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Research Article

Knowledge, Input-Output Complexity and the Notion of Sustainability

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Abstract

The paper attempts to synthesize the analytical nucleus of classical political economy and modern ecological economics. In essence this means making a connection between social issues of income distribution, accumulation of capital and economic growth with biophysical limits to economic development. We first model a simple growing system of production and explore its potential to maintain sustainability when using a single natural resource. Taking into consideration the laws of thermodynamics we show that the long-term sustainability of such a simple system is unlikely. When the model is extended to incorporate a wider range of inputs used and commodities produced, such complexity accompanied by knowledge-based structural changes provides necessary conditions for the long-run sustainability of a growing economic system. Since input-output complexity results from the division of labour on the one hand and from intentional R&D policies on the other, this conclusion also brings forward some policy implications regarding income distribution in the society.

Keywords: *sustainability, socio-economic development, complexity, political economy*

1. Introduction

The paper intends to redefine sustainability, trying to capture growth of knowledge as one of the crucial factors for sustainable future development. Methodologically, the paper draws on classical political economy, with its distinctions between productive and unproductive labour, the central role accorded to profitability, class distinctions, etc., augmented with the work on thermodynamics and economic theory (Georgescu-Roegen, 1986). An attempt to provide a model of a growing capitalist economy and its interaction with the world of natural resources leads to many interesting implications, one of them being a different view on sustainability in a growing economic system facing a limited stock of natural resources at its disposal.

The paper is structured into four sections. In section two we reconsider the relations between sustainability and limited natural resources. Section three brings the basic one-commodity model of a growing economy, followed, in section four, by a discussion of its sustainability in a world with finite resources. Section five adds complexity in the form of a qualitative evolution of inputs and outputs. Conclusion provides a brief summary of findings.

2. Sustainability and the Role of Structural Change

Economic growth theories often lead to optimistic predictions, which are not only unrealistic with respect to actual historical facts regarding civilizations and their decline, but are also logically at odds with the laws of thermodynamics. This is not a new phenomenon in economic reasoning. In fact, it goes back to Dionysius Lardner who in the middle of the 19th century argued that depleting coal mines would not necessarily be a problem, since an alternative energy source would be found before that could ever happen (quoted in Jevons, 1865, p. 84). This belief in the technological prowess of modern societies was absorbed by neoclassical economics at the end of the 19th century and has remained there ever since. It rests on the assumption that a given output of commodities can always be produced in various ways, meaning that at a given point in time there always exists an alternate technology to create at least a similar medley of commodities. While this might be true for some commodities, it definitely does not hold for aggregate output in complex industrial societies. Developing new methods of production takes time, and the process of substitution has to occur before the current group of inputs becomes too scarce. However, there is no guarantee that modern societies will be able to sustain their current growth patterns by finding a steady flow of new materials and energy sources. To give but one example: even with growth in green energy, a drop in fossil fuel availability would, given our current levels of technology, lead to a serious drop in per capita output.

We argue that this requires a new outlook on sustainability, one which is in line with the basic tenets of thermodynamics and takes into account the specifics of modern industrial societies. We intend to show that while growth, a key and inescapable feature of capitalism (Binswanger, 2009), can be potentially problematic with respect to sustainable use of limited natural resources, there exists another feature of capitalist economic development, namely complexity, which has the potential to ensure that even a growing economic system can reproduce itself infinitely, thus reaching a sort of intertemporal sustainable growth path.

An important feature of the proposed theoretical model is the role accorded to functional distribution of income. In fact, this feature originates in the work of classical economists such as Smith and Ricardo. What also follows from this same tradition is that society is seen as composed of different groups that compete for output based on their bargaining power. The struggle for income between different groups also indirectly affects the relationship between the economic and natural realms. Changes in the functional distribution of income lead to changes in the system of actual production, which in turn affect the capacity of industrial societies to thrive over sustained periods of time. Again, some theoretical distinctions made already by classical political economists turn out to be useful. For example, the distinction between productive and unproductive labour, where the former augments the capacity to create wealth, whereas the latter is in fact a form of social consumption (Shaikh and Tonak, 1994). Also, there is a distinction between labour employed in the production of output and labour employed in research and development of new production techniques, a long neglected distinction that was brought into economic analysis by the endogenous growth theory (Romer, 1990). Our contention is that shifts in the structure of both inputs and outputs are crucial, if we are to correctly identify the meaning of sustainability in a growing economic system facing biophysical limits.

3. Dynamic Economic System with One Natural Resource

Let us first define a simple growing economic system. Population (N) grows at constant rate (n) described by equation (1) and is exogenously given. Equation (2) defines the national income in every period of time as a function of the amount of labor employed in the private sector,(L_t) and its productivity,(π_t). A part of the national income goes to the government in the form of taxes (G_t) and this is described by equation(3), where t represents the aggregate tax rate in the economy. The amount of labor employed depends on the amount of hitherto accumulated physical capital stock (K_t) in the economy. The level of employment (L_t) is captured in (4) and we can see two parameters on the right-hand side which, together with the capital stock determine the amount of labor employed: h_L and β. The first parameter (h_L) is the inverse of the length of the workday: the longer the workday in the economy, the less labor needs to be employed for a given amount of machinery. This lever can be used to reduce the effective labor force, thereby reducing unemployment and all of the socially unproductive expenditures that go along with it. The second parameter (β) represents a technical labor-to-capital ratio, which tells us how many hands are needed to man a certain piece of equipment. As we see, the amount of labor employed is therefore both a technical and a social issue at the same time. Equation (5) is a standard representation of capital accumulation, where investments (I_t) represent additions to the capital stock and there is also an exogenous rate at which capital is scrapped (δ). Investments are determined in the fashion of classical economists, out of profits from the previous period (P_{t-1}). However, not all profits are used for investments, part (α) of the profits are consumed(6).

$$N_t = (1+n)N_{t-1} \quad (1)$$
$$Y_t = \pi_t L_t \quad (2)$$
$$G_t = tY_t = t\pi_t L_t \quad (3)$$
$$L_t = h_L \beta K_t \quad (4)$$
$$K_t = (1-\delta)K_{t-1} + I_t \quad (5)$$
$$I_t = (1-\alpha)P_{t-1} \quad (6)$$

Research and development in this system is carried out (or at least funded) by the government. A certain part of government funds is allocated to R&D activities (R_t) as shown by (7). The number of researchers employed in each time period (LR_t), depends on the amount of research funds and the exogenously given wage rate (w_R) paid to researchers (equation 9).

$$R_t = rG_t \quad (7)$$
$$LR_t = R_t / w_R \quad (8)$$
$$w_R = \overline{w_R} \quad (9)$$

Let us assume that all workers are employed either as researchers, or in the private sector. Once we know the number of employed researchers and the number of private sector workers, we can get the rate of unemployment (u) as described by(10). Additionally, relation (11) tells us that the wage rate in the private sector (w) is a function of unemployment, since if unemployment is high, the bargaining power of labor is low and vice versa. In more formal terms, the partial derivative of the wage rate with respect to the rate of unemployment is negative, $\partial w/\partial u < 0$. Having the wage rate, we also know the wage bill (wL_t), which allows us to determine the amount of profits. Profits in the time period *t* (P_t) are a residual as we can clearly see from equation (12) after subtracting taxes (which are equal to government spending in our model) and the wage bill from the national income. A part of profits in every period of production will be dedicated to the private consumption of capitalists (CC_t). Equation (14) determines the propensity to consume for owners (α) and it depends on two factors: their habits, norms and preferences $(customs)$ and profit expectations (P_t^e). *Customs* are exogenous and not much can be said about them. Should norms in society change, should conspicuous consumption become more acceptable, then obviously a larger share of profits would go into luxurious consumables instead of into accumulation of capital and vice versa. On the other hand the relation between profit expectations (P_t^e) and the propensity to consume is rather straightforward: as profit expectations increase, the propensity to consume decreases, $\partial\alpha/\partial P_t^e < 0$. Since the propenstiy to consume is the obverse to the propensity to invest, we can imagine that an increase in expected profitability of investments will have a positive effect on the propensity to invest and a corresponding negative effect on the propensity to consume out of profits. In equation (15) we assume simple adaptive expectations (P_t^e) with regards to profits. It is important to note that the endogenous element which determines investment decisions, capital stock formation, employment, and ultimately output is the future profitability of the system. While this was not true for every economic arrangement in history, expected profitability is key when it comes to future investment decisions, so much so that Shaikh (2016, p. 617) has recently argued that there is no supply side, or demand side economics, because the regulator of both supply and demand in capitalism is profitability. This feature distinguishes our model from neoclassical decisions between consumption and saving, both of which are secondary to profitability in our system.

$$u = (N_t - L_t - LR_t)/N_t \quad (10)$$
$$w = w(u) \quad (11)$$
$$P_t = \pi_t L_t - wL_t - G_t; \; (P_t = Y_t - wL_t - T_t = p_{it} - wL_t - G_t) \quad (12)$$
$$CC_t = \alpha P_t \quad (13)$$
$$\alpha = \alpha(customs, P_t^e) \quad (14)$$
$$P_t^e = P_t P_t / P_{t-1} \quad (15)$$

Let us now turn to the determinants of labor productivity (π_t). Unlike with the population growth, the growth rate of labor productivity is endogenous to our theoretical economic system (16). The growth rate of labor productivity (g_π) is determined in a very Smithian fashion (Roncaglia 2005, pp. 127-129) – it is essentially a positive function of the division of labor in society, namely division of labor between researchers and private sector workers (17). Obviously there should be qualitative differences between the effects that researchers have on labor productivity as opposed to normal workers. We can expect basic scientific research to open new technological avenues, the application of which is then perfected by regular workers through processes akin to learning-by-doing, etc. Therefore, if more people do research and work, this will increase the growth rate of labor productivity. Again, in formal terms this implies positive partial derivatives of the labor productivity growth rate with respect to both stocks of labor in the economy, researchers and private sector workers.

$$\pi_t = (1 + g_\pi)\pi_{t-1} \quad (16)$$
$$g_\pi = g_\pi(LR, L) \quad (17)$$

where $\partial g_\pi / \partial LR > 0; \; \partial g_\pi / \partial L > 0$

The state in our model is limited to play just two roles: it invests in R&D and it provides a social service for the unemployed in form of welfare payments. The sum of goods allocated to welfare payments is defined by (18), as simply that part of government expenditures that is not alloted for R&D (rG_t). In reality, parameter *r* would depend on the outcome of political decisions. A single welfare payment then depends on aggregate welfare payments $(welfare_t)$, divided by the number of people that are unemployed at any period in time (U_t), as defined by equation (19).

$$welfare_t = (1 - r)G_t \quad (18)$$
$$welfare\; payment = Welfare_t / U_t \quad (19)$$

Note that as opposed to all other categories in the system, this part of consumption (welfare) has no positive feedback on the labor productivity. There are important implications of this fact, because if the system is incapable of providing enough employment opportunities, this leads to an increase in the share of unproductive consumption. In a scenario with high unemployment the government would, because of political pressure, have to increase the share of government funds intended for welfare, thus decreasing the share of funds allocated to R&D and *ipso facto* also decreasing the long-term growth rate of the system. A possible solution to these problems lies not just in the technology and increased capital accumulation, but also in how labor is divided amongst the laborers (Pasinetti 1993, p. 87; Patnaik 2011, p. 121): if the workday were to decrease, more people would be productively employed and less spending on social benefits would be needed.

4. Resource Exhaustion in a Dynamic Economic System

If we were only interested in the social system, the model in the previous section could already be said to represent a working, albeit somewhat simplified description of a growing economic system. However, our aim is to connect the social dynamics of the economic system with the use of natural resources.

Let us begin with a less realistic example where in order to produce output, the economy only uses one natural resource. Resource exhaustion for every period of production (RE_t) will therefore depend on the volume of economic activity (Y_t) and the efficiency with which this activity is carried out *vis-a-vis* the natural resource in question (μ_t) (equation 20). Again we assume a connection between the resource-to-output ratio (μ) and both stocks of labor, in the private sector and in research. Or to be more precise, we assume that the growth rate of the resource-to-output ratio

(g_μ) is linked to both stocks of labor (equation 22). The more labor of both kinds is employed, the more efficient the use of the natural resource in question ought to become (equation 22), implying that the coefficient μ should decrease (equation 21). While no such assumption is necessary, it seems likely that the private sector would optimize the knowledge which comes from the government sponsored research in a fashion similar to the Internet, which was developed by the state, but whose use was eventually enhanced by private firms and their employees.

$$RE_t = \mu_t Y_t \quad (20)$$

$$\mu_t = (1 - g_\mu)\mu_{t-1} \quad (21)$$

$$g_\mu = g_\mu(L, LR) \quad (22)$$

where $\partial g_\mu/\partial LR > 0$; $\partial g_\mu/\partial L > 0$.

At this point we know how much of the resource in question the economic system uses in a given period of production. If we also knew the natural rate at which this resource is formed, for example, how fast a forest expands by itself, or how fast a fossil fuel is formed, we would be able to assert – by comparing the two rates (the rate of formation and the rate of use) – whether or not the system is sustainable. There are ample empirical reasons to assume that a growing economic system eventually outscales the natural formation rate of any one single resource that it uses. Imagine, for example, that this scarce resource is oil, or some other fossil fuels. Since it takes a very long time for fossil fuels to form, the economic system could only consume a very small amount in order for the consumption to remain sustainable.

It therefore seems unlikely that a growing economic system could ever truly be sustainable with respect to any single resource in question. This is actually a direct consequence of thermodynamics. The first law of thermodynamics states that energy of the universe is constant; therefore even if mechanical work is being done, the *quantity* of energy in the system never changes; only its *quality* does, which is where the second law comes in. It says that the entropy of the universe tends to a maximum; increasing constantly and irrevocably, as energy undergoes a qualitative degradation from free into bound energy (Clausius 1867, p. 365, and Georgescu-Roegen 1971, pp. 5-6). In other words, all human activity entails the use of energy and matter, which also implies irrevocable changes in physical reality that are theoretically captured by the concept of entropy.

If we take the natural rate at which a certain resource forms itself as exogenously given, then the economic system can be said to be sustainable if the rate at which the resource is exhausted is lower, or equal to the exogenously given formation rate. Resource exhaustion, RE, essentially depends on output, itself a function of labor and its productivity, and the resource-to-output ratio, μ. We assume that both the growth rate of labor productivity (which increases the output per capita) and the growth rate of the resource-to-output ratio are functions of the labor stock and the labor stock employed in R&D. Obviously in reality these two rates would be affected by many more factors, but it is not unreasonable to assume this Smithian channel of labor division as having an effect on both rates. The overall rate of resource exhaustion is increased by the increase in productively employed labor and by its own productivity, since both of these will increase output (equation 2) and thus, *ceteris paribus*, the need for natural resources. On the other hand we can assume the partial derivative of the rate of resource exhaustion with respect to g_μ to be negative, $\partial g_{RE}/\partial g_\mu < 0$. This means that, theoretically speaking, we cannot be sure of the overall effect of an increase in both stocks of labor on the overall rate of resource exhaustion, because while the effects on output are positive, there is an opposite efficiency effect taking place via the decrease in the resource-to-output ratio.

In reality, however, civilizations usually prosper not through their ability to use fewer resources, but by finding new technologies that allow them to harvest even more resources. A good example comes from farming. Looking at the numbers for the U.S. in the period from 1910 to 1983 we see that the average corn yield per acre had increased by 346%. During that same period of time the amount of energy per acre had risen more than eightfold, by a whopping 810% (McKibben 2009, p 64). In other words, the trebling of yield required an eightfold increase in the energy use. In this case not only has the resource-to-output ratio not declined over time, it has increased faster than the actual output.

The aforementioned fears of unsustainability can change, if, instead of relying on a single resource, we introduce into the model a medley of different natural inputs. An illustrative historical example in this respect is England on the eve of the industrial revolution. At that time much of its forests had already been cut down because the natural rate of their formation was slower than the rate at which the economy absorbed them. However, once the early industrial economy had successfully shifted to coal, the rate at which forests were exhausted had decreased. Theoretically, it is possible to imagine a scenario where, due to various reasons, an economy makes a complete shift from one natural resource to another, causing the drop of the exhaustion rate of a particular resource to zero or close to zero and thus making a positive net growth rate. In the next section we therefore present an economic system with diverse inputs and outputs, and demonstrate its potential for long-run sustainability.

5. Diversity of Inputs and Outputs and Sustainability of a Growing Economy

At this point we can augment the previous economic system with a more complex and diverse structure both at the level of inputs and outputs. Le us assume that an economic system produces m different commodities, each with its own amount of labor ($L_{t,i}$) and its own, specific productivity ($\pi_{t,i}$). Formally this can be written as:

$$Y_t = \sum_{i=1}^{m} \pi_{t,i} L_{t,i} \quad (23)$$

The number of outputs m, captured by equation (24), grows from one period to another with the growth rate (g_m), which we assume to be endogenous to the system. We assume a positive connection between the growth rate of the number of outputs and the amount of labor employed in R&D activities (25). Namely, shifts in knowledge create new technologies, which are eventually used in the process of production. Of course, some of these new findings enhance productivity in existing sectors, but some of them help facilitate the creation of new sectors and outputs altogether – a qualitative aspect of development, which is often overlooked. Additionally we assume a positive connection between the growth rate of the number of outputs (g_m) and the number of inputs (d) that are available to the economic system. For example, an economy which uses oil, natural gas and various other natural resources, has a higher potential to create more different outputs than one which is more limited in this respect, such as a traditional pre-industrial society. An economic system can only make use of various inputs, if it has the necessary knowledge required to use them, meaning that the amount of inputs and outputs are invariably connected and both depend on accumulation of knowledge. The growth rate of the number of outputs (g_m), which depends on the amount of labor employed in R&D (LR) and the number of inputs (d), is represented by equation (25). Both the increase in the stock of labor employed in R&D and the increase in the number of inputs, positively affect the growth rate of the number of outputs.

$$m_t = (1 + g_m)m_{t-1} \quad (24)$$

$$g_m = g_m(LR, d_{t-1}) \quad (25)$$

where $\partial g_m/\partial LR > 0$; $\partial g_m/\partial d_{t-1} > 0$.

We can add diversity at the level of inputs as well. Equation (26) connects every unit of output (which is now heterogeneous and made up out of m different commodities) with a required amount of a natural resource that has to be used in its production. So in every period of production an economic system will use μ_j times Y of the j-th input to produce all of the outputs in the production of which the j-th input is required. In any given period of production there are d inputs that the economic system makes use of. Similarly as the diversity of outputs we assume that the diversity of inputs grows with economic development which is why the growth rate of d (i.e. g_d) is also endogenous to the system of production (27). The growth rate of inputs (d_t) defined by (28), is a positive function of both the amount of labor in research activities (LR) and the amount of outputs that the system produces (m), with the logic being similar to the one used with outputs: better understanding of physical realities opens up new avenues with respect to the inputs which can be used in the production process. The positive connection between the growth rate of inputs and the number of outputs is therefore straightforward: the more products we produce, the higher is the likelihood that some of them can be used to procure new, different resources.

$$\sum_{j=1}^{d} RE_{j,t} = \sum_{j=1}^{d} \mu_{j,t} Y_t \quad (26)$$
$$d_t = (1 + g_d)d_{t-1} \quad (27)$$
$$g_d = g_d(LR, m_{t-1}) \quad (28)$$
where $\partial g_d/\partial LR > 0; \quad \partial g_d/\partial m_{t-1} > 0$.

An economic system, as already mentioned, cannot be sustainable vis-a-vis all of the inputs it uses, nor is that something that policy makers should try and pursue, because it violates the basic premise of thermodynamics. What is achievable, however, is the pursuit of knowledge in its various forms. Accumulation of knowledge is a self-reinforcing process with positive externalities (Arrow 1962). Here it has to be pointed out that even though we assume a clear division between labor dedicated to knowledge formation (LR) and labor employed in production of goods and services (L), this is by no means central to our argument. While production inevitably requires the use of natural resources in various forms, it is both through the process of production and through the study of natural phenomena, that the amount of different available resources can be expanded. Sometimes these shifts might be negligible, with limited effects on a small amount of industrial sectors, whereas sometimes they might constitute economy-wide paradigmatic shifts (such as the shift to fossil fuels at the beginning of the industrial revolution, for example). As these shifts occur, some resources which were on the verge of exhaustion lose their importance for the production process and their natural rates of growth may actually start to outpace their rates of exhaustion.

An important consequence of this fact is that for an economic system that uses multiple inputs, there can be no aggregate measure, but only the aggregate notion of sustainability. The production system requires certain inputs and each of those has to be considered in isolation; there is no way we can aggregate oil and steel together in any meaningful way and one cannot be a substitute for the other. This is why we cannot use an aggregate measure of sustainability of natural resources. Moreover, sustainability should not be viewed as the capacity of the economic system to produce greater quantities of certain commodities by using less and less inputs. To be sure, resource-to-output ratios ($\mu_{j,t}$) are assumed to decrease through time, but they cannot go down to zero (for the production of the exact same commodity). Instead, sustainability should be viewed as a capacity of the economic system to switch between different inputs and to create new outputs, which will themselves require new inputs. A sustainable economic system will therefore be complex and adaptable, it will foster the technological capacities to switch between different inputs and it will create a wide array of outputs, which will not only enrich the material wellbeing of the society, but also its capacity for long-term survival. Drawing on classical political economy by applying its principles to the issue of sustainable development, our analysis of the complex growing economic system also points to the connection between the distribution of output and the sustainable future growth.

We find that in order to achieve long-term sustainability, it is not always preferable to conserve the inputs by means of dampening economic activity, especially if this leads to an increase in unemployment and to the resulting unproductive expenditures. In growing industrial economies it is not natural resources which constitute the greatest wealth of the economic system, but the knowledge which allows us to utilize those resources. In the final stage it is knowledge which represents the wealth of nations (Pasinetti 1993). And, as we have shown, this is not only true in a static case, but more importantly, it becomes even more relevant in a dynamic case, with a growing economic system. Should the system fail to find new resources, then, unless all the natural resources have a higher rate of formation compared to the rate of exhaustion due to the economic activity, output has to fall. In other words, a growing economic system without the capacity to adapt and to change the composition of its inputs, will necessarily face a fall in output and should this fall be severe, it could even lead to a Malthusian type scenario. The long-term stability of a system therefore requires it to be complex and evolving not merely in the sense of quantity, but more importantly, in the sense of changes in quality. Knowledge, and its companions, complexity and structural change, therefore, represent a hedge against the Malthusian scenarios. Sustainability should therefore be viewed through the lenses of complexity and the ability of an economy to foster this key feature. When we say that available resources are limited, this is only true with respect to the given level of technology – fossil fuels such as coal and oil have been around for as long as humanity, yet only in the past few centuries have we had the required knowledge and social structures that allow us to utilize these sources on a large scale.

Finally, it has been emphasized that relations in the economy, in terms of the division of labor and distribution of incomes (profits, government income), have consequences on its productive capacity and as such also on the interactions of the economic system with the natural world. Investments and capital formation in the system are regulated by profit expectations, which are themselves a function of past profitability. This means that profits effectively determine the expansion of productive capacity. Social norms and customs also play a role, whether or not conspicuous forms of consumption are the norm, or the exception will also determine how much of the profits will actually go back into capital accumulation (thus augmenting employment directly and development indirectly). Cultural factors therefore also partially determine the social structure and the interaction of the economic system with the natural world. In economic theory, taking into account the importance of cultural circumstances has been a typical feature of economic institutionalism (e.g. Gruchy, 1987).

A consequence of this process is that a part of the population is left unemployed. While the unemployed get a part of the national product, their activity, or lack thereof, does not in any way contribute to the productive capacity of the system. While this state of affairs might benefit some economic agents, it constitutes a net loss for the economy as a whole, because its full potential is not realized. The important point to note here is that distribution of income, coupled with social structure and social norms (such as consumption behavior in our model) are shown to have an important impact on the sustainability of modern societies as it is understood in this paper. Furthermore, there is no guarantee that the spontaneous operations of the market economy will bring about the desired distribution if left to their own forces. In fact it is more than likely that the system will strive for maximum profits at the expense of output and employment. What we also find is that inasmuch an economic system wishes to endow its posterity, the biggest gift it can bestow is not a physical stock of natural materials but the capacity to morph those resources into new products, which then allow the society to find and eventually make use of new resources. Long-term sustainability will therefore benefit from economic activity and high levels of employment and not vice versa. Lower levels of economic activity can actually be unsustainable, because they act as a brake on economic development due to their tendency to slow down the process of qualitative change in the production of outputs and the varied use of new inputs.

All the above reasoning is essentially deterministic, implicitly assuming that if a society decides to invest its resources into the creation of new commodities, finding new raw materials and new produced inputs, it will be successful. In reality, however, there is no objective reason why this should always be the case; which effectively means that a society can run out of a crucial resource before it is able to find a substitute for it. Another thing to note is that there is a qualitative difference in new technologies which are based on an existing source of raw materials, or energy, as opposed to technological breakthroughs that increase the capacity of our economies to use new resources. This is why Georgescu-Roegen (1986) makes a clear distinction between improving existing technology – a modern car works on the same principle as the first car ever made, using the same energy source, using the same principles, it just does it more efficiently – and what he calls “Promethean shifts” which produce these great qualitative leaps that allow humanity to make use of new energy sources. These latter shifts, which effectively represent the input side of our model, are much less common and have in the past been random at best. In practice therefore, a precautionary principle (Aldred 2012) towards economic development and the use of important scarce resources, coupled with increased investments in research and development seems to represent the safest route towards a sustainable future.

6. Conclusion

Our augmented model features structural changes, by which the economic system not only grows in size but also in its complexity. Both the number of outputs and the number of inputs increase through time and both of these two trends reinforce one another, since new inputs allow for the creation of new commodities and, in that same vein, new products can potentially be used as tools to gather new resources. The addition of this complex element is essentially the addition of real economic development as a process of qualitative change. It is curious that economic theory has for so long been almost obsessed with economic growth, largely neglecting structural change. However, even in a complex growing system, the issue of sustainability remains, for if a given natural resource has its own growth rate which is lower than the rate at which the economic system depletes its stock, then the economic system is still on an unsustainable growth path, but only with respect to that single input.

There is one crucial difference between a simple and a complex growing system. In the latter case the society can employ different inputs at different points in time, which means that there exists an evolutionary element which is not present in the original one-commodity model. Sustainability on the aggregate level therefore has to be seen as a process of structural change based on constant pursuit of knowledge, which allows for paradigmatic shifts in the use of energy and materials that enable the society to produce ever greater quantities of different commodities. Claiming that a growing economic system can be sustainable with a given stock of resources would essentially violate the laws of thermodynamics. While we can produce sustainable energy, the production capabilities for sustainable electricity generation still require the use of scarce raw materials. But if through the development of knowledge and technology we can find new sources of materials and energy and/or increase the use of renewable energy sources, then the issue of a given and limited current stock becomes less vital. In the context of current growing economic system, sustainable development can only come from acquiring knowledge and transferring it into practical use.

Another point considered in the paper is that the survival and continuation of industrial capitalist economies crucially depends on the dynamics of social relations. Classical political economy is built around the premise that functional distribution of income determines long-run growth prospects of capitalist economies. By applying this same logic and looking at the interactions of the social sphere with the biosphere we find that the same is true when we look at the issue of sustainable growth. The division of income between wages and profits and the use of profits for either consumption or investment, the role of the state in funding research or spending on welfare, all of these decisions based on income distribution have implications for both the social and the natural sphere. Even 'soft' factors like profit expectations, customs and cultural norms can impact the social division of labour that ultimately determines whether or not the economy will be dynamically stable by finding new resources at its disposal or whether it will fail to do so and contract. A society that has to divert huge amounts of resources, for example in the form of 'bread and circuses', to simply maintain social order will have less labour available to focus on the discovery of new technologies and the efficient use of existing ones. Sustainability is therefore far from being just an economic and technological issue, it is a wider social issue, connected with distribution of income, government policies, and social norms and customs.

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