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Modelling sustainability performance to achieve absolute reductions in socio-ecological systems

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Abstract

As the world's natural resources dwindle and critical levels of environmental pollution are approached, sustainability becomes a key issue for governments, organisations and individuals. With the consequences of such an issue in mind, this paper introduces a unifying approach to measure the sustainability performance of socio-economic systems based on the interplay between two key variables: essentiality of consumption and environmental impact. This measure attributes to every system a 'fitness' value i.e. a quantity that reflects its ability to remain resilient/healthy by avoiding ecological, social and economic collapse as it consumes the available resources. This new measure is tested on a system where there is a limited supply of resources and four basic consumption types. The analysis has theoretical implications as well as practical importance as it can help countries, organisations or even individuals, in finding better ways to measure sustainability performance.

Keywords: *Sustainability Management; Sustainability Performance; Modelling; Systems Dynamics; Absolute Reductions*

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1. Introduction

The globalisation of markets has encouraged millions of people to adopt consumption patterns of Western countries (Prahalad and Hart, 2002). However, increasing rates of consumption puts pressure on those same markets, for example, due to the loss of biodiversity, insufficient energy supply and the pollution of natural resources (WRI, 2002). These pressures will be accentuated if consumerist life-styles spread through emerging large-population countries such as China, India, Indonesia and Brazil. The rapid growth of energy consumption in China and India alone is evidence of this trend, making global sustainability a concern for policy makers, business leaders and scientists (IEA, 2010).

Despite advancements in environmental policies, business practices and public awareness, doubt exists over whether the magnitude and velocity of improvements are sufficient. To reduce environmental damage, the Stockholm Resilience Centre (Rockstrom et al, 2009a; Rockstrom et al, 2009b) recommends the adoption of planetary boundaries i.e. limits to consumption that respect the planet's ability to renew itself. The concept of planetary boundaries has been criticised over its use of controversial thresholds and fundamental principles of irreversible damage (Biello, 2009). Among critics, the Breakthrough Institute (Nordhaus, Shellenberger, and Blomqvist, 2012) argues that there is no evidence that the boundaries will lower the impact from human activities. Also, they claim that the setting of boundaries was arbitrary and that a lax boundary may accentuate degradation. Regardless, the planetary boundaries concept has occupied institutions, including the United Nations High-level Panel on Global Sustainability, and could translate to corporate sustainability (Whiteman et al, 2013). Despite controversy, thresholds may become necessary at global and local levels (Biello, 2012), encouraging debate on the planet's carrying capacity, the use of thresholds (Martinet, 2011), cap-and-trade systems (MacKenzie and Ohndorf, 2012) and individual quotas for firms (Holland and Schnier, 2006; Péreau et al, 2012).

The debate between these views is based on models of sustainability performance, which consider scenarios with homogenous 'baskets of consumption' where all items are essential. This simplification may sometimes be useful but needs refinement to increase its applicability, for example, to classify goods/services using two dimensions of sustainability: (i) their essentiality and (ii) environmental impact. Each basket of consumption can represent a group of goods/services having similar levels of essentiality and environmental impact. Their consumption is influenced by national policies, resource availability, price, market dynamics and other systemic forces.

We embed essentiality in a model of the 'general health' of a system which we call the *system fitness.* In ecology and other scientific areas (Richter and Engelbrecht, 2014), fitness is defined as the ability of the system to thrive in its environment. We define system fitness as a measure of how far a system is from collapse by requiring a balance between the satisfaction of essential needs and the environmental impact created by meeting these needs. In this paper we build a simplified model to explore how essentiality and environmental impact affect sustainability performance measurements and sustainability strategies.

The paper starts by reviewing concepts of sustainable development and models of sustainability performance measurement. It then introduces concepts relevant to our model, describes its methodology and explains how sustainability performance is measured. The illustration of the model follows, and conclusions complete the paper.

2. Sustainability and its management

Despite debates about our planet's sustainability, several issues remain unexplored. The concept of sustainable development is difficult to translate into practice for countries, cities, companies and even personal life-styles (Barber, 2007). This difficulty relates to the complexity and uncertainty in the design, implementation and assessment of environmental strategies and sustainability performance indices (Bossel, 1999; Boyko et al, 2012; Gasparatos et al, 2009).

Consider the often-quoted concept of sustainable development by the World Commission on Environment and Development:

> "Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987 p8).

Usually overlooked are the paragraphs that follow this quote adding the aspirational needs of humans:

> "The satisfaction of human needs and aspirations is the major objective of development. The essential needs of vast numbers of people in developing countries for food, clothing, shelter, jobs - are not being met, and beyond their basic needs these people have legitimate aspirations for an improved quality of life. A world in which poverty and inequity are endemic will always be prone to ecological and other crises. Sustainable development requires meeting the basic needs of all and extending to all the opportunity to satisfy their aspirations for a better life." (WCED, 1987 p43-44)

Philosophically, sustainable development implies limits although "not absolute limits, but those imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities" (WCED, 1987 p8). While the concept of need is discussed, how to measure sustainability in different contexts, considering their unequal stages of development, is unclear. Despite the breadth of the concept, two variables can be extracted: essentiality (representing the needs of human beings) and environmental impact (representing consumption of resources). The latter should be minimised to ensure that future generations have access to natural resources (i.e. avoiding an ecological crisis), without neglecting the former, a complex task discussed later.

The difficulty lies in defining an encompassing measure of sustainability performance, which is suggested by the so-called triple bottom line indicators: economic, social, and environmental (Elkington, 1998). These dimensions have been represented graphically as pillars, overlapping ellipses, and circular flows (Cato, 2009), see Figure 1. However, these do not represent reality and conflict with the concept of environment stated in the ISO 14004 Environmental Management Systems Guidelines (2002):

> “Environment is the surroundings in which an organization operates, including air, water, land, natural resources, flora, fauna, humans, and their interrelation” (ISO 14004)

A better representation is depicts the dimensions as connected inner, outer, and far outer spheres showingthe economy as integral to society, and both are within the environment (Hutchinson et al, 2002; Cato, 2009; Nunes and Bennett, 2010). This schema reinforces the need to define appropriate boundaries of an ecological system when measuring its sustainability performance (Ostrom, 2009).

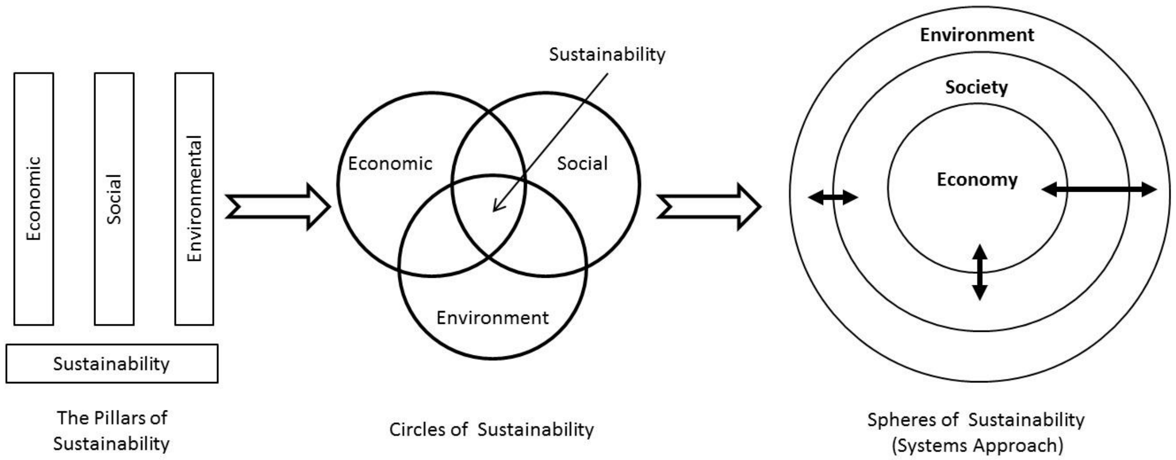

Figure 1 - The evolution of sustainability schema.

The concept of ‘ecological boundaries’ is not new. Concerns of being unable to balance demand and supply lie in the philosophical underpinnings established by Malthus (1789). The use of environmental limitations for socio-economic activities is considered in a more complex assessment done by Meadows (1972). King (1995) suggested that environmental conditions should be constantly monitored to avoid ecological surprises (i.e. sudden changes that encourage the environmental collapse). ‘Planetary boundaries’ extends in this direction.

The literature on sustainable development and sustainability management indicates the need to manage and measure sustainability performance by identifying system characteristics e.g. its boundary and resource availability (Enfors, 2013) followed by the assessment of interventions to promote higher levels of resilience. Next we discuss the measurement of sustainability performance.

3. Measuring Sustainability Performance

The importance of identifying thresholds within socio-ecological systems is vital to reduce their vulnerability to socio-economic and ecological crises (Young, 2010). Prior to the planetary boundaries approach, Meadows et al (1972), Wackernagel and Rees (1998), and

Meadows et al (2004) used similar methods to assess the carrying capacity of our planet and tipping points. Such studies sought to understand the complexity of societal, economic and ecological systems through Forrester's concept of system dynamics at industrial, urban, and world scales (Forrester, 1961, 1969, 1971).

At the country level, despite the use of gross domestic product (GDP) and the Human Development Index (HDI) in national policies, these "are failing to capture the full wealth of a country" (UNU-IHDP and UNEP, 2012 p.xi). The Inclusive Wealth Report (UNU-IHDP and UNEP, 2012) includes more realistic measures of wealth using three macro-indicators: natural capital (e.g. forests), human capital (e.g. level of education) and produced capital (e.g. roads).

At the corporate level, there is difficulty in measuring sustainability performance that is aligned to the natural environment's sustainable development (Hart, 1995; Hart, 1997). For example, most studies focus on absolute and relative amounts of emissions, waste and consumption (Hahn et al, 2008). However, socio-economic indicators often neglect the value of products and processes to meet society's needs (Caeiro et al, 2012), perhaps as the social dimension is difficult to assess (Hahn and Kühnen, 2013). Corporate sustainability performance indices do little to define clear corporate roles for sustainable development. Recent Dow Jones Sustainability Indices (DJSI, 2012) address these issues (López et al, 2007) by assessing ethical dimensions. By ignoring time and space dimensions, the value of these indices are reduced.

Unsurprisingly most sustainability indices are not adapted to the level of individual life-styles (Lorek and Spangenberg, 2001; Caeiro et al, 2012). Sustainable life-styles are advertised as those that consume as little as possible or as mindful consumption (Sheth et al, 2011), or rational/reasonable consumption (Kronenberg, 2007).But these definitions fail to consider the importance of socio-economic factors and location-specific issues (Tukker et al, 2008).

To address these gaps we introduce a system fitness index based on two aspects of sustainable development: environmental impact and essentiality. In the next section we present these followed by the review of our model.

4. Essentiality

Natural sciences use the concepts of essentiality, criticality and scarcity when defining essential elements of a system as non-substitutable Scholz and Wellmer (2013) .

However, within social systems the concept of essentiality has not been developed. We use the notion of 'need' to model essentiality as a variable vital to the achievement of sustainable development. This is aligned with 'Hierarchy of Needs' (Maslow, 1943) and scales to understand human (Max-Neef et al, 1992) and non-human needs (Jolibert et al, 2011)..

We define essentiality as a measure of how the consumption of resources meets a system's needs. In societal terms, essentiality is a value given to a unit of consumption relative to its ability to meet a societal need. It can be measured either as the need of an individual, a population or a sub-system (e.g. communities). Through essentiality we conceptualise how available resources can sustain survival.

Maslow's hierarchy proposes that survival depends upon physiological, safety and social needs, while psychological survival relies on esteem and self-actualization needs. While the consumption of resources for physiological and safety needs are the same for all humans, resources to meet social and psychological needs might vary across cultures, time and geographic regions. Max-Neef's Human Scale Development (HsD) methodology classifies the fundamental universal needs (e.g. protection, affection) and the means or satisfiers (e.g. food, shelter). The method and choices of satisfying a need will impact on the use of resources.

Maslow's hierarchy and Max-Neef's HsD provide a starting point to discuss the essentiality of economic and social activities. We can link how consumption and production systems are aligned to a population's needs when considering their essentiality levels. The essentiality of each socio-economic activity should be carefully defined. For example, although the food industry is linked to physiological needs, not all products meet nutritional requirements. Being a subjective concept, a product's essentiality value depends on cultural aspects and location-specific factors such as climate and infra-structure (Tukker et al, 2008). Because most consumer choices are personal, a 'standard' essentiality value can be applied to a basket of consumption rather than discretionary values being assigned to individual products within that basket.

It is pertinent to mention that we adopt a broader definition of 'goods and services'. While psychological needs like 'sense of belonging' cannot be bought, a first approximation can be included in our model as a product with high essentiality and low impact.

Essentiality is a new concept in the literature and can be assessed objectively and subjectively. While some physiological needs are objective (e.g. water, food), most social and esteem needs (or aspirations) are subjective. This reflects that the essentiality of products change over time e.g. as public transport improves, car ownership may fall. In our model, we consider a binary position (1=essential; 0=superfluous) to classify essentiality of consumption – see Table 1. However, the model can use discretionary values and identify a ‘gravity centre’ for each basket.

5. The importance of Environmental Limits

At a macro-level, the Impact of Population, Affluence and Technology (IPTA equation) $\left(I = P \times \frac{A}{T}\right)$ is popular. Another tool is the *ecological footprint* methodology (Wackernagel and Rees, 1998) which focuses on land use but incorporates carbon emissions and water consumption. These tools analyse environmental limits i.e. the maximum allowed consumption before irreversible damage.

At a corporate level, environmental impact assessments are considered in ISO14000 standards. However, corporate adoption of environmental limits is only considered in legislation or voluntary environmental goals.Key definitions from ISO 14004 include:

- “Environmental aspects: element of an organization’s activities, products or services that can interact with the environment” p2
- “Environmental impact: any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization’s activities, products or services” p2

For organisations, anthropogenic impacts result from environmental aspects, and both define environmental limits. However, from environmental and sustainability management literature, often only environmental aspects (e.g. emissions, water consumption) are assessed when measuring sustainability performance (e.g. emissions per product). Without a full analysis of the impacts these sustainability performance indexes do not respect the physical boundaries where consumption happens. We believe this is a consequence of the lack of environmental limits to sustainability performance indices. Evidence of this gap in the literature is verified by how rarely resource availability is included in studies of performance measurement and life-cycle analysis. The Leopold Matrix (Leopold et al, 1971) and Life-Cycle Analysis are environmental impact assessment methods that can be instrumental in visualising sources of environmental degradation. But they can be overly complicated to use, requiring extensive analysis of complex information (Orsato and Wells, 2007).

There is a practical and theoretical gap concerning how to measure the sustainability performance of systems. Next, we present a methodology to address this problem.

6. Methodology

This paper uses a toy model to address the problems of conceptualising, measuring and analysing the sustainability performance of systems. A toy model describes the technique of constructing a simplified mathematical model as a first step in understanding a complex phenomenon. Toy models are typical in physics and chemistry but only recently been appreciated in humanities. Successful toy models to analyse systems that affect society include Watson and Lovelock's Daisyworld (1983), von Neumann and Morgenstern's Game Theory (von Neumann and Morgenstern, 1944) and Lotka-Volterra's prey-predator model (Berryman, 1992).

The toy model simplifies assumptions by considering only the most relevant variables in a model's formulation. Simplicity is seen in recent models for analysing the effect of trade on biodiversity (Polasky et al, 2004) and measuring value in ecosystem services (Tilman et al, 2005). In fact, there have been recent calls to reduce complexity of the models for social-ecological systems (Sekulova et al, 2013), suggesting toy models are appropriate here.

A toy model seeks to identify the fundamental mechanisms and relationships that would otherwise be blurred by considering too many details. The design of a toy model relies on (1) defining a system's boundaries (2) identifying relevant variables of the phenomenon and their behaviour, (3) modelling the relationship between variables and their dynamics, (4) checking which variables or relationships can be ignored without affecting the system characteristics, and (5) assessment of the model validity and future modifications. This procedure is applied iteratively until the simplest model of the important features is obtained. Once the model is analysed, more features can be added systematically to consider increasingly complex effects (see Figure 2).

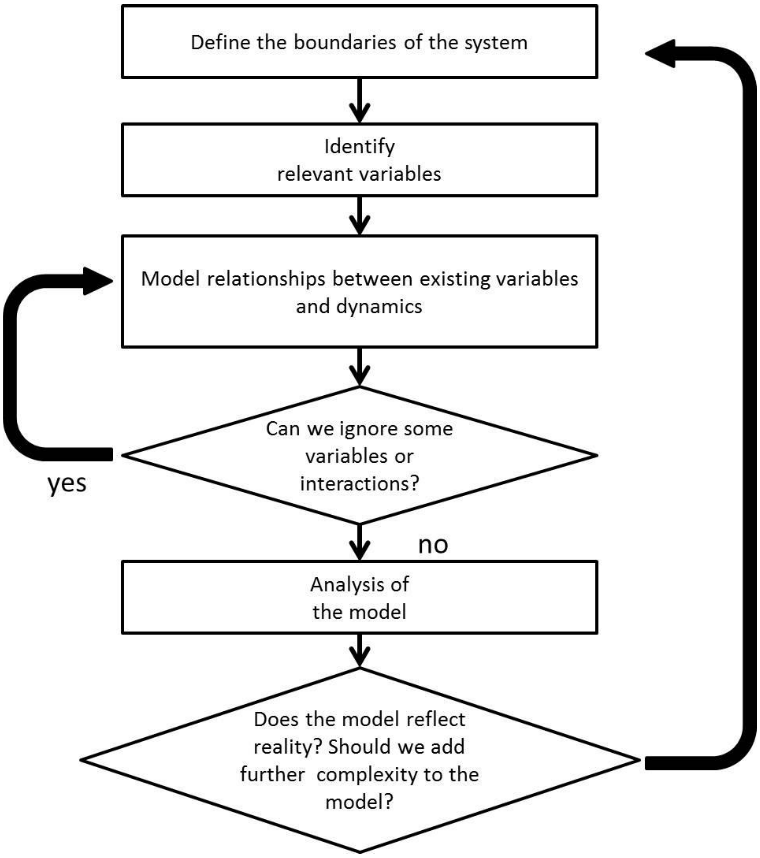

Figure 2 - Procedure to develop a ***toy model****.*

Our model offers a unifying equation to measure sustainability via various levels of macro variables of a societal system. The differences between the needs of each level (global, regional, local, individual) can be simplified to: the balance between satisfaction of needs/aspirations; the respect of environmental limits. For example, at an individual level the food needs/aspirations are balanced with a hypothetical limit of consumption. The internal essentiality limits set the balance on how food meets nutritious needs and the differences between needs and wants. Some health limits (such as cholesterol) indicate how well the individual is over or under consuming resources to meet his/her needs. The same applies to an organisation which has corporate needs (e.g. profit) but operates within limits for consumption and pollution. At the city, country, and global levels our model is intuitive as every region's consumption has constraints for resources.

Our model simplifies complexity by reducing the system to one resource versus one consumption limit for four types of consumption baskets, with no possibility of import-export or stock resources. Thus, we focus on the relationship between satisfaction of needs, consumption and resource availability (See Figure 3).

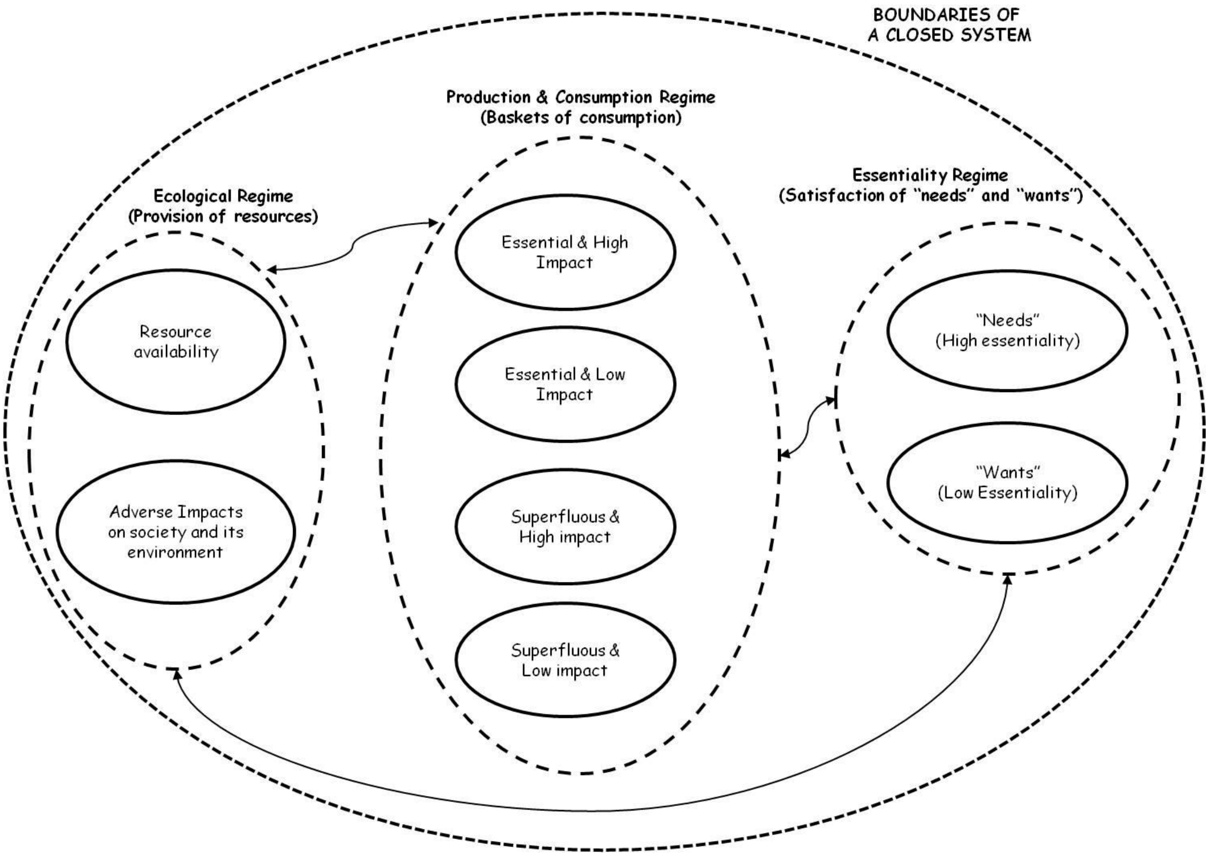

Figure 3 – The link between resources availability, consumption of resources, and satisfaction of "needs" and "wants".

If the system lacks fairness in distribution it should appear in the essentiality balance score because, once a significant population does not have its needs or aspirations satisfied, the essentiality of the system falls. Falling below the minimum limit set in the model negatively affects the essentiality balance leading to lower fitness levels.

7. Modelling Sustainability of a System

Our objective is to model the evolution of a system (a continent, country, company, or individual) within a set of constraints. Our model considers that quantities vary according to time (t) which changes in discrete steps, with the time unit depending on context. For simplicity, in formulae we sometimes omit a reference to time e.g. we use $x(t)$ interchangeably with x, but the variable is considered at each time step t.

For every system a variable tracks the available resources at each time t, denoted by $R(t)$. The quantity R is an overall measure of the available raw materials and the environmental resources required; for instance, clean water. The units of R depend on the context (e.g. level of energy consumption).

The environmental impact of our system at time *t*, corresponding to the amount of resources being consumed, is symbolised by the letter *I* and, for consistency, this is measured in the same units as *R*. The dimensionless quantity $I_r = I/R$, called the *relative impact*, measures the fraction of resources being used at each time step. I_r is continuous, the minimum value of which (zero) is attained if no resources are being consumed. If $I_r > 1$, then $I > R$ and more resources are being consumed than are available.

The *system surplus*, representing the amount of resource which was *not used* at each time step, is *S=R-I* and we call the *relative surplus* $S_r = S/R = 1 - I_r$ at time *t*. Note that 'surplus' here is not related to a production surplus, but to a surplus of natural resources used by the system. Depending on the resources, the surplus can be stored or accumulated at the next time step (e.g. for fossil fuel) or simply lost (e.g. for water flowing along a river). Therefore, when $S_r = 1$, no resources are being consumed but, if $S_r = 0$, all available resources are being consumed.

One difference between our model and others (e.g. Watson and Lovelock, 1983; Meadows et al, 1972; Wackernagel and Rees; 1998; Meadows et al, 2004) is that they are based on homogeneous baskets of consumption and on the environmental impact *I,* i.e. they only consider the surplus S_r. Critically, they ignore the needs/aspirations of humans. To assess the health of the system, we measure essentiality of the units of consumption.

We model essentiality values as numbers from zero to one according to how consumption is linked to levels of need. Essential consumption (mostly linked to physiological, safety and social needs) is assigned a value of one for each unit consumed. Superfluous consumption (mostly linked only to esteem and self-actualization needs) is assigned a value of zero for each unit consumed.

Essentiality becomes meaningful when considered against other social and economic factors, according to which levels of essentiality are acceptable. To incorporate this degree of freedom, *essentiality balance B* is a dimensionless variable with the interval [0,1]. The definition of *B* (clarified later) is a band inside which essentiality can vary while still allowing for optimal health of the system (see Figure 5). The choice of essentiality balance is due to the health of a system being compromised when essentiality approaches extremes. If the system only includes essential products there is no room for non-essential activities like leisure or arts. Thus, society is under continuous survival stress without capacity to cope with unexpected events. Alternatively, a society where most products are non-essential indicates a systemic waste of resources e.g. over consumption of food with little nutritional value.

As essentiality is a sustainability dimension as important as environmental impact, a more realistic modelling of consumption baskets should use these two dimensions and not simply rank them by their environmental impact. Essentiality and environmental impact are continuous measures, but to maintain simplicity in our toy model, we initially separate consumption baskets into four categories (see Figure 4): (1) Low Impact/High Essentiality (the Peasant's), (2) High Impact/High Essentiality (the Knight's), (3) High Impact/Low Essentiality (the Noble's), and (4) Low Impact/Low Essentiality (the Jester's).

The Peasant's basket represents products that have low environmental impact and high essentiality e.g. highly-nutritious food (to maintain biological functions), health services (to monitor, prevent and correct biological functions), and education services (to develop basic cognitive and social skills). The Knight's basket represents products that have high environmental impact and high essentiality e.g. transport (to provide essential mobility), computers (to enhance learning and productivity), and medical operations (to increase longevity). The Jester's basket represents products that have low environmental impact and low essentiality e.g. self-indulgent foods and extra units (for status/fashion purposes) of essential products like clothes. Finally, the Noble's basket represents products that have high environmental impact and low essentiality e.g. luxury products (such as first-class flights) and harmful products (such as illicit drugs). Each basket can be attributed a value of essentiality and environmental impact based on the average of its products.

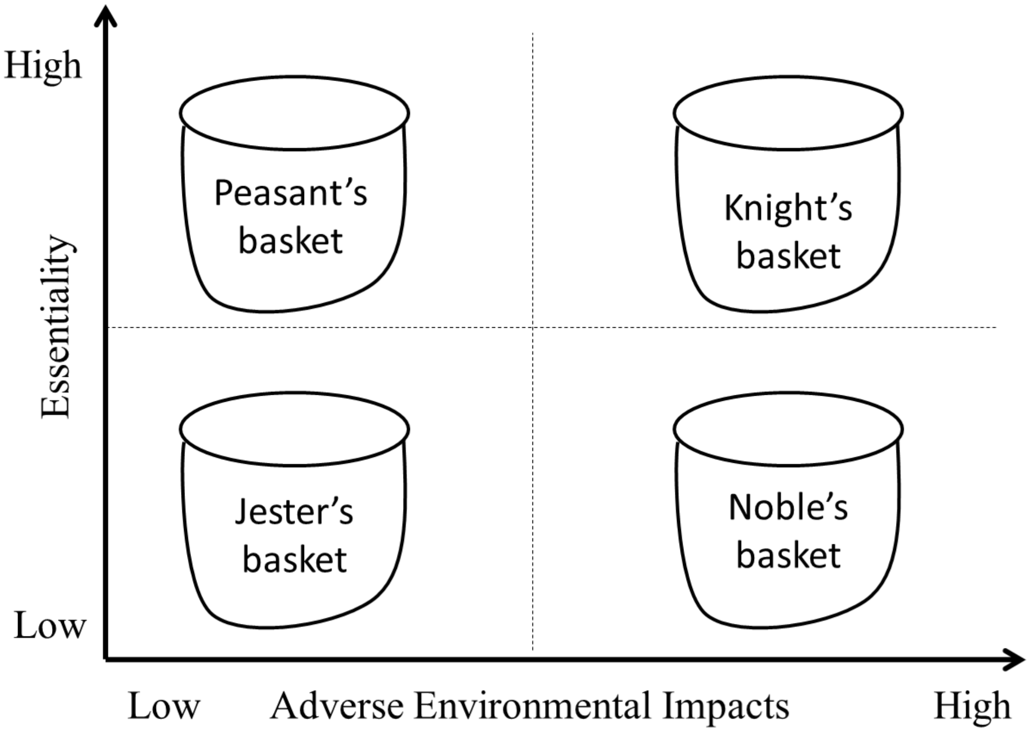

Figure 4 - Four basic consumption baskets

The division between these four baskets is subjective, allowing for choice in classifying particular systems, product, technological and socio-economic context. The above matrix enables a classification of discrete units of consumption (Lorek and Spangenberg, 2001; 2014) such as housing, food, transport, consumer goods, clothing, education, communication, hygiene, health care, recreation, and social life. Then, a quantitative assessment involves defining the essentiality values based on the average essentiality value of products in the basket.

The concepts presented above measure sustainability, through *system fitness F*. Being a quantitative measure, its characterisation requires a mathematical description to calculate environmental impact and essentiality balance. This is done in the next two sections, after which the concept of *system fitness* is described through a unifying formula.

7.1 Essentiality Balance

We introduce the essentiality measurement by attributing to each different consumption basket *i* the same average value of essentiality for all its products. This will be a continuous variable in the unit interval, namely $E_i \in [0,1]$. A zero value indicates that products do not contribute to fulfilling basic needs (analogous to Maslow's ideas), while a value of '1' indicates that products are essential at its optimal consumption rate.

A measure of how essentiality is satisfied will, like environmental impact, consider the amount of products in the system from each basket. However, we need a collective measure inside the unit interval to keep the interpretation attached to it. To achieve this normalisation, we define the relative contribution of each basket to the system by the following weights:

$$w_i = \frac{c_i}{C},$$

where $C = \sum_i c_i$ is the total amount of products in the whole system. The weights are the percentage of each basket with respect to the total amount of products. Then, we define *essentiality E* as the weighted average of the baskets' essentiality:

$$E = \sum_{i=1}^{4} w_i E_i.$$

As already argued, although *E* can measure how the essential needs of the system are being met, the health of the system will depend on the correct balance of basic needs, the ones essential to physical survival and aspirations, which are not physiologically necessary but are important for its well-being. This is measured by *essentiality balance B*.

We define upper and lower limits for *E*, respectively as E_{max} and E_{min}, which delineate the acceptable band for the essentiality. The *essentiality balance* $B \in [0,1]$ is a function of *E* which takes the value 1 inside that band and less than 1 outside of it. The quantification of *B* outside the acceptable band requires careful study. The requirements outside the acceptable band are that, at the extremes of essentiality, *B* should tend to zero indicating proximity to collapse. This reflects that when $E = 1$ only basic needs are being satisfied and the system is prone to collapse. When $E = 0$ only superfluous products are being consumed, indicating a waste of capacity. Both extremes reflect dysfunction.

For our toy model, we assume the simplest shape outside the acceptable band, which is given by a linear falloff described by the formula

$$B(E) = \begin{cases} \dfrac{E}{E_{min}}, & 0 \leq E \leq E_{min}, \\ \dfrac{E-1}{E_{max}-1}, & E_{max} \leq E \leq 1. \end{cases}$$

Figure 5 shows a graphical representation of our choice for the essentiality balance function. Here, the values of $\mathrm{E_{max}}$ and $\mathrm{E_{min}}$ depend on spatial and temporal features of the system like historical and cultural contexts.

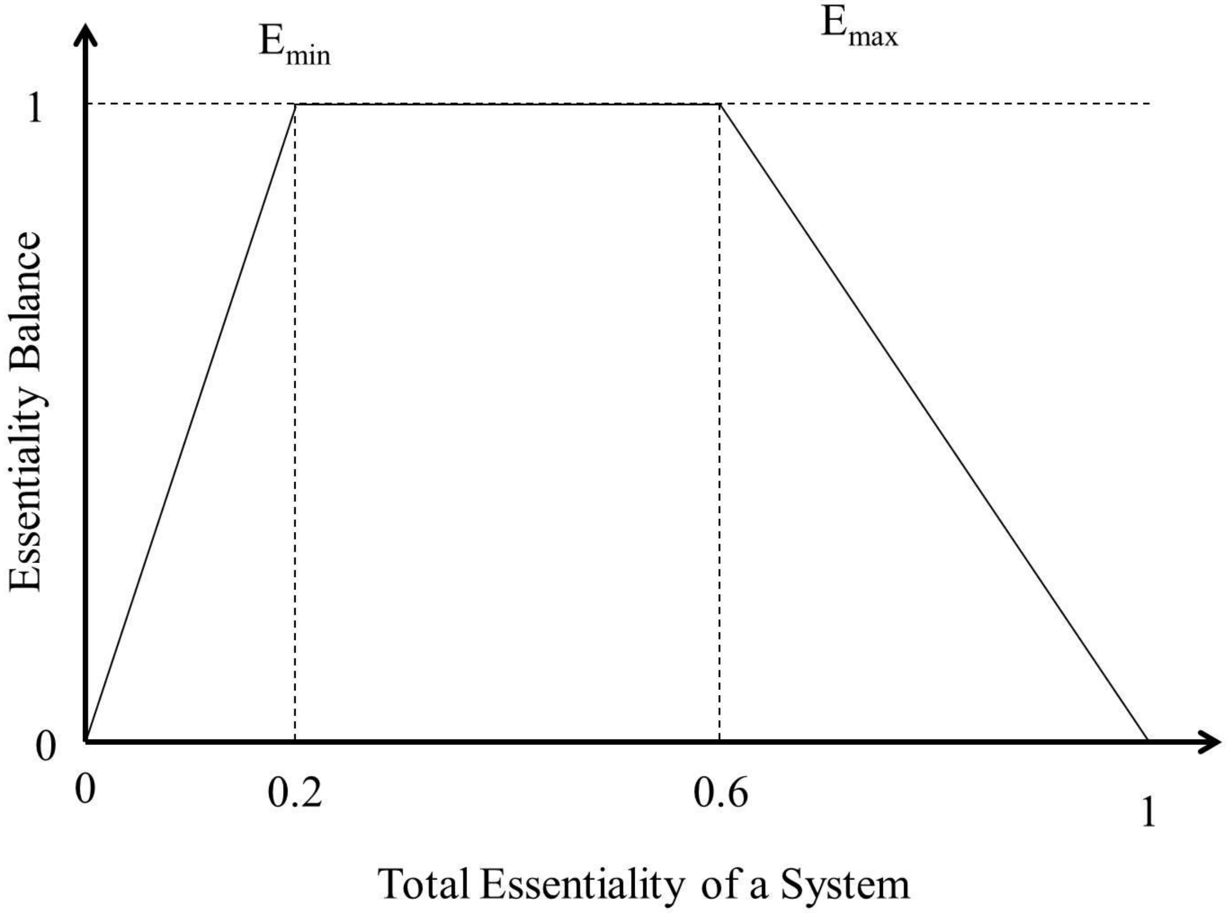

Figure 5 - Essentiality balance B as a function of the bare system essentiality E with acceptable band limits E_{min}=0.2 and E_{max}=0.6.

7.2 Environmental Impact

We now define the *environmental impact I* as a real number larger than zero. Negative values *could* be accommodated if the system is contributing to an increase of the natural resources at each time step. However, this is an unusual situation not analysed here.

Clearly, each unit of consumption in a system has a unique environmental impact. We simplify this by attributing a single average value of impact for all products in the same basket and symbolise these new variables by I_i, such that the index $i = 1, \dots, 4$ refers to each of the four categories described previously (Peasant's, Knight's, Noble's, and Jester's). The variable I_i is a measure of the environmental impact of each *individual unit of production/consumption* of an item in basket *i*. As already stressed, attributing the same average value of impact for all products in a basket is a simplification that can be refined according to the requirements of the problem being analysed.

We now define the quantity c_i, the number of units of products from basket *i*. The *collective impact* of basket *i* on the environment is given by the product $c_i I_i$ and, by adding the collective impact of all four consumption baskets, we develop our definition of *environmental impact* through the formula:

$$I = \sum_{i=1}^{4} c_i I_i.$$

An issue to clarify is how c_i is related to the population of the system e.g. country. As a measure of consumed items, c_i is the total amount of products *i* consumed by the population. For instance, if the size of the population is *N* and each individual consumes the same amount n_i of products in the basket *i*, then $c_i = N n_i$. A complication appears if different classes of individuals consume different amounts of products from each basket. This is a refinement which is easy to accommodate in our framework, but is not analysed here.

This completes the modelling of the quantities required to define the dynamic *system fitness F*, which we do next. The model's significance is apparent when analysing system dynamics – the characterization of which is addressed next.

7.3 System Fitness

We now introduce our central concept, *system fitness F,* alongside the mathematical modelling of essentiality. Being a function of essentiality and environmental impact, system fitness measures the general health of a system i.e. its sustainability level. The objective is to simultaneously measure how well a system is performing environmentally and with respect to how the economy and society are benefitting from its activities, addressing calls for research from Enfors (2013) and Engle (2011). This is done using our unifying formula of sustainability performance measurement, shown in Figure 6. The translation of sustainability into a single index helps the debate of resilience of socio-ecological systems (Enfors, 2013; Fisher et al, 2013) and the interventions needed to enhance its adaptive capacity (Engle, 2011) .

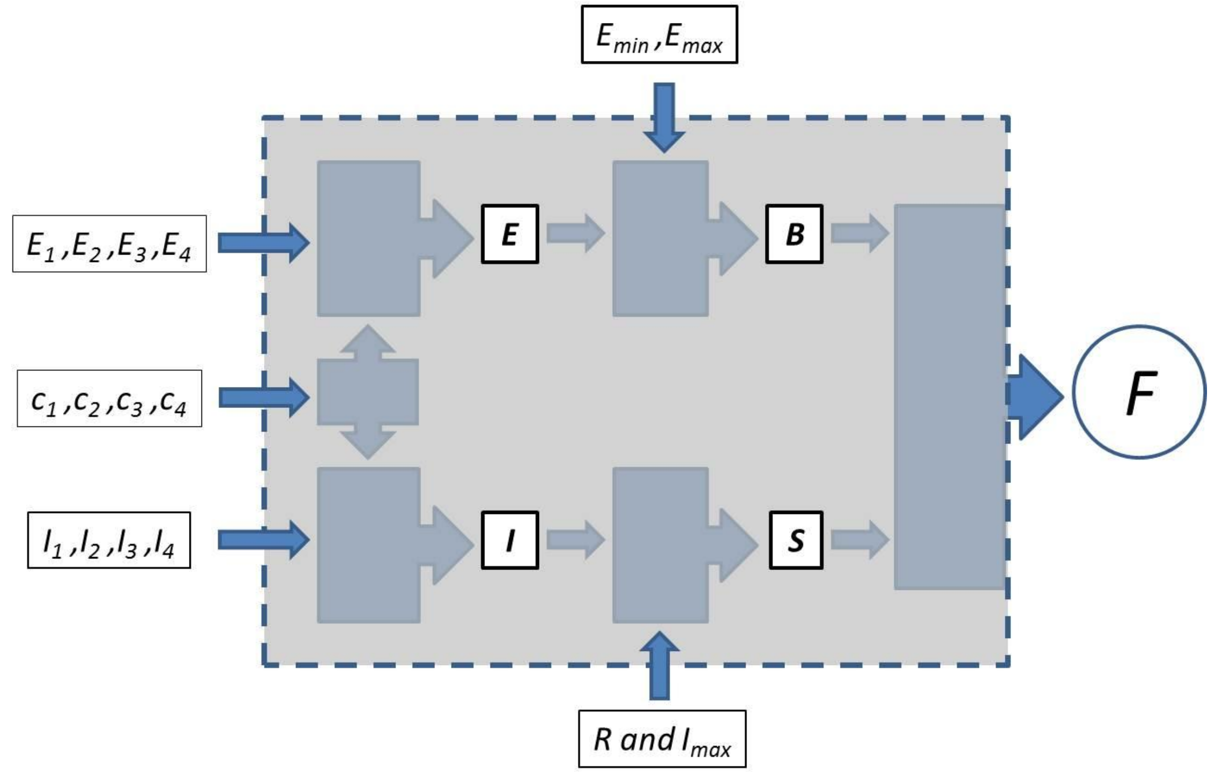

Figure 6 – Graphic representation of our model.

In Figure 6, the boxes on the left, bottom, and top show the inputs required by the model. On the left, the values of essentiality and impact are given for each basket as well as their absolute consumption. ‘R’ and ‘I_{max}’ appear at the bottom. ‘R’ represents the amount of resources given to the system at each time *t*, and ‘I_{max}’ is the environmental limit allowed in the system. On the top, ‘E_{min}’ and ‘E_{max}’ represent the limits of essentiality for the system. The model itself is enclosed by dotted lines. The boxes inside represent windows into the model containing partial outputs. The circle on the right is the final output, ***system fitness*** F.

Traditional measures of sustainability tend to consider the arithmetic mean between economic, social, and environmental performance. However, this fails to provide information about a crucial question: is the system close to collapse? Consider, for example, what would happen if we adopted this procedure using the measures of our model, relative surplus and essentiality balance. This would be equivalent to defining an index of sustainability by adding $S_r + B$. However, we could have environmental collapse with $S_r = 0$ which would be hidden by a high value of *B*, resulting in a misleading assessment – a conclusion shared by Becker (2004). The solution is to multiply (not add) the quantities – proposed by Ebert and Welsch (2004). This is equivalent to taking the geometric mean instead of arithmetic mean (see Figure 7). More precisely, we define the *system fitness F* as our unifying sustainability performance formula:

$$F = \sqrt{S_r B}\,\Theta(S_r),$$

where $\Theta(x)$ is the so-called Heaviside step function defined as $\Theta(x) = 1$ if $x > 0$ and zero otherwise.

To highlight the advantages of the geometric average when compared with the arithmetic mean of surplus and balance, we note that fitness becomes a simple continuous number in the interval [0,1], with clear upper and lower bounds. If $F = 0$ or is close to it, this suggest imminent environmental ($S_r \leq 0$) or social collapse ($B = 0$). The other extreme of the interval automatically defines a benchmark given by the upper bound $F = 1$, which indicates the maximum possible health of a system (a utopian system where its needs are perfectly balanced). Any deviation will give a number less than one, the geometric average of the variables S_r and B, which measures a trade-off between these two quantities.

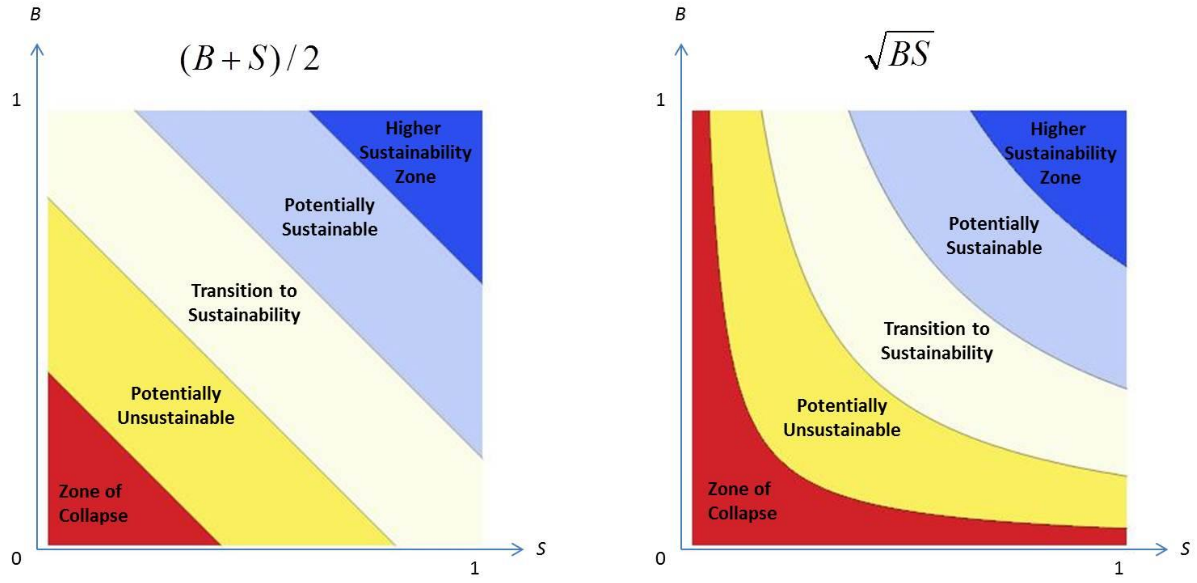

Figure 7 - Difference between arithmetic mean (left) and geometric mean (right) on system fitness F.

8. Illustration of System Fitness

Sueland is a fictitious economic entity (e.g. a region) similar to those in developed countries. It has a stable supply of renewable resources, a fixed population, and everyone has already met their basic needs. Our goal with modelling Sueland is to link the use of resources and well-being in a dynamic socio-ecological system.

Following the toy model methodology, we simplify by assuming that Sueland has 100 citizens and must control the consumption of only one resource (e.g. water). Despite the model's ability to accommodate more complex features, we model Sueland as a closed system to bring clarity to our sustainability management modelling i.e. it cannot exchange resources, products and people with outer systems.

The consumption of resources in Sueland is measured in dimensionless units of consumption based on the four basic baskets. One resident can consume different quantities of resources from each basket. Given the societal values and technological sophistication in Sueland, consumption of essential products (from Peasant's and Knight's baskets) grows at the rate of 2% annually; while that of superfluous products (from Jester's and Noble's baskets) grows at the rate of 6% annually.

Initial consumption settings are presented in Table I:

Table I. Initial consumption settings for Sueland

	Units of consumption	Growth Rate	Individual Essentiality value	Individual Impact
Peasant's basket	100	0.02	1	0.5
Knight's basket	80	0.02	1	2.5
Noble's basket	50	0.06	0	2.5
Jester's basket	100	0.06	0	0.5

In Year One the total impact of resources in Sueland is 425 consumption units [Peasant's (100*0.5) + Knight's (80*2.5) + Noble's (50*2.5) + Jester's (100*0.5) = 425]. We set the environmental system to supply a constant amount of 1300 units of resources per year to Sueland. For the current model, we opt for a non-cumulative resource i.e. whatever is unused in one year cannot be stored for the following one. Eventually, the baskets of consumption will naturally expand until overall consumption reaches supply, leading Sueland to an environmental collapse from a laissez-faire policy. Thus, we tested different policies to maintain Sueland's health and fitness i.e. a condition in which essentiality levels are acceptable and environmental impact (resource consumption) neither disturbs the system's stability nor leads to collapse.

8.1 Modelling Sustainability Performance of Sueland

Figure 8 shows the information needed to model the sustainability of Sueland. By running the model we assess the system fitness at time *t* and decide to encourage or impede consumption of resources from each basket. The constraints in Sueland are set such that the system's overall essentiality level should not fall below 0.4 and the maximum impact should not be above 70% of the total resources provided to the system yearly. By limiting the impact to a 70% maximum, we emulate the precautionary principle (Janssen et al, 2004) in our sustainability strategy.

The decision delay was set to zero for simplicity so a decision is taken and implemented at the beginning of each year. The system is considered over a time span of 300 years. Interventions were set as follows:

a) If the system's essentiality level falls below 0.4 (or rises above 0.7), then consumption of products from the Jester's and Noble's baskets are reduced by 10%.

b) If the relative surplus falls below 30% (i.e. I_{max} is above 70% of total resources), consumption of the heaviest basket will be reduced by 10%. The second heaviest basket will be reduced by 5%, and the third and fourth will be reduced by 4% and 1%, respectively.

These interventions represent a combination of factors (e.g. market, governance, technology, cultural change, etc) that impact positively or negatively on the consumption of products (Vergragt et al 2014;) in each basket as part of the natural feedback loops (Robards et al, 2011) within socio-ecological systems as well as population's social learning and social memories (Folke, 2006). Learning is essential in managing transition processes within human activities (Nevens et al, 2013). The non-linear dynamics result from established growth rates, thresholds and interventions as stated above. The level of intervention from each factor will depend the influence of critical aspects in the system (e.g. as in Bossel's (1999) orientor theory).

As will be seen, item ***a*** is an essentiality-based intervention and ***b*** is an impact-based intervention. If at a specific time *t*, the system is below the minimum essentiality and surplus levels, both policies act simultaneously. The approach based on the absolute 'weight' of the basket, described in ***b***, intends to push decision makers to consider absolute limits of low-impact consumption. It allows rethinking and learning to decide what is essential and what is superfluous.

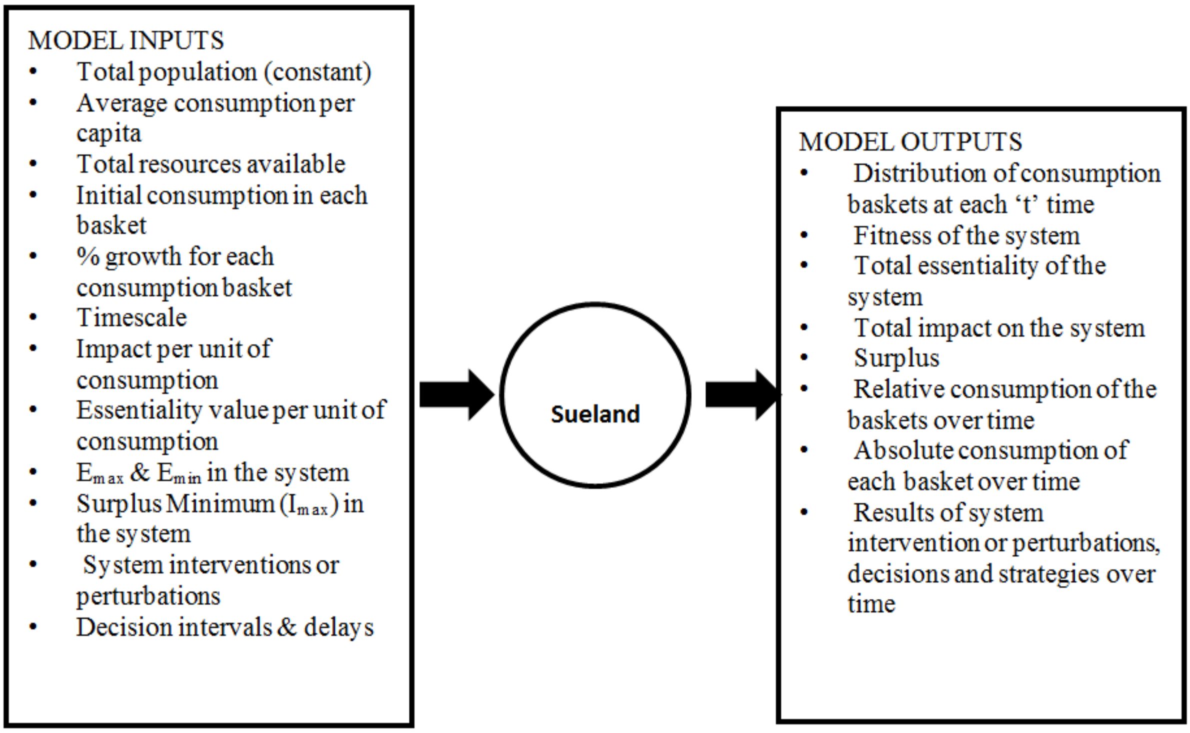

Figure 8 – The model for sustainability management of Sueland

8.2 Findings from modelling sustainability performance in Sueland

Figure 9 presents the system's fitness, essentiality and surplus levels, while Figure 10 shows the evolution of the baskets. In an early stage, when there is an abundance of resources, Figure 10 demonstrates that all baskets expand at their highest growth rate (2% for high-essentiality and 6% for low-essentiality baskets). Similarly, with a *laissez-faire* policy (as in the free-market state), they are allowed to act without restriction.

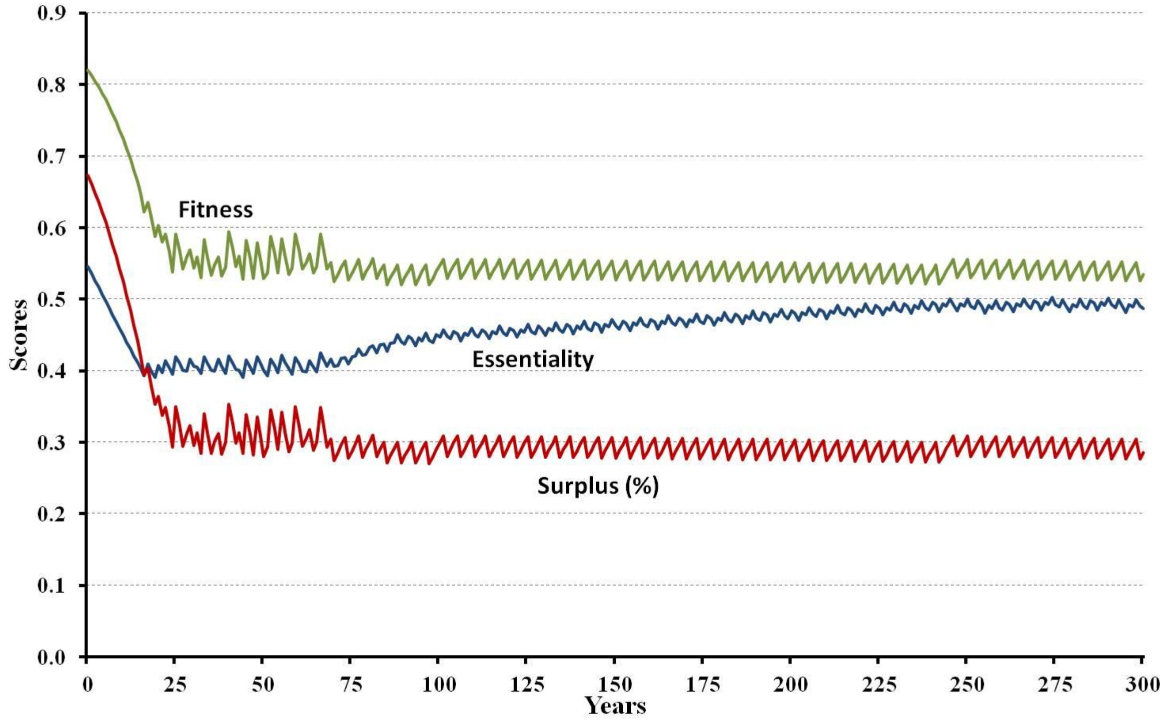

Figure 9 – Sueland's scores of essentiality, surplus, and fitness

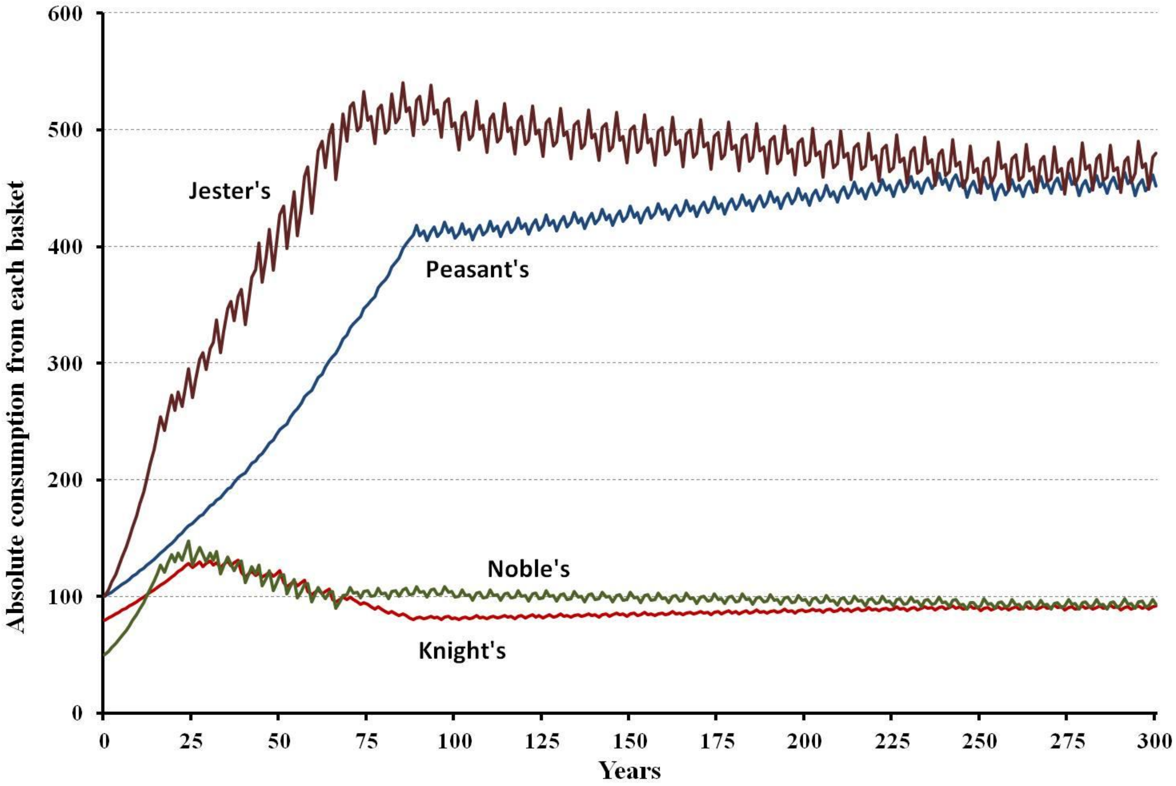

Figure 10 – Evolution of absolute consumption for each basket in Sueland

The system first experiences an excessive waste of resources led by overconsumption of products from the Jester's and Noble's baskets when resources are abundant (only 788 out of 1,300 resource units are consumed – 62%). This leads essentiality to a lower level than the pre-assigned minimum in year 19 (see Figure 9), so an intervention (e.g. market forces, government policy) of reducing the absolute consumption of these products is implemented, bringing the essentiality level back to 0.41 in year 20. Subsequently, as the ratio between impact and resources increases, a new intervention is needed to maintain the surplus within the 30% target (e.g. increased efficiency). Coincidently, this happens when the system's essentiality level is below 0.4 (year 24). Consequently, the system forces a 10% reduction in both Noble's and Jester's baskets in year 25, alongside an additional reduction of the overall consumption of all baskets in the following order: Noble's by 10%; Knight's by 5%; Jester's by 4%; Peasant's by 1%. However, this happens after the baskets' natural growth has occurred. Thereby, the only basket that grows the following year is the Peasant's. The model shows that sometimes reducing Knight's and Noble's baskets (both containing high-impact products) only is sufficient to achieve Sueland's targets for relative surplus and essentiality. Nevertheless, later, the system experiences the pressure of overall consumption from the Peasant's and Jester's baskets despite previous interventions. Although the products from both baskets have low individual impact, their overall absolute impact (consumption of resources) becomes collectively significant (Figure 10). Then, a new intervention is needed to control the consumption of all baskets simultaneously. Without this control and self-organisation based on both essentiality and impact, Sueland becomes unstable and approaches collapse. The overall results in Sueland with evolution of all baskets of consumption are presented in Table 2.

Table 2. Overall results of computer simulation (Sueland)

	Units consumed in each basket							
Year	**Peasant's**	**Knight's**	**Noble's**	**Jester's**	**Essentiality**	**Impact**	**Surplus (%)**	**Fitness**
0	100	80	50	100	0.55	425	67.31%	0.82
50	243	122	118	427	0.40	936	28.00%	0.53
100	407	82	99	506	0.45	910	29.99%	0.55
150	434	85	104	500	0.46	938	27.81%	0.53
200	445	87	97	470	0.48	918	29.42%	0.54
250	451	88	92	446	0.50	899	30.85%	0.56
300	452	92	93	480	0.49	928	28.58%	0.53
Growth	**352%**	**15%**	**86%**	**380%**	**-11%**	**118%**	**-58%**	**-35%**

Table 2 shows how each consumption basket reacts to the interventions in the Sueland system to keep it fit. It also shows the level of essentiality the absolute impact on the overall resource base of Sueland and the fitness scores for given years. The Knight's and Noble's baskets have the smaller expansion - oscillating between expansion and contraction given their large consumption of resources when interventions happen. Peasant's and Jester's have a large growth but are pushed for decay in some years and finally towards a vacillating behaviour of expansion and contraction that permits Sueland to remain fit long term. Only monitoring the absolute values of consumption, essentiality, and impact can we recommend policies and predict the effectiveness of various interventions such as consumption patterns, market forces, etc.

The next section discusses the lessons from applying the model.

8.3 Lessons learnt on the management of sustainability in Sueland

There are many lessons for sustainability management from modelling Sueland.

First, as expected the combined essentiality-environmental impact intervention is the best policy to keep Sueland healthy. The model was tested with different settings, and the intervention based on environmental impact can also keep Sueland healthy if there are lower growth rates for the baskets, albeit with a lower fitness score than a combined policy. In a *laissez-faire* policy (Figure 11), Sueland approaches collapse in year 28 and its fitness score remains zero as surplus continues to decline towards higher negative values. In an essentiality-based policy (controlling Jester's and Noble's baskets only), Sueland's survival is increased only to year 43 due to the collapse of local resources.

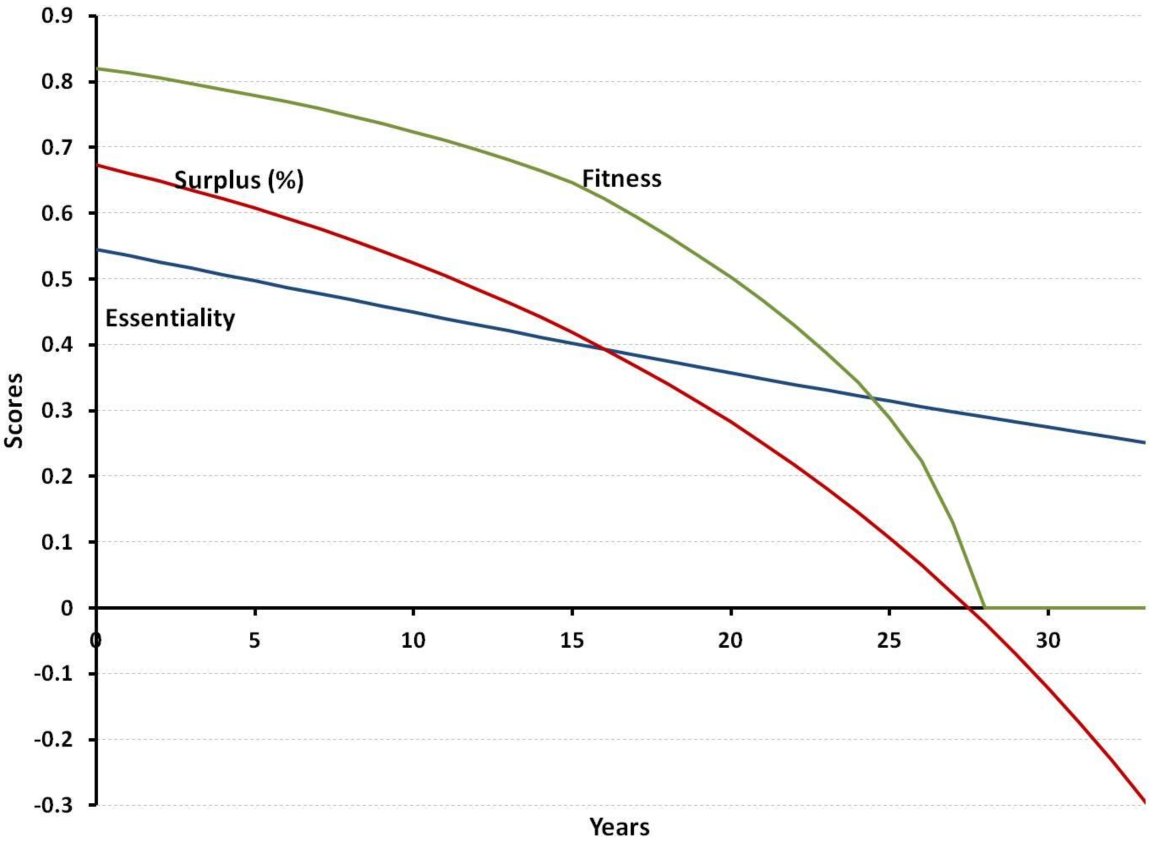

Figure 11 – Sueland's scores of essentiality, surplus, and fitness in a *laissez-faire* policy

We set different growth rates between the essential goods (2%) and superfluous products (6%) on the assumption that essential goods have lower economic elasticity. Growth rates determine how diverse consumption will be. Nonetheless, the distinction between being essential and non-essential for the system's survival creates an important reflection allowing policy makers to make better decisions. This feature is particularly important because it corroborates more with the concept of sustainable consumption and contrasts with the idea that green consumerism can avoid a system's collapse (Akenji, 2014).

With regard to environmental impact, establishing the difference between low-impact and high-impact products is problematic (Figge et al, 2014). The fact that the Peasant's and Jester's baskets consist of low-impact products does not eliminate their absolute collective impact, which needs to be controlled sometimes to avoid system collapse. For instance, this is a serious concern for areas where the collective impact of small farms (Nunes et al, 2014) leads to desertification of semi-arid lands. Aiming at the reduction of only high-impact products leads to system collapse; while aiming at the reduction of baskets' impact leads to long term survival and diverse consumption.

Despite the apparent generous cushion given to the system by setting the minimum relative surplus at 30%, Sueland could only remain stable and healthy because of constant monitoring and rapid decision making. While defining limits is an important step (Akenji, 2014), monitoring and making decisions each year is vital to avoid unstable behaviour of fitness curve. Neglecting the system's essentiality and impact level can damage the system's health/fitness, requiring more radical and difficult corrective decisions. Thus, adaptive capacity (Engle, 2011) is strongly related to agility (i.e. speed to respond to surpassing a threshold) in our model. Reviewing the fitness of the system continuously also improves social learning and memory (Folke, 2006), which could lead to better decision-making.

9. Conclusions

This paper presents our first steps towards a new measure of sustainability performance (system fitness) that can be used to help the management of sustainability in countries, regions, firms, and even for individual life-styles. This was made possible by developing the concept of system fitness based on the essentiality balance and relative surplus in a system. These two variables were derived, respectively, from essentiality and environmental impact. The essentiality concept is novel for sustainability management, which provides purpose to consumption. By considering essentiality as a sustainability dimension, contextual perceptions of consumption can be accommodated alongside environmental impact when assessing sustainability performance. By reflecting on product essentiality, societies could move towards higher levels of sustainability. The assessment of the economic and social value of goods and services when using resources to meet the population needs and aspirations is fundamental to sustainable development strategies. Thus, the local context is respected considering both the availability of resources to produce/consume goods and services as well as the differences in perceptions of essentiality of these (Tilman et al, 2005; Tukker et al, 2008; Caeiro et al, 2012; Sheth et al, 2011). As noted by Boyko et al (2012), the use of appropriate indicators is key to foster long-term survival.

The classification based on essentiality and environmental impact is also new. By understanding that most systems have heterogeneous baskets of consumption (represented by the Peasant's, Knight's, Noble's, and Jester's baskets), the model advances learning in the field of systems dynamics and sustainability management as advocated in several previous studies (Fisher et al, 2013; Enfors, 2013; Young, 201; Duit et al, 2010; Saysel et al, 2002).

While the model itself may not yet be developed for applications in the real world, its underlying principles can be useful in educating for sustainability analysis. Pedagogically, our model can become an educational tool and the lessons from ‘playing’ or using Sueland can help planners and modellers in preparing for different scenarios. Analysing past events such as water crises or energy shortages through the lens of our model would bepedagogically useful. When environmental limits are visible and threatens laissez-faire consumption, superfluous consumption should likely be cut via intervention. Then, consumption that has high impact (collectively or individually) would also be pushed to reduction.

Quantitative methods in social sciences are often criticised by stating that social systems are extremely complex and no *useful* quantitative prediction can be obtained. However, this criticism is usually the result of incorrect expectations about models. The role of numerical data in *toy* models is to provide *qualitative* insight about system behaviour. This paradoxical affirmation means that the numerical output of the model indicates boundaries and relative effects relative to the given numerical input. The latter reveals the overall tendency of system evolution, not its behaviour with unlimited precision. A good example of a mathematical toy model in social sciences is the small-world networks (Barabási, 2002) by which we can qualitatively infer that in any large social networks people are connected in average by a fairly small number of friends – an insight with social and economic consequences.

The current version of the system fitness model has limitations to be addressed. First, we have considered that the system has the economic power to grow baskets whenever resources are available. In reality, consumption growth is not easy to spur even with abundant resources. Similarly, the model implements decisions effectively and quickly, while real decision makers will face delays and other issues with implementation. Also, the availability and visibility of critical information for decision makers is not always present. Difficulties and accuracy in measuring essentiality of the goods and services can be challenging. Other refinements to the toy model could include natural dynamics of systems such as substitutability or complementarity between products in different baskets (Figge et al, 2014), reuse of resources or by-products, resource storage over time, exchange of resources between interdependent systems (e.g. China and Africa as discussed by (Mol, 2011), amongst other dynamics in the complex industrial ecosystem (Chertow and Ehrenfeld, 2012).

Another aspect for development is the classification of baskets. Our division into four main baskets can be refined which, although not relevant in this study, can be useful. For instance, more subdivisions can be added according to the characteristics of the system which do not respect the boundaries used here.

Thus, research could improve the model to accommodate the needs of policy makers and corporate strategists. A survey of essentiality could evaluate perceptions about modern goods and services for different cultures. Such data on essentiality, information on resource availability and environmental impact of products' life-cycles could subsequently enable the model to address real-world problems.

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