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Towards a General Theory of Sustainable Development: Using a Sustainability Window Approach to Explore All Possible Scenario Paths of Economic Growth and Degrowth

Jyrki Luukkanen [1,*], Jarmo Vehmas [1], Jari Kaivo-oja [1] and Tadhg O'Mahony [1,2]

[1] Finland Futures Research Centre, University of Turku, 20014 Turku, Finland; jarmo.vehmas@utu.fi (J.V.); jari.kaivo-oja@utu.fi (J.K.-o.); tadhg.omahony@utu.fi or tadhg.omahony@ucd.ie (T.O.)

[2] School of Architecture, Planning and Environmental Policy, University College Dublin, D04 V1W8 Dublin, Ireland

* Correspondence: jyrki.luukkanen@utu.fi

Abstract: Across decades of contemporary discussion on sustainable development, a core concern has been the balance between economic, social, and environmental dimensions. A critical strand of the debate focuses on economic growth versus economic degrowth and, more specifically, on whether economic growth can be sustainable in environmental terms and whether degrowth can be sustainable in social terms. This conceptual and theoretical article used the *Sustainability Window*, or "*SuWi*"' method, to theoretically determine the sustainable window of economies. The window is defined as the upper and lower bounds of future change in GDP that could be deemed in line with achieving both environmental and social sustainability. The conceptual analysis considers all theoretically possible scenario paths for development by combining the outcome paths of economic, environmental, and social dimensions with the environmental and social productivities of GDP. Through SuWi analysis, it is found that only four of the logically possible scenario paths could be considered theoretically "sustainable"—two cases involving economic growth and two of degrowth. In the cases of each of the four paths, sustainability only emerges where they adhere to strict conditions in terms of environmental and social outcomes, as well as related productivities. The SuWi approach and its applied analytical formulas have many potential uses in 21st-century policymaking for sustainability, including supporting the United Nations Sustainable Development Goals. It provides a unique and comprehensive theoretical and analytical framework that enables the categorisation of the complex challenges of sustainability and quantitative analysis of policy choices. Such foresight analysis could greatly assist in providing an evidence base for future development planning and policy formulation, ex ante of locking in a pathway. Further implementation in applied studies that explore a comprehensive indicator set, robust and consistent across all relevant dimensions, offers a promising opportunity to advance empirical analysis of key questions in sustainable development globally at a critical juncture in human history.

Keywords: sustainable development; Brundtland Commission; economic growth; degrowth; scenarios

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1. Introduction

Across forty years of evolution in thinking on sustainable development, the debate on the place of growth has been central [1–3]. While economic growth can be linked to improvements in welfare and poverty alleviation, it is now broadly accepted that it is also a mega-driver of global climate change and ecological breakdown [4–6] and drives problems of equity and growing in-country inequality [7–10]. The question of how to achieve sustainable development in the 21st century continues to be accompanied by disagreement on the role of economic growth, including the growth–degrowth debate [11,12], prospects for green growth [13], limits to growth [14], and questions on the implications of productivity growth [15].

There is a broad scientific literature focusing on economic growth and economic development issues, especially in the field of development studies and research [16–21]. Economic growth and economic development are two related but distinct concepts that measure the performance and progress of a country or region. Referring to this broad scientific discussion, key differences between these two central concepts can be identified: (1) Economic growth refers to the change in the amount of goods and services produced in a given period of time, while economic development refers to the improvement of human well-being of the population in terms of health, politics, social or any other specific socio-cultural themes of social systems deemed relevant. (2) Economic growth is usually measured by real Gross Domestic Product (GDP), which is the value of goods and services produced by the national economy at constant prices, with many empirical studies relying on this indicator. (3) On the other hand, economic development is often measured using the Human Development Index (HDI), a key statistical indicator taking into account life expectancy, education level, and purchasing power parity (PPP) income per capita. (4) Economic growth is one of the components of economic development, but it is neither the only nor necessarily the most important one. Contemporaneously, the "happiness" of the population is often measured and given analytical and policy importance [3,5]. Economic development also requires other socio-cultural factors, such as political stability, rule of law, low level of corruption, environmental protection, equality, human rights, and cultural diversity [22–25]. It is important to note that economic growth can, in some cases, become an obstacle to economic development, where growth in the economy drives harm or delivers public bads, with examples including environmental degradation, natural resource depletion, increasing inequality, social unrest or loss of cultural identity. When acknowledging that there are a variety of social priorities that are accorded value [3] in the context of achieving sustainable development, the process of economic development must then deliver a balance between economic growth and other priorities [26–28].

The original idea of sustainable development, proposed by the Brundtland Commission's report "Our Common Future", was of three "pillars": economy, environment, and society [29,30]. Scientometric reviews of global research on sustainability and sustainable development reveal that the Brundtland Report has been an important and highly impactful report for global sustainability research [31–34]. Several research traditions based on the Brundtland Report use indicators to analyse the different dimensions of sustainability [35–37]. For instance, Holden et al. [35] suggest using four main composite indicators–ecological footprint, the Human Development Index (HDI), the Gini coefficient, and the share of renewable energy—in order to cover the four main dimensions of sustainability: (i) safeguarding long-term ecological sustainability, (ii) satisfying basic human needs, and promoting (iii) intragenerational equity and (iv) intergenerational equity. Figure 1 illustrates the ubiquitous three intersecting circles of sustainability and common alternative depictions from Purvis et al. [38]. The following article discusses the interpretation of sustainable development over time in terms of economic growth, social development, and ecological sustainability.

Sustainability has diverse origins from the 17th century onwards [39], yet the modern concept, which arrived in the mainstream in the 1980s, emerged from The Club of Rome's "Limits to Growth" [40]. This world systems scenario study was criticised by many economists, as the simulation did not include a price mechanism, the primary signalling mechanism for consumer behaviour [41–43]. Many economists, political scientists, ecologists, and scientists started thinking about optimal growth paths and how to provide for the growing human population in a world that had limited empirical analysis of global systems at the time. This branch of literature extended to scarcity, overpopulation, and environmental degradation [27,44–48]. Yet, in line with the Brundtland definition of sustainable development [29], economic growth has continued to persist centrally in debates. A conventional taxonomy of possibilities for growth could be presented as follows: (1) there must be continued economic growth, (2) there cannot be economic growth beyond a certain limit, and (3) economic growth must decline, as limits have already been exceeded. While the former assumes that economic growth is necessary for social development and can be ecologically sustainable, the latter two characterisations broadly contend that growth is neither necessary for social development nor can it be environmentally sustainable.

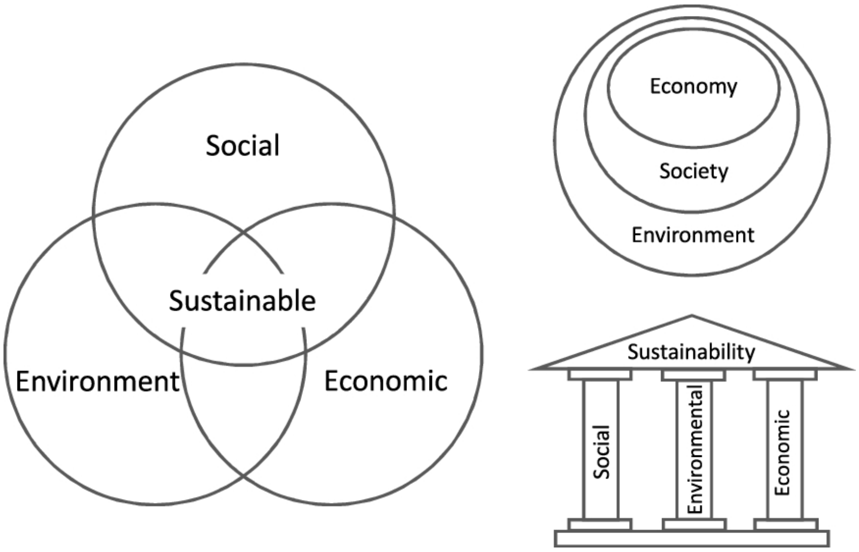

Figure 1. (**Left**): a typical representation of sustainability as three intersecting circles, (**right**): alternative depictions: below as literal "pillars" and above as concentric circles, from Purvis et al. [38].

A range of economists and system theory scholars have contributed to these discussions. In the economics literature, the first approach—there must be growth—was articulated in the Brundtland Commission report, and the neoclassical approach to sustainable development was found primarily in the writings of Robert Solow [49] and Joseph Stiglitz [50]. Endogenous growth theory also has a sustainable growth model [51,52] related to Solow–Stiglitz's thinking. Herman Daly was critical of this approach, noting that there cannot be economic growth beyond a certain limit, or there cannot be economic growth [53–58]. The third approach—economic growth must decline as limits have already been exceeded—was linked to the degrowth movement led by Joan Martinez-Alier [2,19,43,59–61] and Serge Latouche [62,63]. The work of Nicholas Georgescu-Roegen [64] on entropy and economics is fundamental to this strand as a key contributor to steady-state and degrowth economics.

In seeking to understand the relationship of growth to pollution, the Environmental Kuznets Curve (EKC) by Grossman and Krueger [65] has been a dominant approach among economists. However, the results of EKC studies vary depending on the pollutant and other factors outside of income, with questions on its empirical robustness [66]. In line with recognising the need to explore other drivers outside of income, including structural and intensity effects, attention shifted to further disaggregation of the analysis. The IPAT and Kaya identities have been important in sustainability evaluation by deepening an understanding of the systemic driving forces of environmental problems, including the role of economic growth. The IPAT identity [67–69] defines major reasons for environmental impact (I) as a multiplicative identity of Population (P), Affluence (A), and Technology (T). The Kaya identity is a specific application of the IPAT identity that identifies the major drives of carbon dioxide emissions, such as population, GDP per capita, the energy intensity of the economy, and carbon intensity of the energy mix [70]. Decades of decomposition analysis studies have deepened knowledge of these drivers, including activity, structure, and intensity effects [71]. These studies have emphasised how increased affluence has been driving global resource consumption and related emissions, and this has highlighted the necessity to decouple the impact of affluence from environmental impact through both structural and technological factors. While sustainability analysis, such as in the case of an

EKC, can be performed on a single dimension, it has been noted that this approach fails to comprehensively address all three dimensions of sustainability, requiring a more complex analysis of multiple dimensions [72,73].

While the purpose of this paper is not to present a comprehensive literature review on sustainable development research, context can be established by referring to useful review articles on the issue of sustainable development and sustainability research, including assessments critical of the concept, such as [74–78]. In this article, we argue that the theories of sustainable development are fragmented, in parallel with the fragmentation of global governance of sustainable development [79,80]. The implications are that the theoretical starting point necessarily depends on the research topic, focus, and perspective taken [81,82]. Related to this complexity, generic theories of sustainable development that take into account all dimensions of sustainability are difficult to find in the literature. Attempts to develop theoretical approaches to the complexity of the sustainability dimensions, especially in the case of economic sustainability [83–86] and also attempts to develop a new theory of social sustainability [3,87,88] are examples of significant though rare advancements in sustainable development theory.

Sustainable development aims to enhance the resilience of social, economic, and environmental systems to withstand shocks and stresses, such as natural disasters, economic crises, or social unrest. Addressing the challenges of sustainable development requires a deep understanding of these complex interactions and feedback loops and the ability to manage them effectively through adaptive, inclusive, and systemic approaches. Complex problems relating to the nexus of unsustainable environmental and socio-economic development require robust research methods that facilitate this holistic analysis [83–86].

The Sustainability Window analysis proposed by Luukkanen et al. [48,72,89] facilitates such integrated analysis as a coherent, comprehensive, and operationalised framework that can describe the change in multiple sustainability dimensions over time. The research seeks to clarify the problem and theoretical challenge posed by Dutch economist Roefie Hueting [90] regarding conflicting goals in the sustainable development process. The Sustainability Window (SuWi) provides an integrated assessment of complex multidimensional sustainability problems by determining the maximum economic growth—to avoid negative change in the environmental condition of a selected environmental indicator—and the minimum economic growth—to achieve positive social development of a selected social indicator. These maximum and minimum levels of economic growth define the Sustainability Window and can be specified in either relative or absolute form, depending on the requirement. The approach provides a general platform for building sustainability science as an evolving academic discipline, which can point the way to sustainable development paths, addressing challenges that existing approaches have not yet fully addressed. This includes the UN Sustainable Development Goals (SDGs) and inherent contradictions concerning economic growth, as emphasised by Hickel [91]. While acknowledging the complexity of theoretical discussion in the article, in conceiving all possible paths and all theoretically relevant sustainability criteria, in the application, the analytical structure of SuWi can support ease of use for analysts and ease of understanding for policymakers. SuWi can permit interdisciplinary, integrated assessment and stringent critique of policy and of future scenarios and forecasts once the selected environmental and social criteria have been appropriately understood and defended.

Cognisant of decades of debate on the role and impact of economic growth, this article seeks to determine the sustainability window as the theoretical upper and lower bounds of economic growth that could deliver social and environmental sustainability. The article considers all theoretically conceivable combinations in Section 2; this allows all logically possible combinations to be identified, also in Section 2. From the latter, Section 3 identifies those combinations that could be considered socially and environmentally sustainable by considering both possible paths and absolute targets. This rationalised process of elimination allows the article to focus on the theoretical place of economic growth in a general theory of sustainable development.

2. Materials and Methods

This section first describes the conceptualisation of the Sustainability Window (SuWi). The SuWi approach can be utilised to analyse different dimensions of sustainability, both generalised and specific. Any of the 17 dimensions of the UN Sustainable Development Goals could be used in the analysis if suitable data are available, or it could be limited to a narrower field of study. While sustainability is often analysed in three dimensions—economic, environmental and social—it is relevant to note that these dimensions can consist of numerous sub-categories. For clarity of analysis, we present the cases here using three dimensions, but the SuWi method itself does not limit the use of dimensions of development. In all cases, to identify minimum and maximum economic growth, environmental and social dimensions are analysed pairwise with GDP and then combined to produce the sustainability window of GDP. The intergenerational equity emphasised by the Brundtland Commission [29] and explicitly suggested as a fourth dimension of sustainability by Holden et al. [35] could also be included by using the dynamic SuWi approach [73,75], which allows the analysis of changes and trends over time—even over generations—in the width of the Sustainability Window and in construction of related future scenarios.

The innovation of the SuWi approach is that it provides a means to analyse development in three dimensions simultaneously. In SuWi, quantitative indicators describe the change in these three different dimensions. For the environmental dimension, indicators that track changes in environmental vectors or the state of the environment, such as greenhouse gas emissions, land-use change, biodiversity, water quality, or chemical pollution, can be selected. The increase in the value of the environmental indicator means that environmental pressure is increasing, indicating an undesirable direction of development. For the social dimension, indicators that track social processes and outcomes can be used, such as education, income, gender equality, social equity, unemployment, health, life expectancy, governance, democracy, food and water availability, or sanitation. An increase in the value of the social indicator means that social welfare is improving, indicating a desirable direction of development. In the SuWi, the economic dimension is typically described by GDP, specifically to understand the implications of economic growth paths. It is widely acknowledged that GDP, as an indicator of economic production, provides a poor proxy for human well-being, or indeed sustainability [3,74,92,93]. However, in this context, using GDP allows economic output to be separated from social and environmental dimensions toward deliberate analysis and critique of economic growth paths themselves. To determine the "sustainability window," the analysis combines two different two-dimensional frameworks: first, development in environmental stress and economic output, and second, changes in the dimensions of social welfare and economic output. Combining these two frameworks facilitates the description of sustainability amongst all three dimensions. Because there is no general indicator describing environmental stress, different indicators could be used for it. Similarly, there is no general indicator for social welfare, and different indicators could be used for this dimension. In order to obtain a multifaceted view of sustainability, several different indicator combinations should be used in the analyses.

In this article, we apply the concepts of weak and strong sustainability in the following manner: "Weak sustainability" is defined in relative terms as an outcome where the intensity of environmental stress (Environmental stress/GDP) does not increase. In contrast, "Strong sustainability" is defined in absolute terms, where the environmental stress itself reduces from a base year value, with an associated stasis or absolute increase in social welfare. Following this, the strong Sustainability Window can then theoretically be either a case of economic growth or degrowth, where the maximum economic growth, GDP_{max}, avoids increasing environmental stress, and the minimum economic growth, GDP_{min}, avoids a decrease in social welfare. This section addresses the cases of both economic growth and degrowth to clarify the different possibilities for sustainable development in the context of change in the economy. The rationale is advanced first in a narrative form and then illustrated graphically to explain the theoretical combination of paths for the economy with possible levels of environmental stress and of social welfare. To explore the different possible system relationships, such as changes in productivity, the narrative discusses changes in *environmental stress productivity* and *social welfare productivity*. Environmental stress productivity is defined as environmental stress divided by GDP, and social welfare productivity is defined as social welfare divided by GDP for a given year and indicator. While defining absolute or productivity changes necessarily defines the related absolute or productivity indicators, the narrative form moves pairwise through different subsets of absolute and productivity indicators, thus allowing all possible cases to be theoretically explored.

Through the combination of these theoretical outcomes, the Sustainability Window, or "SuWi", is determined. This allows for all possible scenario paths of development to be explored. To facilitate this theoretical discussion of all possible combinations, the first part of the results, Section 3, considers relative changes in environmental and social welfare outcomes in the context of economic growth and degrowth. Relative change here is defined as a change from the base year value. However, it is also recognised that to move from a grounding that could be described as "theoretically possible" to "theoretically sustainable", a relative change by improving productivity will often not be sufficient. In many cases, for environmental indicators, such as a change in greenhouse gases, absolute limits and reductions are necessary for sustainability. This is the case even though the Paris Agreement on climate change states, "To limit global warming to 1.5 °C, greenhouse gas emissions must peak before 2025 at the latest and decline 43% by 2030", setting a relative target. In other cases, for social welfare, an absolute increase may be required, such as in cases where poverty reduction and elimination are required. To move from relative change to absolute change, in line with a specified target, Section 3 combines target levels in the narrative explanation and related graphical presentations for illustration. Section 3, therefore, contributes to moving from outcomes that are defined more by covering the theoretically possible window—of all possible development paths—to the sustainability window of economic growth—as the actual requirements of what could be considered real-world sustainability for a given change in an economy. Within this configuration, the "development path", is a broad multidimensional representation of how global, national or regional development may evolve across multiple drivers [94]. It is simplified in SuWi as quantitative economic, environmental, and social dimensions through change in total economic output and in the macro-environmental and social productivities of systems at the chosen level of analysis.

The SuWi approach is first demonstrated with an example case and then widened to include all possible development paths. Figure 2 illustrates an example of development in environmental and economic dimensions. The indicators for economic output (GDP) and environmental stress (Env) are indexed to have a value of 1 in the base year, indicated with point A, and having values GDP_0 and Env_0 on the *x* and *y*-axis. Point A determines the base year environmental stress productivity, defined as the amount of environmental stress produced per unit of economic output (of GDP), with both measured by indexed indicators, with line $r1 = Env_0/GDP_0$. In this case, an indicative final point of development is denoted by point E, which has the values GDP_1 and Env_1. The improved environmental stress productivity of GDP is expressed with line $r2 = Env_1/GDP_1$ ($Env_1/GDP_1 < Env_0/GDP_0$). However, if we assume that the criterion for environmental sustainability is that environmental stress should not increase, and under the ceteris paribus condition for environmental stress productivity r2, then the maximum sustainable economic output, in this case, is indicated by point B and has the value GDP_{max}. Determining that environmental stress must not increase, where the improvement in environmental stress productivity is limited, demands that sustainable GDP growth be limited.

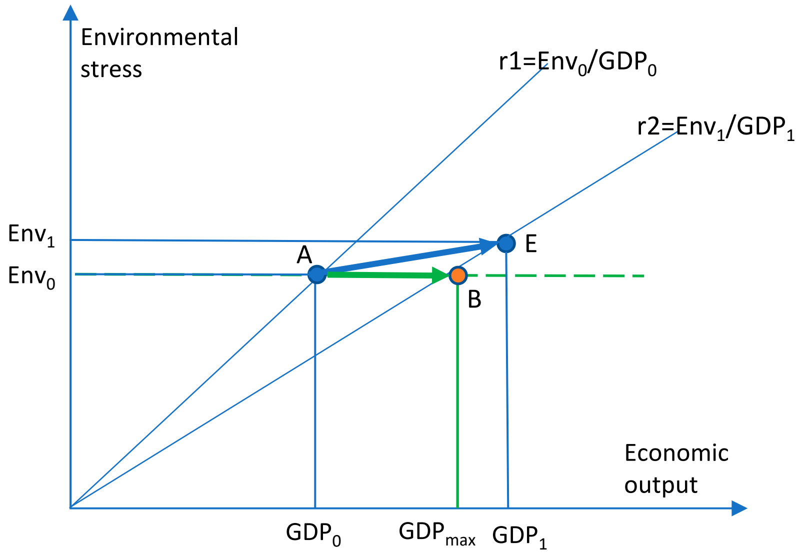

Figure 2. Determining the maximum economic output related to the production of environmental stress.

An example of determining the minimum economic output concerning social welfare development (Soc) is shown in Figure 3. The indicators for economic output and social welfare are again indexed to have the value 1 in the base year and have values GDP_0 and Soc_0 on the x and y-axis. Point A determines the social welfare productivity of GDP and how much social welfare is produced per unit of GDP, with line r1 = Soc_0/GDP_0, which has the same value as in Figure 2 (indexed starting point). A final point of development is indicated with point S, having values GDP_1 and Soc_1. At this point, the social welfare productivity of GDP is expressed with line r3 = Soc_1/GDP_1. In this case, the criterion for social sustainability is that social welfare should not decrease. By using the ceteris paribus condition for social welfare productivity r3, the minimum sustainable economic output is indicated with point C, having the value GDP_{min}. The decreasing welfare productivity r3 ($Soc_1/GDP_1 < Soc_0/GDP_0$) defines a minimum GDP value that is higher than the base year value in order not to decrease social welfare but lower than the actual GDP_1 value.

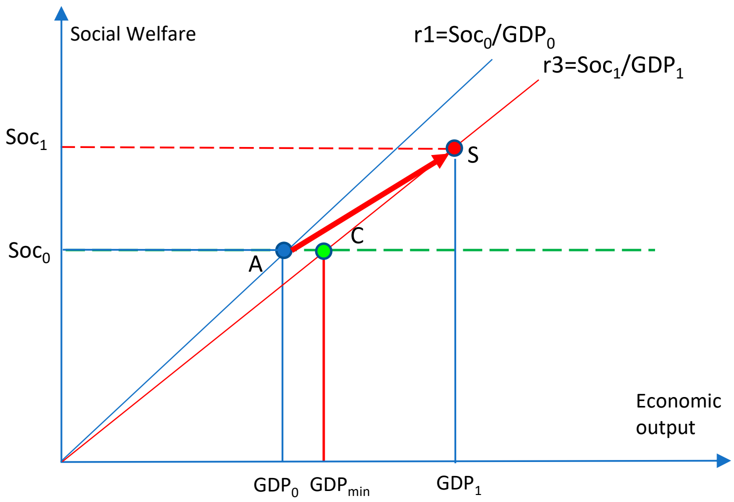

Figure 3. Determining the minimum economic output in order to not decrease social welfare.

When these cases of environmental and social sustainability are combined, from Figures 2 and 3, we can determine the Sustainability Window with the minimum economic output that preserves welfare and the maximum economic output that avoids increasing environmental stress, as illustrated in Figure 4. The maximum sustainable economic output, GDP_{max}, is defined with the productivity line r2 = Env_1/GDP_1 (environmental stress productivity point E) to be at point B, and the minimum sustainable economic output, GDP_{min}, is defined with the social welfare productivity line r3 = Soc_1/GDP_1 (defined by point S) to be at the point C. In this case, the real GDP growth is too high (GDP_1 is higher than GDP_{max}), and the sustainability criteria defined by the Sustainability Window ($GDP_{min} < GDP_1 < GDP_{max}$) are not satisfied. If welfare is to be maintained, and environmental stress not increased, then the economic Sustainability Window, SuWi, requires an outcome $GDP_{min} < GDP_1 < GDP_{max}$.

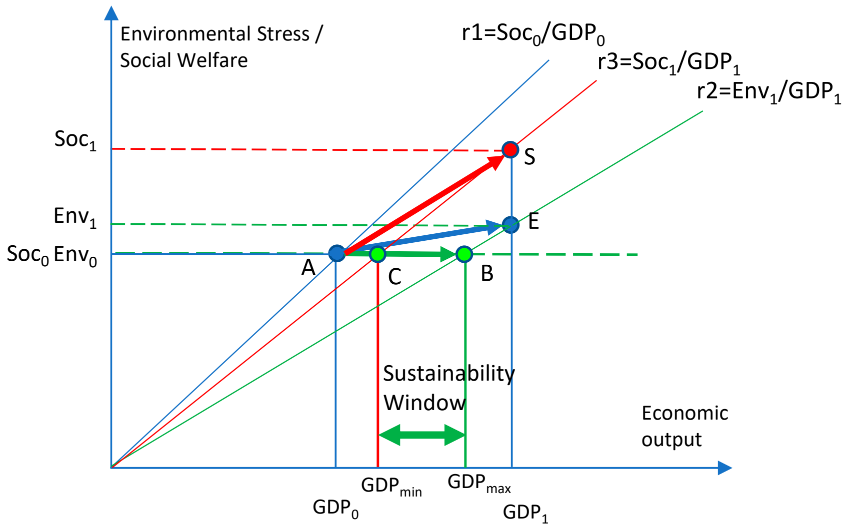

Figure 4. Determining the Sustainability Window (SuWi) with the minimum (GDP_{min}) and maximum (GDP_{max}) economic output.

The illustrated case shows an example where environmental stress increases while environmental stress productivity decreases, and social welfare increases with decreasing social welfare productivity. Next, a case of decreasing environmental stress and stress productivity is combined with increasing social welfare, increasing GDP, and decreasing social welfare productivity.

Figure 5 illustrates this possible development path where the economic output is growing and the environmental sustainability criteria are fulfilled. The starting point is A with environmental stress Env_0 and GDP_0, and the final point is E with environmental stress Env_1 and GDP_1. In this case, the environmental stress decreases ($Env_1 < Env_0$), and the environmental stress productivity decreases (r2 = $Env_1/GDP_1 < Env_0/GDP_0$), determining the maximum economic output, GDP_{max}, at point B not to increase environmental stress.

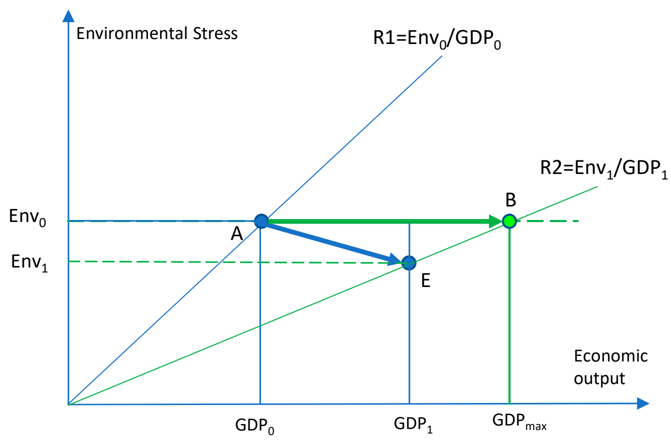

Figure 5. Determining maximum economic output when environmental stress is decreasing ($Env_1 < Env_0$) and environmental stress productivity is decreasing ($Env_1/GDP_1 < Env_0/GDP_0$).

Figure 6 illustrates social welfare development in this case. The starting point is A, and the final point is S. In this case, social welfare increases ($Soc_1 > Soc_0$), and social welfare productivity decreases ($r3 = Soc_1/GDP_1 < Soc_0/GDP_0$). The productivity line r3 determines the minimum economic output, GDP_{min}, at point C in order not to decrease social welfare.

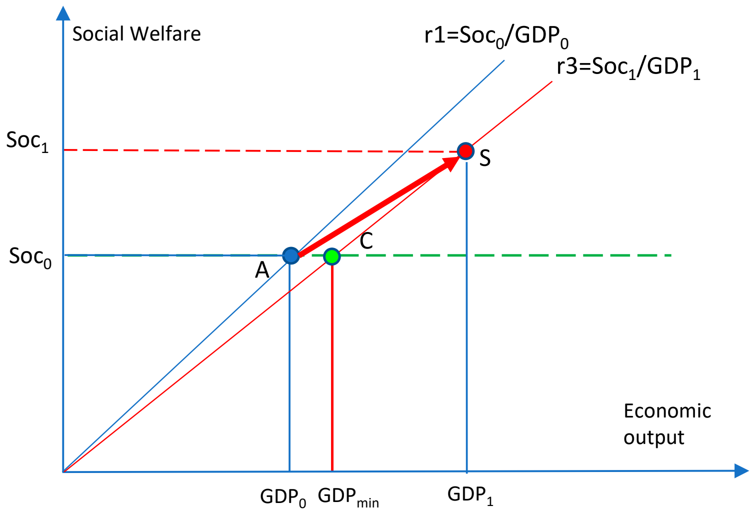

Figure 6. Determining minimum economic output when social welfare is increasing ($Soc_1 > Soc_0$) and social welfare productivity is decreasing ($Soc_1/GDP_1 < Soc_0/GDP_0$).

The results from Figures 5 and 6 are combined in Figure 7 to illustrate the Sustainability Window. In this case, the maximum economic output, GDP_{max}, is higher than the actual GDP_1, and the minimum economic output, GDP_{min}, is lower than GDP_1. This means that the development fulfils the sustainability criteria.

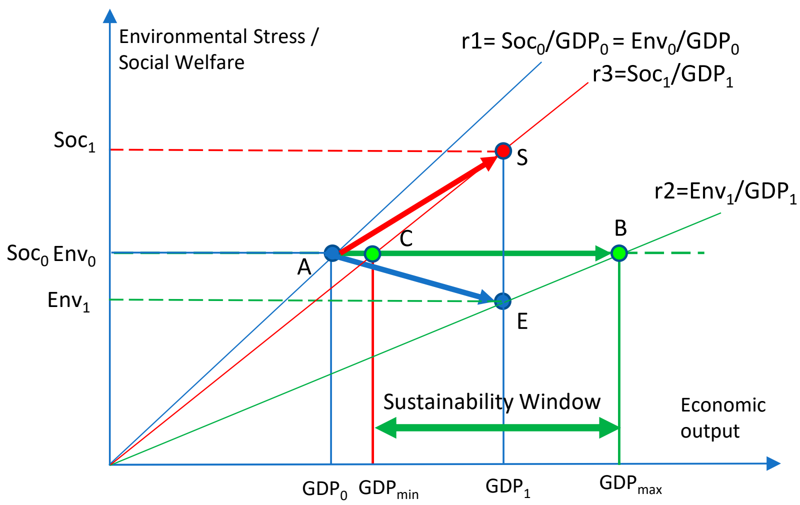

Figure 7. Determining the Sustainability Window in a case where the actual GDP output is within the Sustainability Window ($GDP_{min} < GDP_1 < GDP_{max}$).

The case examples presented above show that with economic growth, it is possible to achieve sustainable development but only under specified conditions. The following Figures 8–10 illustrate an economic degrowth case where the economy decreases ($GDP_1 < GDP_0$). In Figure 8, the starting point is A with environmental stress Env_0 and GDP_0. The environmental stress decreases to E with the value Env_1 ($Env_1 < Env_0$). In Figure 8, the environmental stress level Env_1 and GDP level GDP_1 define the productivity line r2, decreasing environmental stress productivity ($Env_1/GDP_1 < Env_0/GDP_0$), which determines the potential maximum sustainable economic output, GDP_{max}, in relation to environmental stress to be at point B.

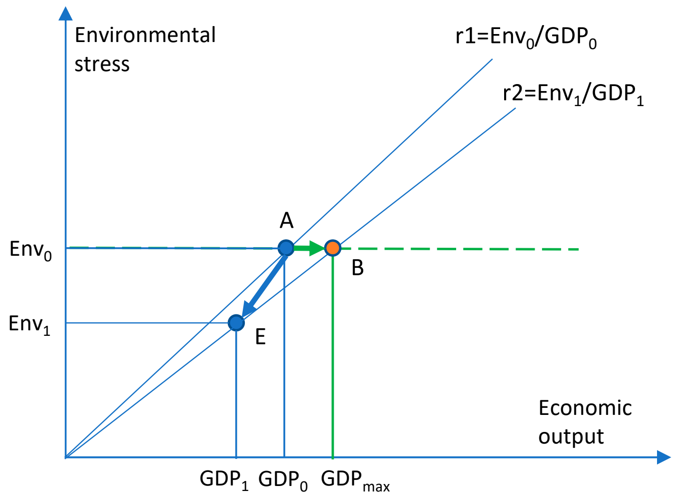

Figure 8. Determining maximum economic output when the economy is decreasing ($GDP_1 < GDP_0$), environmental stress is decreasing ($Env_1 < Env_0$), and environmental stress productivity is decreasing ($Env_1/GDP_1 < Env_0/GDP_0$).

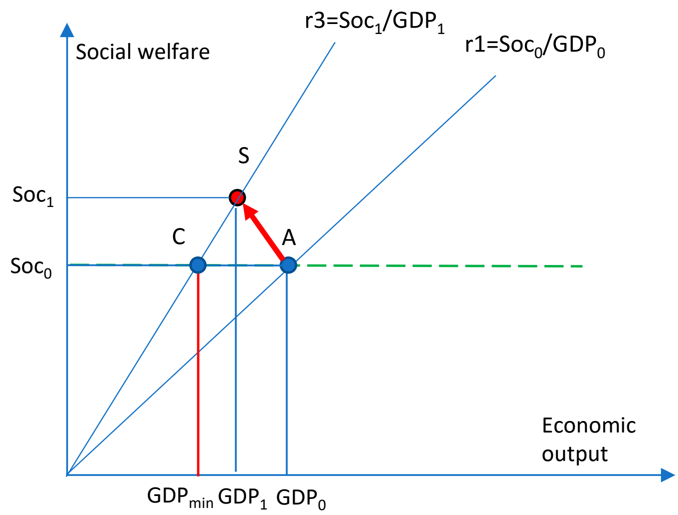

Figure 9. Determining minimum economic output when the economy is decreasing ($GDP_1 < GDP_0$), social welfare is increasing ($Soc_1 > Soc_0$), and social welfare productivity is increasing ($Soc_1/GDP_1 > Soc_0/GDP_0$).

In Figure 9, the starting point is A with social welfare at Soc_0 and economic output at GDP_0. At the final point S, the level of social welfare Soc_1 and economic output GDP_1 define the productivity line r3, in this case increasing social welfare productivity ($Soc_1/GDP_1 > Soc_0/GDP_0$), which determines the minimum sustainable economic output in relation to social welfare to be at point C.

To produce the sustainability window in an economic degrowth case, Figure 10 combines Figures 8 and 9 as maximum and minimum GDP output to define the Sustainability Window. In this case, the sustainability criteria are fulfiled since the actual GDP output (degrowth) is within the Sustainability Window ($GDP_{min} < GDP_1 < GDP_{max}$). It can be noticed that the potential maximum sustainable economic output GDP_{max} is higher than the original GDP_0 level, but the actual economic level of GDP_1 shows a degrowth case.

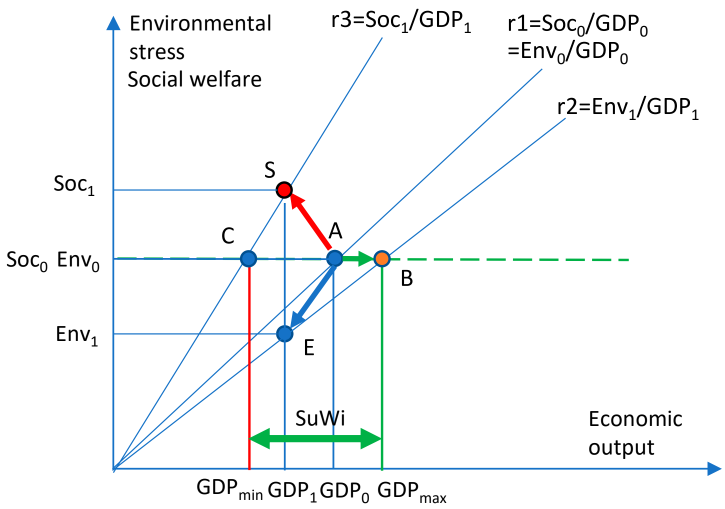

Figure 10. Determining the Sustainability Window in a case where the actual decreasing GDP output (degrowth) is within the Sustainability Window ($GDP_{min} < GDP_1 < GDP_{max}$).

The analyses of these case examples are widened in Appendix A to illustrate all possible cases related to changes in environmental stress, environmental stress productivity, social welfare, social welfare productivity, and GDP. Based on the different combinations of these changes, a table of all possible development paths and their sustainability outcomes are combined in Table 1 and presented next in Section 3.

Table 1. All combinations of GDP, environmental stress, social welfare, and related productivities with Sustainable Window analysis. The sustainable options are marked with green colour. The arrows indicate the direction of change (increase or decrease).

Economic Output (GDP)	Environ-mental Stress (Env)	Environmental Stress Productivity (Env/GDP)	Social Welfare (Soc)	Social Welfare Productivity (Soc/GDP)	No. of Combi-nation	No. of Logically Possible Combination	No. of SuWi Scenario Path	Figure Number in Appendix A	SuWi Identifi-cation Code	Sustainability Window	DGDP Inside SuWi	DSoc−DEnv	Comments
↗	↗	↗	↗	↗	1	1	1	Figure A1	E1S11	Positive	No	+	Unsustainable growth
							2	Figure A1	E1S12	Negative	No	−	Unsustainable growth
				↘	2	2	3	Figure A1	E1S13	Negative	No	−	Unsustainable growth
			↘	↗	3								Impossible
				↘	4	3	4	Figure A1	E1S14	Negative	Yes	−	Unsustainable growth
		↘	↗	↗	5	4	5	Figure A2	E2S21	Positive	No	+	Unsustainable growth
				↘	6	5	6	Figure A2	E2S22	Positive	No	+	Unsustainable growth
							7	Figure A2	E2S23	Negative	No	−	Unsustainable growth
			↘	↗	7								Impossible
				↘	8	6	8	Figure A2	E2S24	Negative	Yes	−	Unsustainable growth
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		↘	↗	↗	13	7	9	Figure A3	E3S31	Positive	Yes	+	Sustainable growth
				↘	14	8	10	Figure A3	E3S32	Positive	Yes	+	Sustainable growth
			↘	↗	15								Impossible
				↘	16	9	11	Figure A3	E3S33	Positive	No	+	Unsustainable growth
							12	Figure A3	E3S34	Negative	No	−	Unsustainable growth
↘	↗	↗	↗	↗	17	10	13	Figure A4	E4S41	Positive	No	+	Unsustainable degrowth
							14	Figure A4	E4S42	Negative	No	−	Unsustainable degrowth
				↘	18								Impossible
			↘	↗	19	11	15	Figure A4	E4S43	Negative	Yes	−	Unsustainable degrowth
				↘	20	12	16	Figure A4	E4S44	Negative	Yes	−	Unsustainable degrowth
		↘	↗	↗	21								Impossible
				↘	22								
			↘	↗	23								
				↘	24								
	↘	↗	↗	↗	25	13	17	Figure A5	E5S51	Positive	Yes	+	Sustainable degrowth
				↘	26								Impossible
			↘	↗	27	14	18	Figure A5	E5S52	Positive	No	+	Unsustainable degrowth
							19	Figure A5	E5S53	Negative	No	−	Unsustainable degrowth
				↘	28	15	20	Figure A5	E5S54	Negative	No	−	Unsustainable degrowth
		↘	↗	↗	29	16	21	Figure A6	E6S61	Positive	Yes	+	Sustainable degrowth
				↘	30								Impossible
			↘	↗	31	17	22	Figure A6	E6S62	Positive	No	+	Unsustainable degrowth
				↘	32	18	23	Figure A6	E6S63	Positive	No	+	Unsustainable degrowth
							24	Figure A6	E6S64	Negative	No	−	Unsustainable degrowth

3. Results

3.1. Possible Economic Growth Paths and Related Sustainability Outcomes

In this section, we illustrate different possible scenario paths depending on the possible direction and relative size of changes in the five variables: environmental stress (Env), social welfare (Soc), GDP, and the environmental and social welfare productivities Env/GDP and Soc/GDP. In Section 3.2, the Sustainability Window with absolute targets for environmental stress and social welfare are presented. Sections 3.1 and 3.2 deal with strong sustainability in terms of absolute changes in the environmental stress and social welfare indicators, but the changes are, however, relative to the base year level, which is not sustainable in absolute terms. With the SuWi approach, it is also possible to analyse weak sustainability if environmental stress intensity is used instead of environmental stress as the environmental indicator. For a detailed discussion of weak and strong sustainability, see [95].

Figure 4, Figure 7, and Figure 10 above illustrate that it is possible to have several different options for future development concerning sustainability, depending on changes in the analysed variables environmental stress (Env), social welfare (Soc), economic output (GDP), and the environmental stress productivity (Env/GDP) and social welfare productivity (Soc/GDP). Table 1 illustrates all the possible scenario paths related to the changes in these variables and the resultant sustainability of the development path. Appendix A includes the graphical presentations of the possible development paths indicated in the column "Reference" in Table 1.

Next, all theoretically possible development alternatives are identified for the future by using the SuWi approach, followed by the determination of the alternatives, which can fulfil the criteria of both environmental and social sustainability. First, the relevant variables of economic output (GDP), social welfare (Soc), environmental stress (Env), social welfare productivity (Soc/GDP), and environmental stress productivity (Env/GDP) are considered. The value of each variable can change, either increasing or decreasing over time. In terms of all possible combinations that can be hypothesised, there are $2^5 = 32$ different possible combinations of changes, as illustrated in Table 1.

Because the productivity indicators, Soc/GDP and Env/GDP, are not independent but depend on changes in GDP, Soc, and Env, all combinations are not logically possible. For instance, when economic activity (GDP) increases, and social welfare (Soc) decreases, then social welfare productivity (Soc/GDP) cannot increase. If GDP increases and environmental stress (Env) decreases, then environmental stress productivity (Env/GDP) cannot increase. Similarly, if GDP decreases and Soc or Env increases, then Soc/GDP or Env/GDP cannot decrease. For this reason, all together, 14 out of the 32 hypothesised combinations are logically impossible. These combinations are marked as "impossible" in Table 1. Among the remaining 18 logically possible combinations, six combinations can have two additional alternatives for the difference between the indexed values of environmental stress and social welfare. This difference, as shown in the column titled ΔSoc − ΔEnv in Table 1, is of great importance since it determines whether the Sustainability Window for the economic growth path is positive ($GDP_{max} > GDP_{min}$) or negative ($GDP_{max} < GDP_{min}$).

In Table 1, all 32 combinations of the five variables, the 18 logically possible combinations and the 24 different Sustainability Window analyses of the possible scenario paths are presented (see Appendix A for the graphical presentations of the 24 identified scenario paths). The sustainable cases are illustrated in Figure 11a–d; see also combinations 13, 14, 25 and 29, marked with green in Table 1.

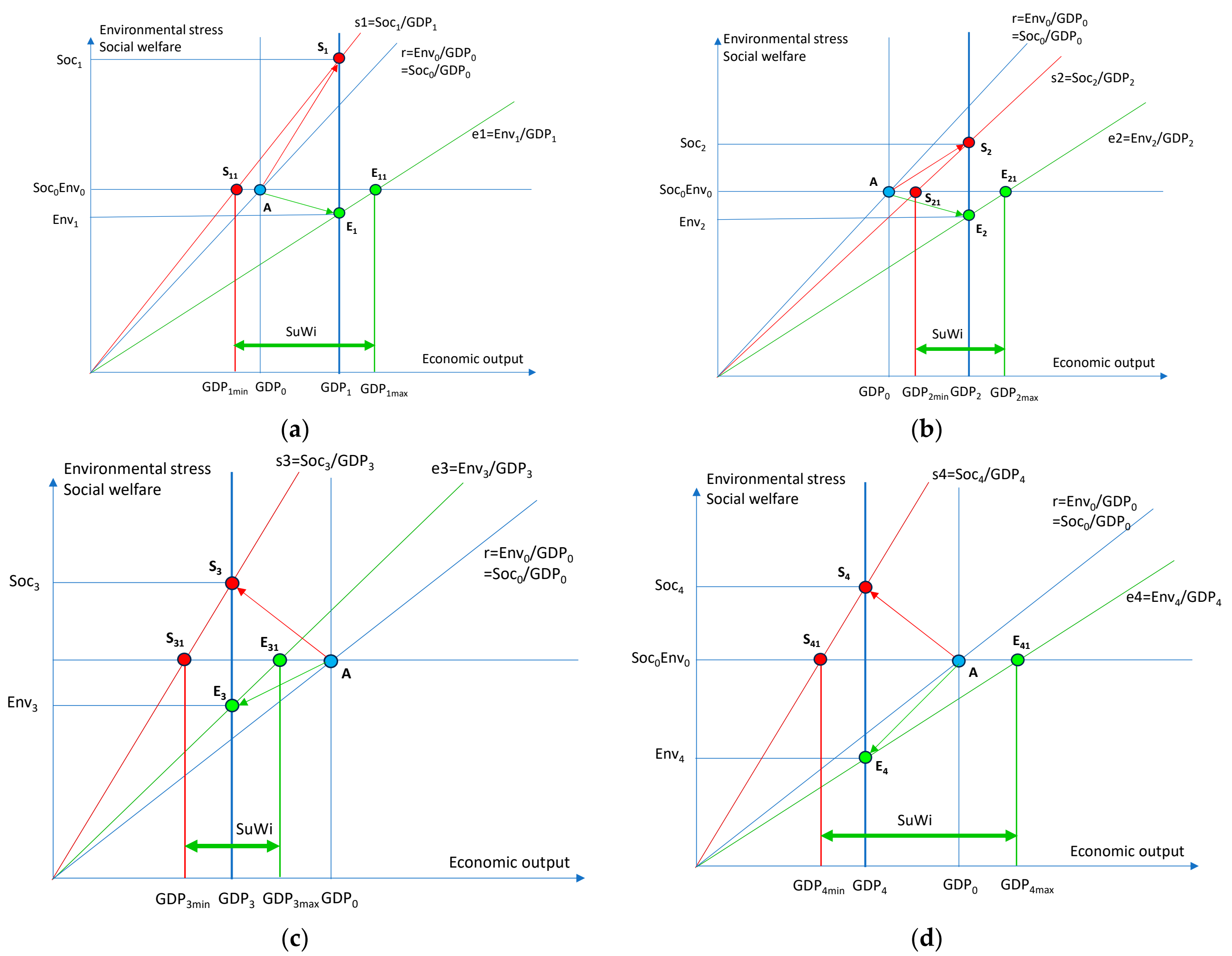

Figure 11. (**a**–**d**). The four sustainable paths of the economy, where (**a**,**b**) are paths of economic growth and (**c**,**d**) paths of economic degrowth. In all figures point A is the starting point. Points E_1, E_2, E_3, E_4 are the environmental indicator points in the analysis year. Points S_1, S_2, S_3, S_4 are the social indicator points in the analysis year.

Figure 11a,b illustrates cases where the economic output (GDP) grows, and Figure 11c,d illustrates cases where economic output decreases. In Figure 11a, welfare productivity ($Soc_1/GDP_1 > Soc_0/GDP_0$) increases, and in Figure 11b, welfare productivity decreases ($Soc_2/GDP_2 < Soc_0/GDP_0$). In both cases, environmental stress productivity decreases ($Env_1/GDP_1 < Env_0/GDP_0$). In Figure 11c, social welfare productivity increases, ($Soc_3/GDP_3 > Soc_0/GDP_0$) and environmental stress productivity increases, too ($Env_3/GDP_3 > Env_0/GDP_0$). In Figure 11d, social welfare productivity increases ($Soc_4/GDP_4 > Soc_0/GDP_0$), and environmental stress productivity decreases ($Env_4/GDP_4 < Env_0/GDP_0$).

The sustainable maximum and minimum economic output can be calculated using the following equations:

$$\frac{GDP_{max}}{Env_0} = \frac{GDP_1}{Env_1}, \tag{1}$$

where

$$GDP_{max} = \frac{GDP_1 \times Env_0}{Env_1}, \tag{2}$$

and

$$\frac{GDP_{min}}{Soc_0} = \frac{GDP_1}{Soc_1}, \tag{3}$$

where

$$GDP_{min} = \frac{GDP_1 \times Soc_0}{Soc_1}, \quad (4)$$

where Env_0 is environmental stress in the base year (measured with suitable indicator and indexed to 1), Env_1 is environmental stress in the analysis year, Soc_0 is social welfare in the base year (measured with suitable indicator and indexed to 1), Soc_1 is social welfare in the analysis year, GDP_0 is the economic output in the base year, GDP_1 is the economic output in the analysis year, GDP_{max} is the maximum economic output in order not to increase environmental stress, and GDP_{min} is the minimum economic output not to decrease social welfare.

These equations are valid for all the cases. A criterion for a sustainable case is the following:

$$GDP_{min} < GDP_1 < GDP_{max} \quad (5)$$

3.2. Analysis of Sustainability Windows with Absolute Targets

It is widely accepted that in the case of many environmental stress variables, such as greenhouse gas emissions and biodiversity loss, an absolute reduction target must be defined for environmental sustainability. In these cases, rather than requiring no increase in environmental stress, the cases would necessarily be framed by the requirement to reach absolute reduction targets. This could also be necessary for social welfare, which is in line with achieving equity. This section considers the Sustainability Window for cases of absolute targets. Figure 12 illustrates a case where there is an absolute target level for environmental stress. The preliminary state of the system is described with indexed levels of environmental stress, Env_0, social welfare, Soc_0, and economic output, GDP_0, at point A. The productivity levels are described as Soc_0/GDP_0 = Env_0/GDP_0 (indexed base year values).

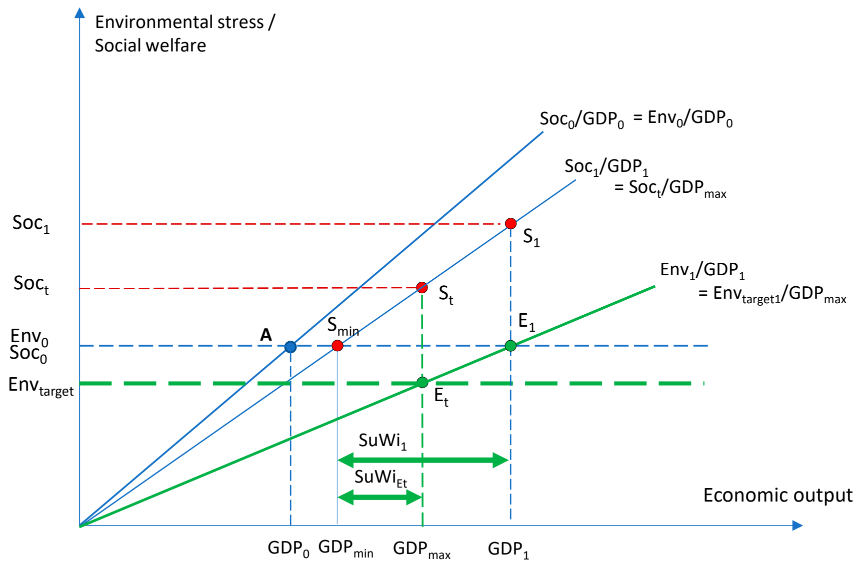

Figure 12. Sustainability Window in the case of an environmental stress target Env_{target}.

If relative criteria for sustainability are used it means that the environmental stress should not increase and social welfare should not decrease. In this case, social development could arrive at point S_1, with social welfare at Soc_1, environmental development at E_1 with environmental stress at Env_0, and economic output at level GDP_1. In this case, the Sustainability Window would be defined by $SuWi_1$, where the minimum economic output is defined by GDP_{min} at point S_{min} (social welfare does not decrease from Soc_0) and maximum economic output at point E_1 with GDP_1 (environmental stress does not increase from Env_0). The described development fulfils the relative sustainability criteria identified.

However, adopting an absolute target for the environmental stress, defined with Env_{target}, requires lowering the economic output to reach the point E_t when environmental stress productivity is Env_1/GDP_1 = Env_{target}/GDP_{max}. This defines the maximum economic output GDP_{max}. In this case, the minimum level of economic output is also determined using the point S_{min} at the level of GDP_{min}, where social welfare does not decrease. Now, the Sustainability Window is $SuWi_{Et}$, within which the maximum environmental stress level achieves Env_{target} and the minimum social welfare level is Soc_0 (at S_{min}). In this case, the maximum social welfare level is reduced from Soc_1 to Soc_t due to the environmental target criterion. In this type of development path, for economic output to be sustainable, the maximum economic output must be reduced, and social welfare must be reduced from Soc_1 to Soc_t.

This type of development, with an absolute environmental target, could enable either economic growth or degrowth to be sustainable. The economic degrowth possibility is the result of improved social welfare productivity ($Soc_1/GDP_1 > Soc_0/GDP_0$), illustrated in Figure 13. Here, the minimum economic output is defined by GDP_{min} at point S_{min}, which is lower than GDP_0 enabling sustainable economic degrowth. The Sustainability Window is determined by S_{min} (GDP_{min}) and E_t, which defines the maximum GDP output, GDP_{max}, in the same way as in Figure 12.

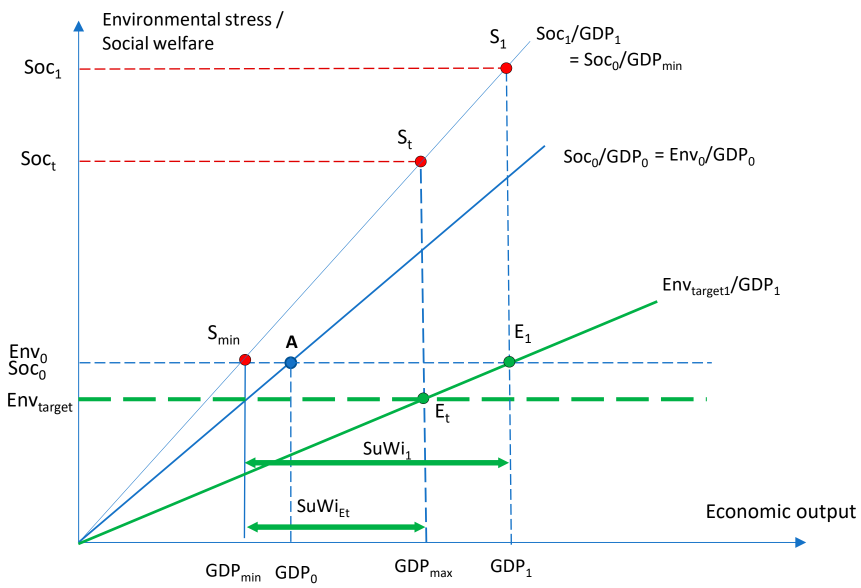

Figure 13. Sustainability Window in the case where social welfare productivity Soc_1/GDP_1 increases and enables the reduction of the minimum economic output (degrowth) when the environmental stress target is determined.

Maximum GDP, in the case where we have an environmental target, can be calculated as follows:

$$\frac{GDP_{max}}{Env_{target}} = \frac{GDP_1}{Env_0}, \quad (6)$$

where

$$GDP_{max} = \frac{GDP_1 \times Env_{target}}{Env_0} \quad (7)$$

Figure 14 illustrates a case where an absolute social welfare target is applied. The starting point is A, with social welfare at Soc_0, environmental stress at Env_0, and economic output at GDP_0. The productivity of environmental stress is assumed to decrease to Env_1/GDP_1 (at point E_1) and social welfare productivity to increase to Soc_1/GDP_1 (at point S_1). Relative environmental sustainability (no increase in environmental stress) limits the maximum economic output to GDP_{max} at E_{t1}. The absolute social welfare target determines the minimum economic output to be at the level of GDP_{min} at S_t, where the social target Soc_{target} is reached. Now, GDP_{min} and GDP_{max} define the Sustainability Window.

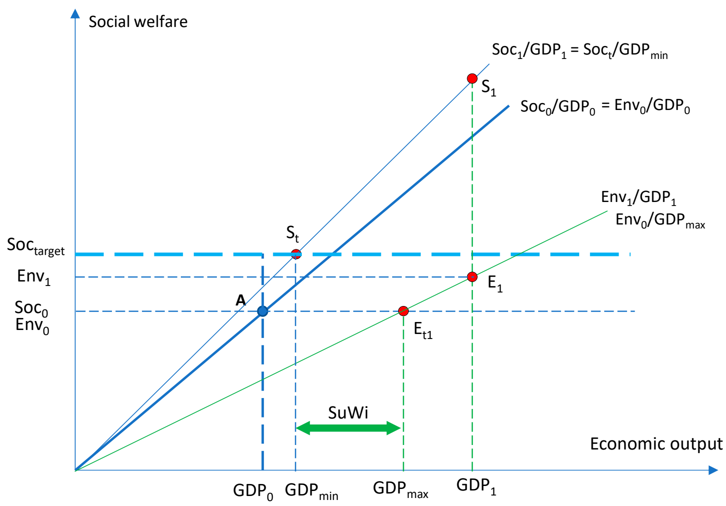

Figure 14. Sustainability Window in the case where the social welfare target is determined.

Minimum GDP, in the case when we have a social welfare target (Figure 14), can be calculated as follows:

$$\frac{GDP_{min}}{Soc_{target}} = \frac{GDP_1}{Soc_1}, \tag{8}$$

where

$$GDP_{min} = \frac{GDP_1 \times Soc_{target}}{Soc_1} \tag{9}$$

Beginning with a target for the level of social welfare allows for the determination of the minimum economic output for SuWi accordingly, as shown in Figure 15, in different cases of social welfare productivity. The starting point here is again point A with Soc_0 as the level of social welfare, and the Sustainable welfare target is indicated with Soc_{target}. At this level, the minimum economic output depends on the social welfare productivity of GDP. The social welfare productivity Soc_1/GDP_1 defines the lowest sustainable level of GDP as GDP_1. This indicates that the economic degrowth option is possible, even with an increased target level for social welfare, if the social welfare productivity is increasing.

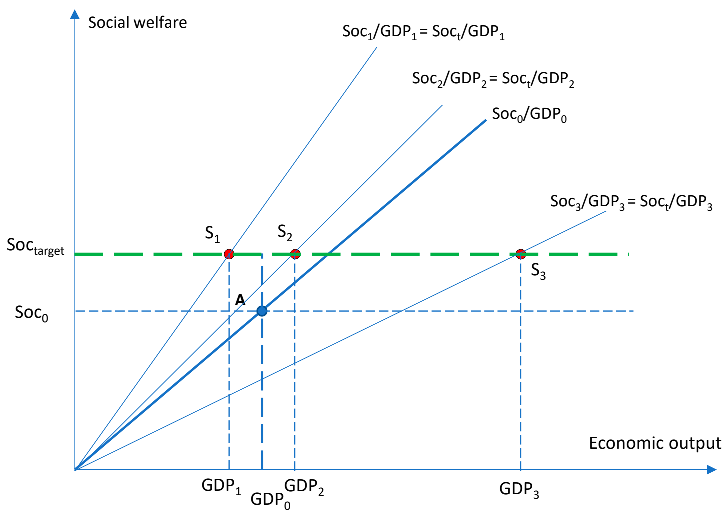

Figure 15. Determining minimum economic output for different social welfare productivity levels (Soc/GDP) in the case where the level of social welfare is defined at Soc_{target}.

With the social welfare productivity level Soc_2/GDP_2, the minimum sustainable GDP, in relation to the sustainable target level of social welfare, must be higher than the original GDP level. With this type of change in welfare productivity, the economic degrowth option is not sustainable; even though welfare productivity is increasing, the increased target level of social welfare cannot be reached with degrowth.

In the case of social welfare productivity level Soc_3/GDP_3, economic output must be higher than GDP_3 to fulfil the social sustainability criterion. This shows that if social welfare productivity decreases, economic output has to be higher to reach a sustainable level of social welfare.

Figure 16 illustrates a case where there are targets for both reduced environmental stress and increased social welfare in an economic degrowth situation. In this case, the environmental stress productivity can even increase ($Env_{target}/GDP_1 > Env_0/GDP_0$) when the social welfare productivity increases ($Soc_{target}/GDP_1 > Soc_0/GDP_0$).

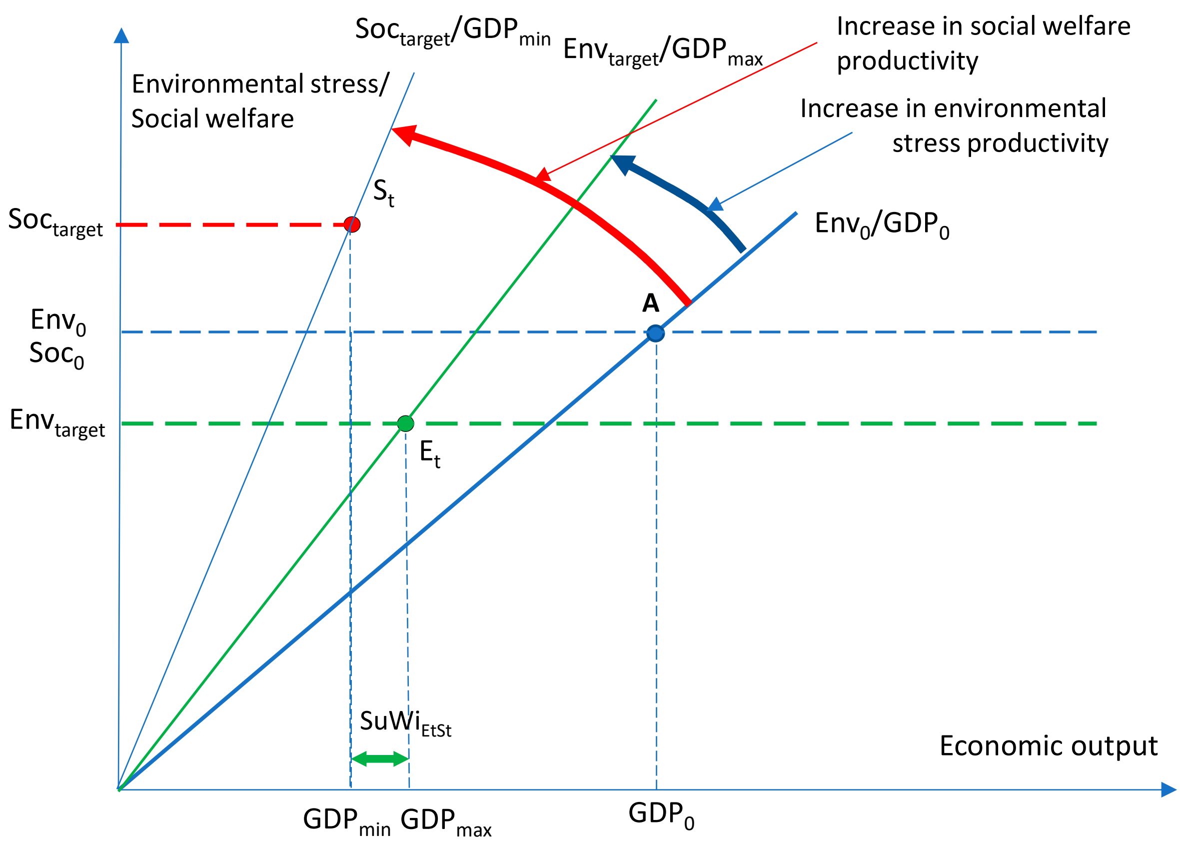

Figure 16. The economic degrowth case with the both environmental and social targets.

In this context, the efficiency gap could be defined as the lack of improvement in environmental efficiency [72] or social productivity to reach a defined sustainability level. Figure 17 illustrates the case of the efficiency gap, where it is assumed that the environmental stress productivity decreases from Env_0/GDP_0 to the level of Env_1/GDP_1. This is, however, not enough to reach relative environmental sustainability because the environmental stress is increasing alongside increasing GDP. The environmental stress productivity should be decreased to the level of $r2 = Env_0/GDP_1$ in order not to increase environmental stress if the GDP level is GDP_1. The efficiency gap, in this case, is $r1/r2$, and this should be used to guide the policy planning process towards sustainability.

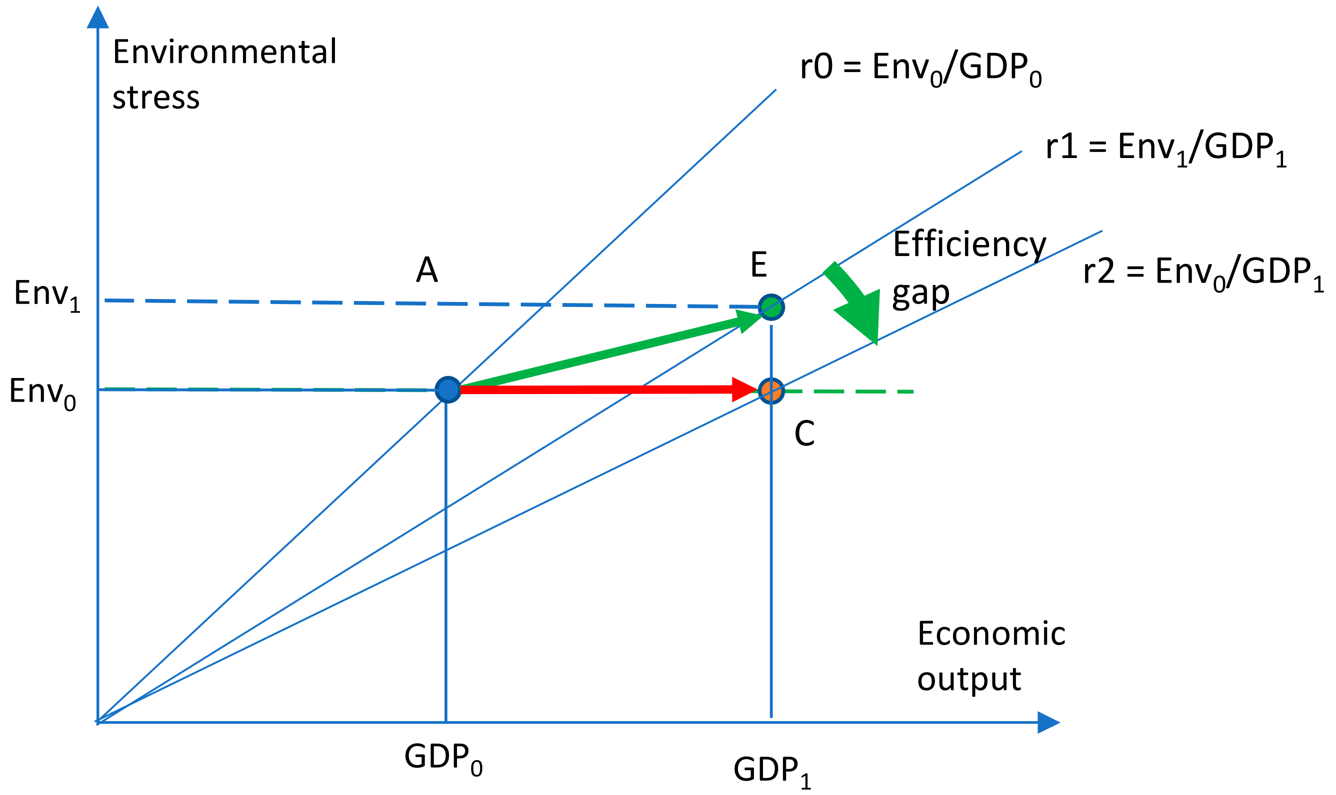

Figure 17. Illustration of an efficiency gap for sustainability planning of the economy.

4. Discussion

Across the decades of contemporary thinking on sustainable development, a core debate has concerned whether economic growth can be made environmentally and socially sustainable. In more recent years, this has become a debate about economic growth versus degrowth, whether the former can be environmentally sustainable, and whether the latter can be socially sustainable [12]. This article has used the Sustainability Window, or "SuWi" approach, to theoretically determine the sustainable window of economies, as upper and lower bounds of change in GDP, that could be deemed in line with environmental and social sustainability. All theoretically possible development paths have been considered by first combining the economic, environmental, and social variables with the environmental and social productivity of GDP. The article demonstrates that of the 32 possible combinations of these five variables, 18 are logically possible.

In moving to sustainability analysis through SuWi, it is noted that there are 24 logically possible development paths, yet only four (4) of them could be considered sustainable under the assumed sustainability criteria, defined as the value of a selected environmental indicator cannot increase, and the value of a selected social indicator cannot decrease. Two of these involve economic growth and two degrowth. In these cases, the sustainability of outcomes is predicated not only on the definition of sustainability but also on the emergence of specific paths in terms of absolute change in GDP and related productivity. Once the environmental and social criteria are set, the development path must emerge according to clearly defined quantitative trends if the economic outcome is to be defended as theoretically sustainable from both environmental and social perspectives. In the two sustainable economic growth cases (increasing GDP), social welfare productivity (Soc/GDP) can decrease, but environmental stress productivity (Env/GDP) must decrease in both cases to achieve sustainability. In sustainable economic degrowth cases (decreasing GDP), environmental stress productivity can decrease or increase, but social welfare productivity must increase in both cases to achieve sustainability. The analysis illustrates the importance of changes in productivity that reflect different system structures in addition to efficiency related to techno-economic change. To meet specified sustainability criteria, it is then also theoretically possible to adjust growth rates for economic growth or degrowth outcomes. By applying the SuWi analysis, this article can be described as providing a general theory for the place of economic growth in sustainable development, as it can be applied to all possible environmental and social outcomes, all possible paths of economic growth, and all possible combinations of environmental and social productivity of GDP.

In the debate on economic growth, including the classic Simon–Ehrlich wager [96], some have argued that science and technology will enable sustained growth of consumption without harmful growth in the use of natural resources by doing more with less. Others propose that this is not possible, emphasising absolute limits in the carrying capacity of the Earth, concluding that there are limits to either population growth or to material consumption in the rich world, with a necessity to reduce demand and by rapidly scaling up system change alongside technological innovation. The specifics of whether an outcome could be deemed "sustainable" are dependent on the specific environmental and social themes and the relevant criteria applied to define sustainability. Using the SuWi analysis, both relative and absolute targets can be considered in both strong and weak sustainability configurations. The SuWi approach can be used to inform about real development options globally, nationally, and regionally while noting that specific answers in applied settings will also depend upon the choice of environmental and social indicators, data availability, and the real dynamics of sustainability paths. The SuWi approach could also assist in holistic analysis and planning for the UN SDGs [34] and sustainable development, in general, to engage with the critical issues of policy coordination, to analyse synergies and trade-offs, and to assist in understanding policy dialogues about absolute and efficiency targets in evidence-based decision-making. As environmental pressures increase, while climate and ecological breakdown resonate alongside the demands of social sustainability, approaches such as SuWi may become indispensable to sustainability science and effective policymaking.

Rather than static ceteris paribus conditions, a SuWi can be performed as a dynamic integrated analysis, using time series rather than beginning and end points [74], which remains a rarity in integrated approaches. The SuWi can be applied to the estimation of an efficiency gap [72] in the case of absolute environmental or social development targets. This makes the SuWi approach a useful tool for policy analysis to indicate priority areas for improvement in efficiency. When noting the efficiency gap between actual and desired outcomes, a widening or narrowing of the window can give valuable information for policy planning and for guidance on the timing of planned actions and their extent. The minimum and maximum economic growth rates could also be used for the construction of a "doughnut model" of sustainability [97,98]. In the doughnut model, the different pairs of SuWi indicator analysis results are arranged in a radial diagram where the inner circle illustrates the minimum economic growth to guarantee sustainable social development, and the outer circle illustrates the maximum economic growth not to exceed the environmental limits of sustainability. The doughnut model can be used to attain an overall view of multidimensional sustainability and to illustrate the problematic and critical areas of development where special attention is necessary. The dynamic SuWi analysis also allows for the consideration of intergenerational equity, if there is availability of sufficient time series data.

The presented novel theoretical framework for sustainability analysis is unique in categorising all possible development paths and developing explicit rules for sustainability in each case. Future research direction should include testing the developed framework in different case studies and analysing the suitability of different indicator frameworks for the analysis. The properties of the indicators used for the analysis are critical, and their numeric characteristics should be similar. For instance, indicators having exponential growth potential, such as GDP, have distinct differences in properties in comparison to indicators with limited increases, such as the Human Development Index with a maximum value of 1. The latter would require modification to be operationalised, as illustrated by the indicators included in the Sustainable Society Index (SSI) [99].

In the analysis of sustainability processes, the complexity of systems cannot be avoided, including cyclic economic growth and associated sustainability challenges, which are implicit in the approach [100]. The SuWi can provide a platform for ex ante scenario planning to evaluate possible, desirable, and even avoidable future developments. Employing a SuWi in this manner could assist in policy planning under conditions of complexity and uncertainty, which characterise interdependent policy challenges for sustainability. In addition to considering the impact of economic development, the flexibility of SuWi permits multiple uses of key interest to empirical analysis in sustainability science in response to the heterogeneous demands of 21st-century policymaking for sustainability.

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Appendix A

This Appendix includes graphical descriptions of all 24 possible development paths presented in Table 1 in the text, regarding the Sustainability Windows of all combinations of environmental stress (Env), social welfare (Soc), economic development (GDP), environmental stress productivity (Env/GDP), and social welfare productivity (Soc/GDP). The 24 possible development paths are grouped into six graphs (Figures A1–A6). The grouping is based on possible combinations of changes in GDP and environmental stress productivity (Env/GDP). In each of Figures A1–A6, four possible social welfare productivities (Soc/GDP) and related social welfare (Soc) levels are identified.

- The original values of all variables are marked with subscript 0 (GDP_0, Env_0, Soc_0, Env_0/GDP_0);
- The new GDP, Env, and Env/GDP values have a subscript referring to the number of the group (GDP_1–GDP_6, Env_1–Env_6, Env_1/GDP_1–Env_6/GDP_6;
- The new social welfare values have a subscript referring to the number of the group and the number of the four cases case (Soc_{11}–Soc_{64}), and the related social welfare productivities have corresponding subscripts (Soc_{11}/GDP_1–Soc_{64}/GDP_6);
- The Sustainability Windows are marked with a subscript E referring to the environmental stress of the group (Env_1–Env_6) and with a subscript S referring to the social welfare case inside each group (Soc_{11}–Soc_{64}), i.e., $SuWi_{E1S11}$–$SuWi_{E6S64}$.

Appendix A.1. Group 1 (Figure A1)

Starting point A. Environmental steress E_1 in the analysis year. Environmental stress increases ($Env_1 > Env_0$), GDP increases ($GDP_1 > GDP_0$), and environmental stress productivity increases ($Env_1/GDP_1 > Env_0/GDP_0$)

Social welfare can have four different options:

1. $Soc_{11} > Soc_0$ and $Soc_{11} > Env_1$ and $Soc_{11}/GDP_1 > Env_1/GDP_1$ and $Soc_{11}/GDP_1 > Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E1S11}$) is positive, but the actual GDP growth is outside SuWi ($GDP_1 > GDP_{max}$). This case does not fulfil the sustainability criteria.

2. $Soc_{12} > Soc_0$ and $Soc_{12} < Env_1$ and $Soc_{12}/GDP_1 < Env_1/GDP_1$, and $Soc_{12}/GDP_1 > Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E1S12}$) is negative ($GDP_{min} > GDP_{max}$), and the actual GDP growth is outside SuWi ($GDP_1 > GDP_{max}$). This case does not fulfil the sustainability criteria.

3. $Soc_{13} > Soc_0$ and $Soc_{13} < Env_1$ and $Soc_{13}/GDP_1 < Env_1/GDP_1$, and $Soc_{13}/GDP_1 < Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E1S13}$) is negative ($GDP_{min} > GDP_{max}$), and the actual GDP growth is outside SuWi ($GDP_1 > GDP_{max}$). This case does not fulfil the sustainability criteria.

4. $Soc_{14} < Soc_0$ and $Soc_{14} < Env_1$ and $Soc_{14}/GDP_1 < Env_1/GDP_1$, and $Soc_{14}/GDP_1 < Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E1S14}$) is negative ($GDP_{min} > GDP_{max}$) even though the actual GDP growth is inside the negative SuWi ($GDP_{max} < GDP_1 < GDP_{min}$). This case does not fulfil the sustainability criteria.

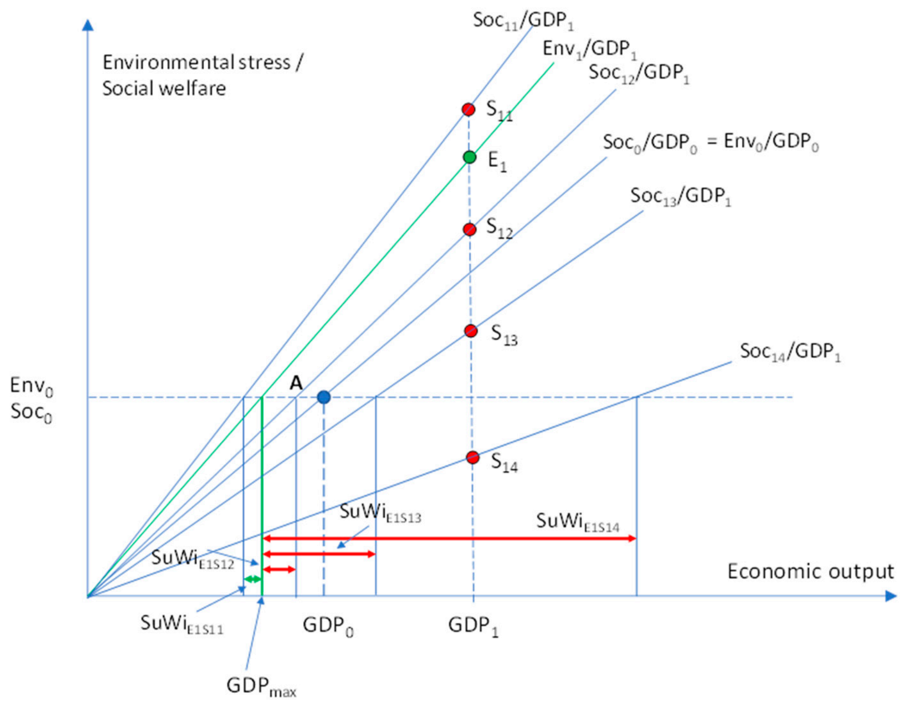

Figure A1. Sustainability Window in all possible cases where GDP, environmental stress (Env) and environmental stress productivity (Env/GDP) increase.

Appendix A.2. Group 2 (Figure A2)

GDP increases ($GDP_2 > GDP_0$), environmental stress increases ($Env_2 > Env_0$), and environmental stress productivity decreases ($Env_2/GDP_2 < Env_0/GDP_0$).

Social welfare can have four different options:

1. $Soc_{21} > Soc_0$ and $Soc_{21} > Env_2$ and $Soc_{21}/GDP_2 > Env_2/GDP_1$ and $Soc_{21}/GDP_2 > Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E2S21}$) is positive ($GDP_{min} < GDP_{max}$), but the actual GDP growth is outside SuWi ($GDP_2 > GDP_{max}$). This case does not fulfil the sustainability criteria.

2. $Soc_{22} > Soc_0$ and $Soc_{22} > Env_2$ and $Soc_{22}/GDP_2 > Env_2/GDP_2$, and $Soc_{22}/GDP_2 < Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E2S22}$) is positive ($GDP_{min} < GDP_{max}$), but the actual GDP growth is outside SuWi ($GDP_2 > GDP_{max}$). This case does not fulfil the sustainability criteria.

3. $Soc_{23} < Soc_0$ and $Soc_{23} < Env_2$ and $Soc_{23}/GDP_2 < Env_2/GDP_2$, and $Soc_{23}/GDP_2 < Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E2S23}$) is negative ($GDP_{min} > GDP_{max}$), and the actual GDP growth is outside SuWi ($GDP_2 > GDP_{max}$). This case does not fulfil the sustainability criteria.

4. $Soc_{24} < Soc_0$ and $Soc_{24} < Env_2$ and $Soc_{24}/GDP_2 < Env_2/GDP_2$, and $Soc_{24}/GDP_2 < Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E2S24}$) is negative ($GDP_{min} > GDP_{max}$) even though the actual GDP growth is inside the negative SuWi ($GDP_{max} < GDP_2 < GDP_{min}$). This case does not fulfil the sustainability criteria.

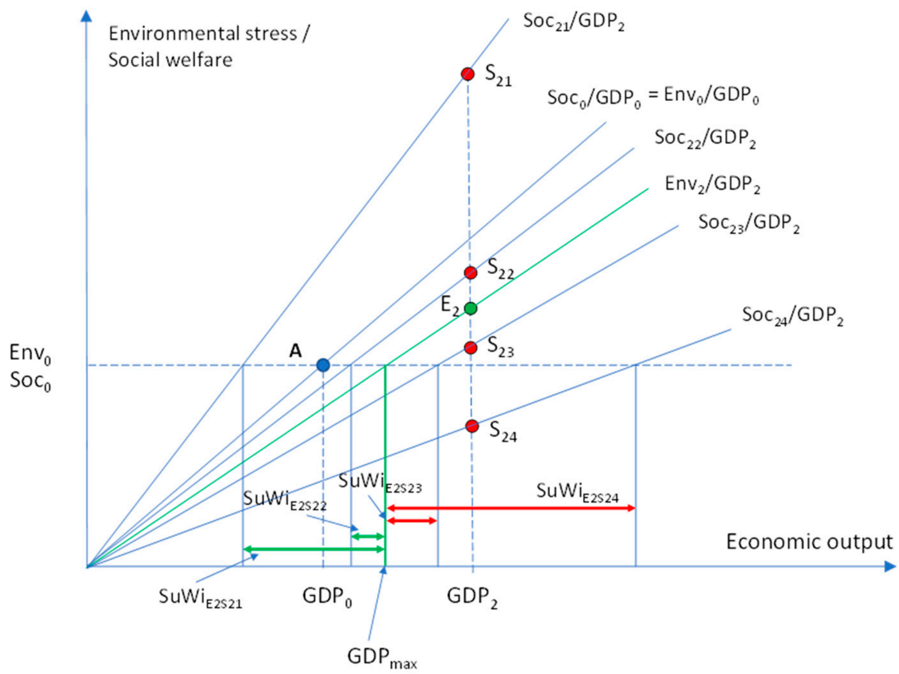

Figure A2. Sustainability Window in all possible cases where GDP and environmental stress (Env) increase, and environmental stress productivity (Env/GDP) decreases.

Appendix A.3. Group 3 (Figure A3)

GDP increases ($GDP_3 > GDP_0$), environmental stress decreases ($E_3 < E_0$), and environmental stress productivity decreases ($Env_3/GDP_3 < Env_0/GDP_0$).

Social welfare can have four different options:

1. $Soc_{31} > Soc_0$ and $Soc_{31} > Env_3$ and $Soc_{31}/GDP_3 > Env_3/GDP_3$ and $Soc_{31}/GDP_3 > Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E3S31}$) is positive ($GDP_{min} < GDP_{max}$), and the actual GDP growth is inside SuWi ($GDP_{min} < GDP_3 < GDP_{max}$). This case fulfils the sustainability criteria.

2. $Soc_{32} > Soc_0$ and $Soc_{32} > Env_3$ and $Soc_{32}/GDP_3 > Env_3/GDP_3$, and $Soc_{32}/GDP_3 < Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E3S32}$) is positive ($GDP_{min} < GDP_{max}$), and the actual GDP growth is inside SuWi ($GDP_{min} < GDP_3 < GDP_{max}$). This case fulfils the sustainability criteria.

3. $Soc_{33} < Soc_0$ and $Soc_{33} > Env_3$ and $Soc_{33}/GDP_3 > Env_3/GDP_3$, and $Soc_{33}/GDP_3 < Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E3S33}$) is positive ($GDP_{min} < GDP_{max}$), but the actual GDP growth is outside SuWi ($GDP_3 < GDP_{3min}$). This case does not fulfil the sustainability criteria.

4. $Soc_{34} < Soc_0$ and $Soc_{34} < Env_3$ and $Soc_{34}/GDP_3 < Env_3/GDP_3$, and $Soc_{34}/GDP_3 < Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E3S24}$) is negative ($GDP_{min} > GDP_{max}$), and the actual GDP growth is outside the negative SuWi ($GDP_3 < GDP_{max} < GDP_{min}$). This case does not fulfil the sustainability criteria.

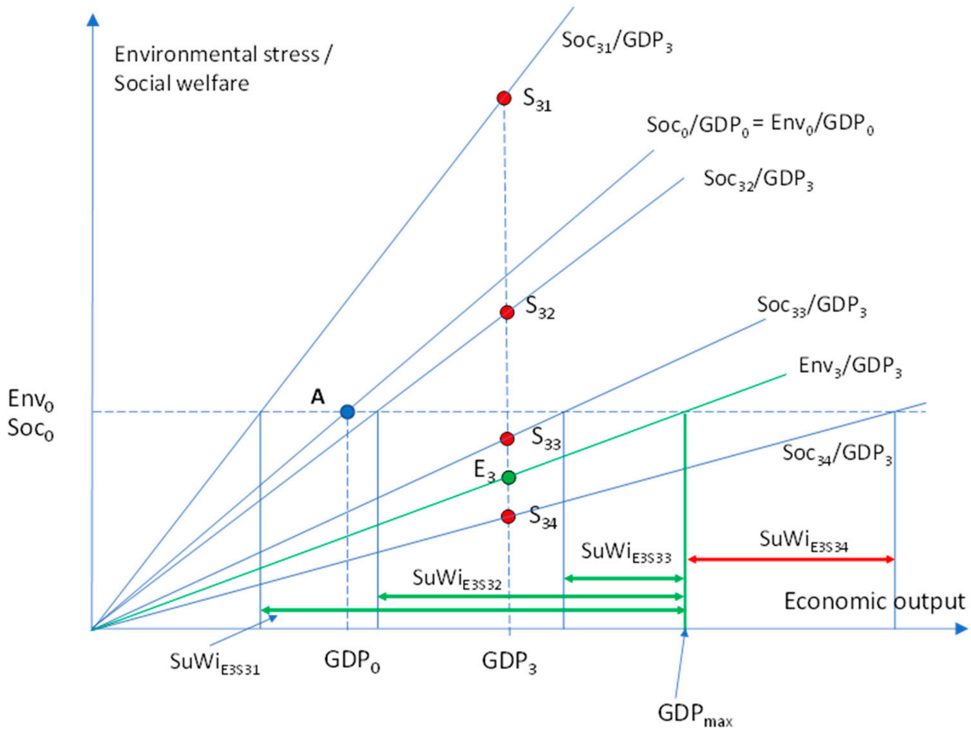

Figure A3. Sustainability Window in all possible cases where GDP increases and environmental stress (Env) and environmental stress productivity (Env/GDP) decrease.

Appendix A.4. Group 4 (Figure A4)

GDP decreases ($GDP_4 < GDP_{0)}$, environmental stress increases ($E_4 > E_0$), and environmental stress productivity increases ($Env_4/GDP_4 > Env_0/GDP_0$).

Social welfare can have four different options:

1. $Soc_{41} > Soc_0$ and $Soc_{41} > Env_4$ and $Soc_{41}/GDP_4 > Env_4/GDP_4$ and $Soc_{41}/GDP_4 > Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E4S41}$) is positive ($GDP_{min} < GDP_{max}$), but the actual GDP growth is outside SuWi ($GDP_{min} < GDP_4 > GDP_{max}$). This case does not fulfil the sustainability criteria.

2. $Soc_{42} > Soc_0$ and $Soc_{42} < Env_4$ and $Soc_{42}/GDP_4 < Env_4/GDP_4$, and $Soc_{42}/GDP_4 > Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E4S42}$) is negative ($GDP_{min} > GDP_{max}$), and the actual GDP growth is outside SuWi ($GDP_{min} < GDP_4 > GDP_{max}$). This case does not fulfil the sustainability criteria.

3. $Soc_{43} < Soc_0$ and $Soc_{43} < Env_4$ and $Soc_{43}/GDP_4 < Env_4/GDP_4$, and $Soc_{43}/GDP_4 > Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E4S43}$) is negative ($GDP_{min} > GDP_{max}$) even though the actual GDP growth is inside the negative SuWi ($GDP_4 > GDP_{max} < GDP_{min}$). This case does not fulfil the sustainability criteria.

4. $Soc_{44} < Soc_0$ and $Soc_{44} < Env_4$ and $Soc_{44}/GDP_4 < Env_4/GDP_4$, and $Soc_{44}/GDP_4 <$ Soc0/GDP0

In this case, the Sustainability Window ($SuWi_{E4S44}$) is negative ($GDP_{min} > GDP_{max}$), and the actual GDP growth is outside the negative SuWi ($GDP_4 < GDP_{max} < GDP_{min}$). This case does not fulfil the sustainability criteria.

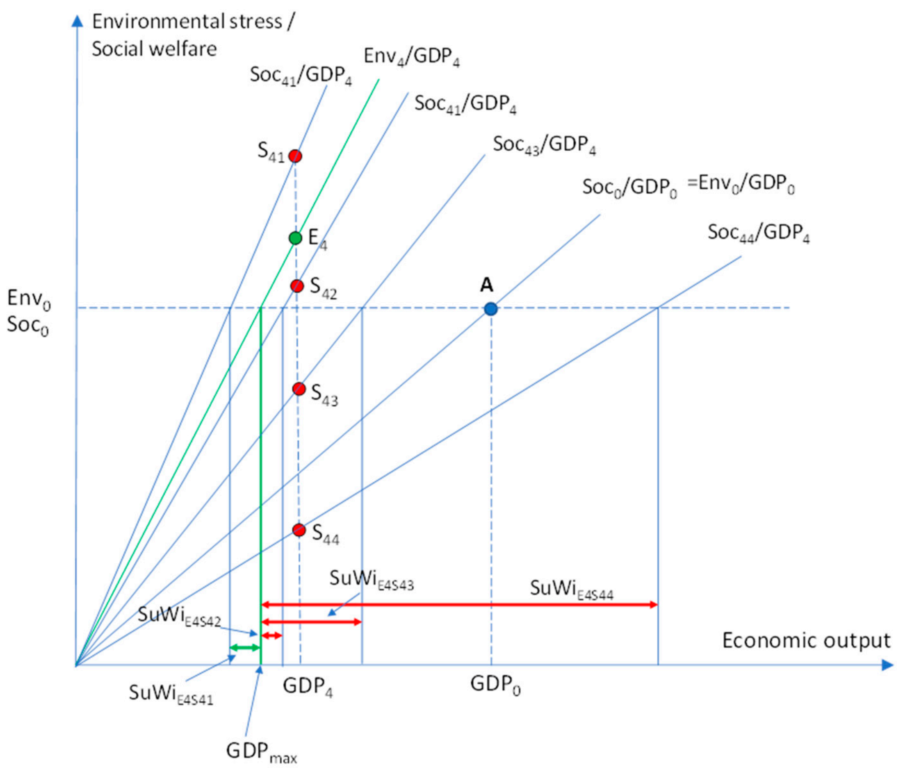

Figure A4. Sustainability Window in all possible cases where GDP decreases and environmental stress (Env), and environmental stress productivity (Env/GDP) increase.

Appendix A.5. Group 5 (Figure A5)

GDP decreases ($GDP_5 < GDP_0$), environmental stress decreases ($E_5 < E_0$), and environmental stress productivity increases ($Env_5/GDP_5 > Env_0/GDP_0$).

Social welfare can have four different options:

1. $Soc_{51} > Soc_0$ and $Soc_{51} > Env_5$ and $Soc_{51}/GDP_5 > Env_5/GDP_5$ and $Soc_{51}/GDP_5 > Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E5S51}$) is positive ($GDP_{min} < GDP_{max}$), and the actual GDP growth is inside SuWi ($GDP_{min} < GDP_5 < GDP_{max}$). This case fulfils the sustainability criteria.

2. $Soc_{52} < Soc_0$ and $Soc_{52} > Env_5$ and $Soc_{52}/GDP_5 > Env_5/GDP_5$, and $Soc_{52}/GDP_5 > Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E5S52}$) is positive ($GDP_{min} < GDP_{max}$), but the actual GDP growth is outside SuWi ($GDP_5 < GDP_{min} < GDP_{max}$). This case does not fulfil the sustainability criteria.

3. $Soc_{53} < Soc_0$ and $Soc_{53} < Env_5$ and $Soc_{53}/GDP_5 < Env_5/GDP_5$, and $Soc_{53}/GDP_5 > Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E5S53}$) is negative ($GDP_{min} > GDP_{max}$), and the actual GDP growth is outside the negative SuWi ($GDP_5 < GDP_{max} < GDP_{min}$). This case does not fulfil the sustainability criteria.

4. $Soc_{54} < Soc_0$ and $Soc_{54} < Env_5$ and $Soc_{54}/GDP_5 < Env_5/GDP_5$, and $Soc_{54}/GDP_5 < Soc_0/GDP_0$

In this case, the Sustainability Window ($SuWi_{E5S54}$) is negative ($GDP_{min} > GDP_{max}$), and the actual GDP growth is outside the negative SuWi ($GDP_5 < GDP_{max} < GDP_{min}$). This case does not fulfil the sustainability criteria.

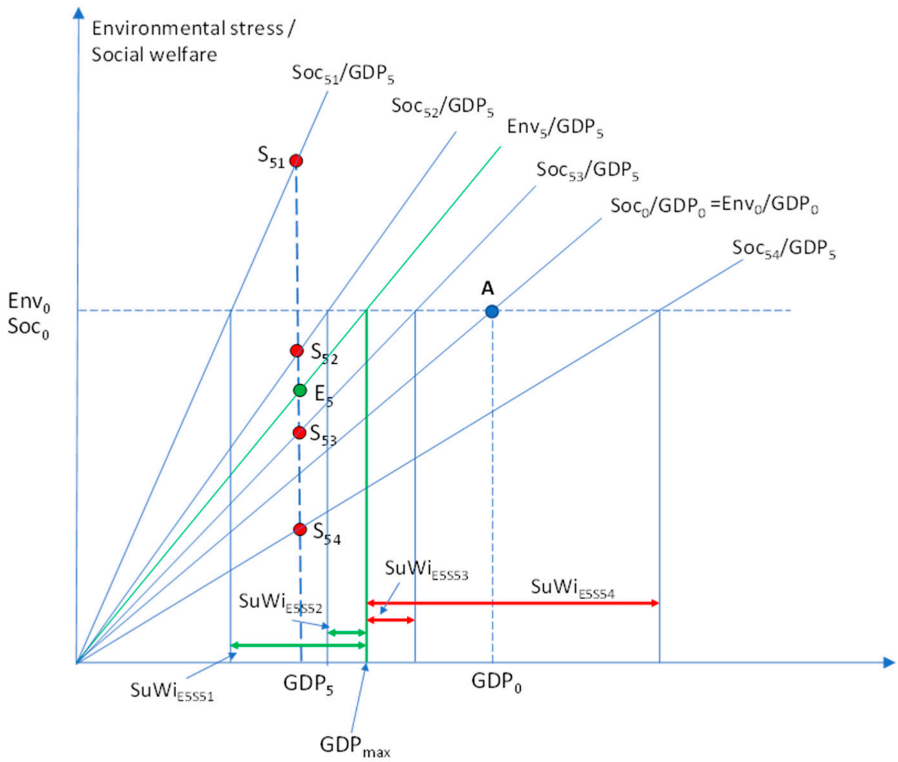

Figure A5. Sustainability Window in all possible cases where GDP and environmental stress (Env) decrease, and environmental stress productivity (Env/GDP) increases.

Appendix A.6. Group 6 (Figure A6)

GDP decreases ($GDP_6 < GDP_0$), environmental stress decreases ($Env_6 < Env_0$), and environmental stress productivity decreases ($Env_6/GDP_6 < Env_0/GDP_0$).

Social welfare can have four different options:

1. $Soc_{61} > Soc_0$ and $Soc_{61} > Env_6$ and $Soc_{61}/GDP_6 > Env_6/GDP_6$ and $Soc_{61}/GDP_6 > Soc_0/GDP_0$

In this case, Sustainability Window ($SuWi_{E6S61}$) is positive ($GDP_{min} < GDP_{max}$), and the actual GDP growth is inside SuWi ($GDP_{min} < GDP_6 < GDP_{max}$). This case fulfils the sustainability criteria.

2. $Soc_{62} < Soc_0$ and $Soc_{62} > Env_6$ and $Soc_{62}/GDP_6 > Env_6/GDP_6$, and $Soc_{62}/GDP_6 > Soc_0/GDP_0$

In this case, Sustainability Window ($SuWi_{E6S62}$) is positive ($GDP_{min} < GDP_{max}$), but the actual GDP growth is outside SuWi ($GDP_6 < GDP_{min} < GDP_{max}$). This case does not fulfil the sustainability criteria.

3. $Soc_{63} < Soc_0$ and $Soc_{63} > Env_6$ and $Soc_{63}/GDP_6 > Env_6/GDP_6$, and $Soc_{63}/GDP_6 < Soc_0/GDP_0$

In this case, Sustainability Window ($SuWi_{E6S63}$) is positive ($GDP_{min} < GDP_{max}$), but the actual GDP growth is outside the SuWi ($GDP_6 < GDP_{min} < GDP_{max}$). This case does not fulfil the sustainability criteria.

4. $Soc_{64} < Soc_0$ and $Soc_{64} < Env_6$ and $Soc_{64}/GDP_6 < Env_6/GDP_6$, and $Soc_{64}/GDP_6 < Soc_0/GDP_0$

In this case, Sustainability Window ($SuWi_{E6S64}$) is negative ($GDP_{min} > GDP_{max}$), and the actual GDP growth is outside the negative SuWi ($GDP_6 < GDP_{max} < GDP_{min}$). This case does not fulfil the sustainability criteria.

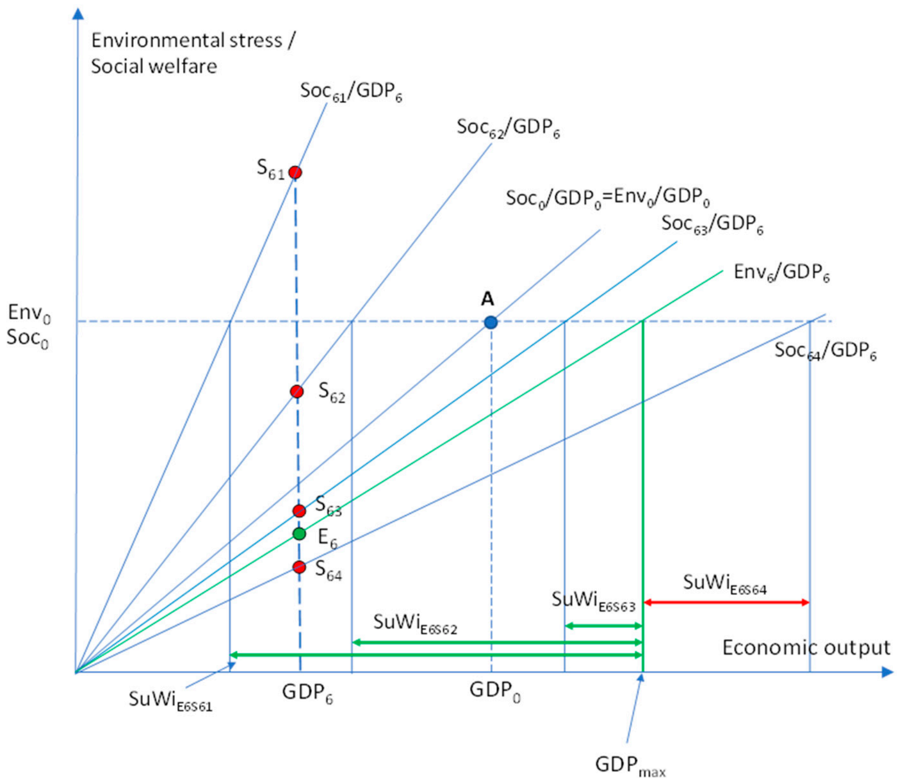

Figure A6. Sustainability Window in all possible cases where GDP, environmental stress (Env), and environmental stress productivity (Env/GDP) decrease.

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