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SUSTAINABILITY AND ITS MEASUREMENT

This paper critically reviews the existential need, history, role and status of applying quantitative scientific sustainable development in all human activities of globally-affecting magnitude, such as energy, water and food, and it organically incorporates criteria and effects of the interactions between technology and society.

Sustainability metrics and their ongoing development are described, and their combination into a single aggregate indicator for functional use in analysis and optimization is formulated. In contrast with most studies that focus on using the metrics and indicators mainly for monitoring progress to sustainability, this paper emphasizes the importance of integrating them into the planning, design, and development process, for a-priori creation of sustainable development, products, and systems. Some of the main obstacles that scientists and engineers face in this endeavor are defined as (a) the reductionist practice of scientific research tends to focus on the details of a system, while paying little attention to the broader implications of the work, (b) the difficulty in crossing disciplinary boundaries due to lack of consilience (c) the arrogance of specialization, (d) definition of time and space boundaries, and use of the very wide-ranged multiple scales, and (e) some weakness of tools for solving Very Large Complex Systems. While formidable, these obstacles can be overcome, especially through education beginning from the earliest ages. The weaknesses of the political system to implement national and global sustainable development because of the need for long-term multi-generational and international scope, as well as the critical need for an ethical approach, are identified. There is clearly a need for effective multidisciplinary work, creating a common language and mutual respect; the advent of sustainability science.

A brief example of the application of sustainability analysis for national planning is included, which is taken from a quantitative examination of sustainable development in 10 developing Southeast European countries, with comparison to

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some developed ones, which Prof. M. Radovanović from Educons University, Novi Sad, and I have recently conducted. One of the foci of the study was to find whether global or conventional sustainability indicators, such as the Gross Domestic Product (GDP-PPP) and conventional climate change indicators are also the most important for such emerging countries. The results show significant differences between levels of sustainable development achieved by using these different approaches. We concluded that sustainable development planners and policy makers should be aware of these facts and should carefully choose indicators and weights that are suitable for their countries, especially when the countries are at their initial stages of sustainable development. Uniformity and scientific consensus-based standardization of sustainability analysis methodology are critically needed.

INTRODUCTION: SUSTAINABILITY DEFINITION AND ITS EXISTENTIAL ROLE (PARTLY FROM [1])

„Sustainability" is an increasingly common term in the broader society, often used in a somewhat loose or even fraudulent fashion. It has many definitions which depend largely on the application and the user. Probably the best known is that of the UN Brundtland commission 1987 report, as that *„humanity makes development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs*" [2]. Two hundred years earlier Thomas Jefferson wrote: *„Then I say the Earth belongs to each generation during its course, fully and in its right… Then no generation can contract debts greater than may be paid during the course of its existence*" [3].

Such definitions must be quantified as a vital first step in an attempt to approach sustainable development scientifically. The current ambiguities in the definition of sustainability not only impede sensible development but also give rise to the fraudulent use of this existentially important concept and its terminology, thus diminishing its value by desensitizing society and sowing distrust [4].

Sustainable development is of existential importance for humanity, and as shown below in more detail, its planning and implementation are rather complex, so the most effective way (or the only practical one) for that is by applying scientific principles. These, like any science, require proper measurement and quantification, to largely replace the myriad of ongoing prattle. As Lord Kelvin stated *„I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be"*.

The *needs* in the definition of sustainability are *economic, social* and *environmental*, and must be provided in a properly balanced manner. These three needs are considered to be the pillars of the sustainability concept, integrated with human *values*, which differ among different nations and societies. The pillars are closely inter-related.

The existential importance of sustainable development is obvious noting that the „Living Planet Index", a metric which measures trends in the Earth's biological diversity, has from 1970 to 2010 declined by 52%, and that in 2010 humanity required the capacity of 1.5 Earths to satisfy its consumption [5]. Among other existence-threatening phenomena resulting in important part from unsustainable development are the rising effect of global warming, including and increasing water contamination and scarcity: currently about one-fifth of the world's population lives in areas of physical scarcity, and 500 million people are approaching this situation, and another quarter of the world's population faces economic water shortage. The UN predicts that by 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world population could live under water stress conditions [6,7]. Sustainable use and development of energy are an overwhelming problem worldwide, mostly due to its environmental impacts and insecurity [8–13]. All these trends are clearly unsustainable, increasingly alarming, and explicitly require immediate changes to implement sustainable development. Humanity's survival depends on adoption of sustainable development, which thus has a meta-ethical foundation, a definition of right and wrong paths of a Universal Truth that is humanity's desire to survive, with good life quality.

The focal topic of this „Technology + Society =? Future" conference is the interaction between technology and society, which is clearly a subset of sustainable development in general, and thus must also be done sustainably to lead to a satisfactory future for humanity. The weaknesses of the political system to implement national and global sustainable development because of the need for long-term multi-generational and international scope, as well as the critical need for an ethical approach, are identified. There is clearly a need for effective multidisciplinary work, creating a common language and mutual respect; the advent of sustainability science.

SUSTAINABILITY ANALYSIS METHODOLOGY PRINCIPLES (PARTLY FROM [1])

For the quantitative analysis, sustainability *metrics,* or *„indicators*", are selected and defined to quantify in sufficient detail the different aspects of the sustainability pillars, and usually a large number of such indicators is needed and used. For example, the U. N. „Millenium Goals", established in 2000 used about 150 indicators to measure sustainability of countries and their development for meeting freedom from extreme poverty and hunger; quality education, productive and decent employment, good health and shelter; the right of women to give birth without risking their lives; and a world where environmental sustainability is a priority, and women and men live in equality [14]. More recently [15] a set of main global sustainability global goals was expanded to 17, with 100 indicators.

Regardless of the specific definition, and their inherent complexity, the sustainability metrics must satisfy some common sense criteria. The metrics must:

— Be inclusive of economic, environmental and social concerns (the three pillars of sustainability)

— Be relatively simple, and widely understandable,

— Be reproducible,
— Satisfy the laws of nature,
— Be normalized to allow easier comparisons

The next step in quantitative sustainability analysis would thus be to aggregate the values of the selected indicators, M_i into a single (at best) *composite sustainability indicator* () using weights (w_i) for each, which express their relative importance, as illustrated in Fig. 1:

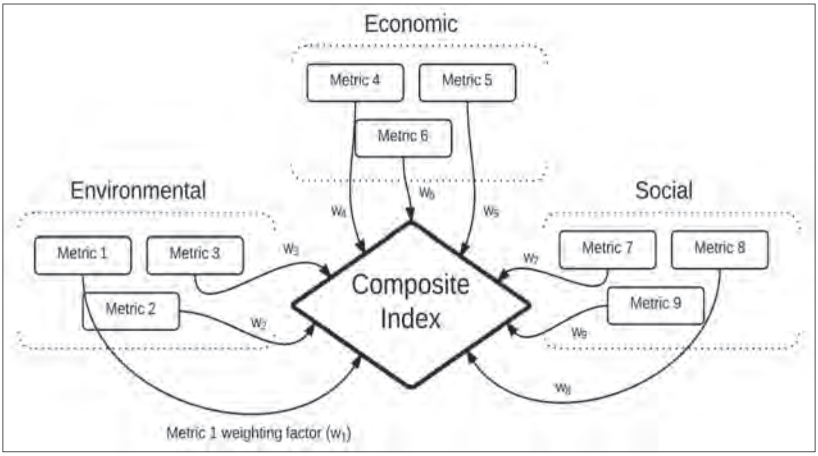


Fig. 1 A diagram for Composite Sustainability Index (CSI) construction

The *CSI* are in their simplest way expressed as

$$\sum_i M_i\left(\vec{x}_{ij}\right) w_i\left(\vec{y}_{ik}\right) \quad \text{or} \quad CSI = \prod_i M_i\left(\vec{x}_{ij}\right) w_i\left(\vec{y}_{ik}\right)$$

or using some other mathematical aggregation method, where

$\vec{x}_{ij}$ the *j* system parameters that affect the metric M_i; Example: if a metric is environmental, the „system parameters" may be impact on biota, gaseous emissions, etc.
$\vec{y}_{ik}$ the *k* system parameters that affect the weight w_i; Example: if a weight is related to an environmental metric, the „system parameters" may be the relative importance of the impact on biota, gaseous emissions, etc.
i index of a metric-weight pair (M_i-w_i)
j index of a metric (M_i) — dependence parameter $\vec{x}_{ij}$
k index of a weight (w_i) — dependence parameter $\vec{y}_{ik}$

This equation mathematically relates the composite sustainability index (*CSI*) to all the chosen 'system parameters' that affect it, so the *CSI* can serve as the objective function for mathematical sensitivity analysis and optimization, down to the level of 'component variables', or be part of it.

Some models for sustainability are in development, for example The EU recently funded project INSURE developed a flexible methodology for representation, analysis and evaluation of sustainability at the regional level. INSURE aimed to develop a practical and ready-to-apply method and toolkit for working with regional sustainable development indicators [16]. Validity of these evolving models is still unknown.

Perhaps the most daunting obstacle to sustainability analysis is not just the definition and quantification of the appropriate metrics and weights, which is a very significant problem and burden for even „just" environmental impact statements, but the significant increase in their number, complexity and indeterministic nature (plurality). While many of the environmental metrics, such as concentrations of chemicals relative to desire values, is relatively simple and deterministic, others such as those dealing with ecology are much more complex and unclear, and so are many of those associated with social impacts. Disciplinary and interdisciplinary work are, however, progressing rapidly to characterize sustainability as a science, and to that end quantitative scientific definitions of its metrics are evolving and gradually becoming a part of standards and regulations (e. g., [13, 17–23]).

Weights (w_i in eq. (1)) are a quantitative expression of the importance of a metric (M_i) relative to the others. In some cases they are calculated using some quantitative analysis, but very often via polling, with some statistical significance, the opinions of experts and stakeholders, including decision makers that may include politicians. Weights can be established directly, or indirectly following a formal method. The determination of weights, whom to ask and by which method to calculate them, is likely to cause more controversy than other parts of sustainability analysis.

A procedurally complicating but vitally important component of the development of relevant and practical sustainability indicators is that broad-based sustainability metrics must carefully consider the needs and opinions of the stakeholders.

The *CSI* characterized by Eq. (1) is most often calculated by using multi-criteria analysis (MCA) techniques.

The recommended quantitative sustainability analysis process steps should follow these steps [1]:

1. Definition of the system and its spatial and temporal extent
2. Preliminary definition of the sustainability objective function and its units
3. Definition of all sustainability metrics and their system-variable dependence quantification (considering spatial effects and temporal evolution)
4. Reduction of their number to a necessary minimum
5. Normalization of the metrics and unification of their units
6. Final definition of the sustainability objective function and its units
7. Definition of the metrics' relative weights
8. Decision on the method of the aggregation of the metrics, considering space and time
9. Aggregation
10. Error analysis
11. Sensitivity analysis

12. Optimization
13. Testing under practical conditions
14. Iteration and development of learning experience for this and future projects.

The development of sustainability metrics is, as described above, a very formidable task, in which some of the main obstacles that scientists and engineers face in this endeavor are:

— The reductionist practice of scientific research tends to focus on the details of a system, while paying little attention to the broader implications of the work.

— Exacerbation by the difficulty in crossing disciplinary boundaries: lack of consilience[1] in the objectives of different disciplines that consider the economic, philosophical, cultural, and scientific and engineering aspects.

— Definition of time and space boundaries and use of the very wide-ranged multiple scales.

— The arrogance of specialization.

— Some weakness of tools for solving Very Large Complex Systems.

While formidable, these obstacles can be overcome, especially through education beginning from the earliest ages.

By definition, sustainable development of large scale must be planned and executed to maintain the well-being of future generations, meaning that it has to extend to the far future and be global in extent. Long-term strategic planning is, however, fraught with difficulties, which presently often make it impossible. In accord with a number of studies [24], it is recommended that currently the best planning option is the reflexive iterative process: monitoring the progress and circumstances periodically, adjusting for need changes in the plan, and carefully learning from the experience, while maintaining the overall objective, with appropriate participation of stakeholders.

Sustainable development also has responsibility across global (and beyond) geographic boundaries, both since the future generations we try to keep happy may live anywhere in the world and not just in the country of their ancestors' (our!) birth/residence, and because it is impossible in the long term to maintain sustainability of a country without ensuring the sustainability of most of the other countries on earth.

In contrast with most studies that focus on using the metrics and indicators mainly for monitoring progress to sustainability, we emphasize the importance of integrating them into the planning, design, and development process, for a-priori creation of sustainable development, products, and systems.

The current democratic political systems are not amenable to sustainable national development because are based on short-term election of political leaders and resulting short-term planning, typically making multigenerational planning impossible, and excessive nationalism makes global planning very difficult. Preferred ways by which democratic governments could overcome them are also described in [24]. They range from more rigorous development and use of scientific

[1] The unity of knowledge, a coming together of knowledge.

methodology in sustainable development, through proper public education, longer terms of office of elected officials responsible for *SD*, and to enlightened legislation that employs reflexive sustainable development with participation of relevant stakeholders and establishes sustainable development leadership bodies that are given a legal/constitutional obligation and responsibility to ensure continuity of *SD* plans and implementation at the multi-generational time scale. All this must stand on a firm ethics foundation: it is widely recognized that corruption, on individual through corporate and to governmental levels, may be the strongest enemy of sustainable development. Much remains to be done, very creatively.

A SUSTANABILITY ANALYSIS EXAMPLE (unpublished work based on [1], [25–27])

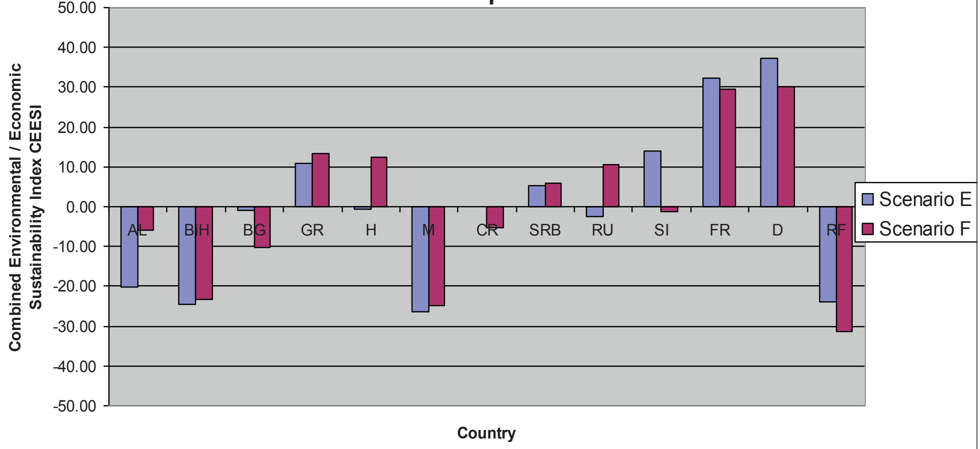
To demonstrate the use of sustainability analysis, a brief example of its application for national planning follows. It is taken from a quantitative examination by the authors of sustainable development in 10 developing Southeast European countries, with comparison to the developed countries Germany France, and the Russian Federation. One of the foci of the study was to find whether global or conventional sustainability indicators, such as the Gross Domestic Product (GDP-PPP) and conventional climate change indicators are also the most important for such emerging countries. Twenty indicators of sustainable development, each with a weight, were selected for the analysis in which composite sustainability indicators were calculated.

The analysis was done for six scenarios. On the economic side, Scenario A is the typically adopted one in which the GDP-PPP indicator's weight dominates over that of the Gini Index of equal GDP-PPP distribution among the citizens, and Scenario B in which the Gini Index weight dominates over that of the GDP-PPP. On the environmental side, one scenario (C) is the typically adopted one in which the weights of the climate change indicators dominate over those of increased agriculture, forestation, and energy use, and the other (D) where the weights of increased agriculture, forestation and energy use indicators dominate over those of climate change.

Scenario E combines the features of Scenarios A and C and thus represents the currently typical approach to sustainability analysis in Europe, and Scenario F combines those of Scenarios B and D and thus represents an approach to sustainability analysis that somewhat lowers the dominant effect of GDP-PPP and climate change to favor sustainability criteria that may be more suitable for developing countries like those in SEE.

Figure 1 shows the results of the research display significant differences between levels of sustainable development achieved by using these two different approaches. It is also noteworthy that in some countries the same changes have different (positive or negative) effects. Sustainable development planners and policy makers should be aware of these facts and should carefully choose indicators and weights that are suitable for their countries, especially when the countries are at their initial stages of sustainable development. Uniformity and scientific consensus based standardization of sustainability analysis methodology are critically needed.

Figure 3. Combined Level of Economic-Environmental Sustainable Development



Regardless of the applied scenario, Germany and France continue to show the best results in the group. Russia, Bosnia and Herzegovina, and Macedonia show the worst three results in both scenaria.

The results under Scenario E (high value of GDP and climate change indicators) among the SEE countries show positive results only by Slovenia, Greece, and Serbia. Application of Scenario F (lesser importance of GDP and higher importance of natural resources) are different than under Scenario E: in most countries the change is moderate (Bosnia and Herzegovina, Greece, Macedonia, Croatia, Serbia, France). In Germany, Bulgaria and Russia the combined *CSI* dropped with a more significant change, and in Hungary, Romania and Slovenia it is significant. Only 3 of the SEE countries, Bulgaria, Croatia and Slovenia, show a reduction of the *CSI* under Scenario F, indicating that this scenario favors the sustainability of most of the SEE countries.

Choosing between economic development at any cost, and finding a balance between the economy and the environment is definitely a country's choice based on its preferences and priorities at any given time. Choice of a sustainable development strategy must be accompanied by the selection of an appropriate measurement methodology that would properly evaluate the conditions of the country and that would be flexible and under constant supervision by professional staff. Use of traditional GDP-based or sustainable beyond-GDP-based measurement and assessment methodologies is a country's choice, but policy makers must be aware of such differences, which may be large, and that strategic decisions based on disputable measurement results may thus have very complex long-term consequences.

Besides the right assignment to the GDP, another weight choice example is associated with use of fertilizers. Without fertilizers a country cannot produce sufficient agricultural product from which it could create an income and GDP-PPP. On the other hand, most current methods for using fertilizers are environmentally harmful. Yet another example of a frequently used sustainability indicator is the extent of the agriculture that is organic, but countries that depend on agriculture as a source of income cannot easily transit to organic production, just because of the environmental benefit, because the cost of organic agriculture products is typically higher and the yield lower.

Sustainable development evaluations that assign higher importance to wealth of natural resources have proved to show higher sustainability indicators for most countries.

CONCLUSIONS

Sustainable development is of existential importance for humanity, its planning and implementation are rather complex, and the most effective way (or the only practical one) for that is by applying scientific principles. These, like any science, require proper measurement and quantification. Significant work critically needed to develop uniformity and scientific and political consensus -based standardization of sustainability analysis methodology.

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