentiates poor from rich societies in the model? In many aspects the model offers many of the same insights as more standard Solow-type models where technological growth is exogenous. Rich societies invest in capital and they thrive on high levels of technology. But rich economies also organise more like ecosystems with complex webs of inputs and outputs, indicating a higher entropy efficiency. Part of this efficiency can be attributed to a simple higher fund to flow quota, which is what is proposed in this thesis. But part of it is also due to the sheer scale of rich economies which allows for (makes profitable) more types of industries and more complex structures. However, efforts to increase diversity and efficiency has also historically led to growth and increases in the scale of the economy (Korhonen & Snäkin, 2005, p177). This model is based on exogenous technological growth rates, if it instead was based on the assumption that a larger population produces more ideas the positive effect of scale on incomes might be further strengthened. Efficiency and scale might unfortunately go hand in hand. Why unfortunately? Because scale makes it difficult for an economy to find a stable ecological niche as a subsystem of the environment (Daly, 1996, p223). In a sense, the model presented here is quite positive about the prospects of the world to sustain high per capita incomes, since efficiency increases do not require previous scale increases.

The research question also hints at an equity dimension. Why are we so rich and they so poor, simultaneously? This is of course a huge research field, to big to be covered by a few lines here. But the model can help us identify a potential area of inequity. Poor societies often specialize in primary production, agriculture and resource extraction. These goods are then sold to rich societies where they are turned into final use products. In other words, productive potential leave poor societies before the labour and capital there has had a chance to do what they can with the potential and get paid for it (for a continued discussion see Hornborg, 1998). This would not be a problem if resources were correctly priced so that poor societies were properly compensated, but as argued in chapter 4.2 the productive potential of natural resources can never be fully compensated since they are complements to capital and labour. Let us hope that the wealth of the global rich does not intimately depend on the different roles of poor and rich societies with respects to the environment and natural resources.

In spite of any and all shortcomings of the model, the mathematical formalisation of complementarity and entropy has created an interesting angle from which to study growth and production, one that I believe should be pursued further.

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