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Fuzzy Logic to Measure the Degree of Compliance with a Target in an SDG—The Case of SDG 11

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Abstract: Sustainable development and its significant challenges motivate various international organisations in a way that has never been seen before. With Europe at the forefront, countries such as the United States want to be included in the progress and what a clear and determined commitment to sustainability means for future generations. Our study aimed to go deeper into the follow-up and monitoring of the development of reliable indicators that make the continuous improvement process in sustainability robust. To this end, and using the fuzzy logic methodology, we applied it to one of the indices that have been developed to date, the "Sustainable Development Report" (in its 2022 edition), working on the specific application of SDG 11. Our results show favourable positions for countries such as Brunei Darussalam, Tonga, Tuvalu, Andorra, and the Netherlands and provide robustness when there is a lack of data quality and improvements in the implementation of the process when experts intervene.

Keywords: sustainability; fuzzy logic; SDGs; smart cities

MSC: 03B52; 91B76; 91D10

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Citation: Parra-Domínguez, J.; Alonso-García, M.; Corchado, J.M. Fuzzy Logic to Measure the Degree of Compliance with a Target in an SDG—The Case of SDG 11. *Mathematics* **2023**, *11*, 2967. https://doi.org/10.3390/math11132967

Academic Editors: Michael Voskoglou, Laura González-Vila Puchades and Jorge de Andres Sanchez

Received: 14 April 2023
Revised: 28 June 2023
Accepted: 30 June 2023
Published: 3 July 2023

1. Introduction

Humanity's continuous challenges are characteristic of a developing world [1]. Technology, and working together with it, is part of this development, making the pace of development faster [2] and giving rise to currents of thought that have to work towards measuring the reaction to the high speed of progress while taking care of the possible negative impacts that may result [3]. The objectives as a society are not only set for the present, but the challenge is to work towards the best objectives and quality of life for future generations. Reflection on progress must be based on homogenisation to have the capacity for objective criteria. In this sense, the SDGs [1] and, in our case, the concern for their fulfilment have been developed. Once homogeneous measurement criteria are in place, it is time to move on to interpretation and work on concrete improvements where objectivity accompanies a rigorous and necessary subjectivity in approximating the reality of human beings' experiences of the fact of the space that surrounds us. This research will focus on establishing criteria to measure, control, and favour decision-making motivated by the treatment of fuzzy logic as a method since it is an approach capable of involving objectivity and subjectivity in an indicator. It is essential to emphasise that this will be undertaken from a theoretical point of view and will not be overdimensioned, based on the model proposed for SDG 11 (sustainable cities and communities: making cities and human settlements inclusive, safe, resilient, and sustainable), which represents one of the significant challenges of the world's population, which is none other than the existence of cities that, as ecosystems, bring together a large part of the population. All of the above highlights the novelty of in the current study, which is none other than the incorporation of fuzzy logic systems in the expert judgement that participates in an improvement of the homogeneous measurement of sustainability based on the SDGs. The development was carried out on SDG 11 and was based on a use case. To develop the research, the link between the SDGs and sustainable development was first explored in depth, and the reality of fuzzy logic systems as a support for decision-making was introduced. The second section examined the progress of different SDG measurement and monitoring systems, focusing on SDG 11. The third section incorporated the proposed fuzzy logic system for action on SDG 11. Subsequently, comparative results will be presented, and finally, the discussion and conclusions will be included.

1.1. The SDGs and Sustainable Development

In today's changing world, knowing where we are heading is essential. There are various tools for monitoring humanity's progress in its sustainable development, one of the most relevant at present being compliance with the Sustainable Development Goals (SDGs) [4].

At this point, it is essential to highlight the current SDGs and their implication for recent development, especially for what is considered sustainable development [5,6]. There are 17 SDGs and the United Nations classifies them as "No poverty", "Zero hunger", "Good health and well-being", "Quality education", "Gender quality", "Clean water and sanitation", "Affordable and clean energy", "Decent work and economic growth", "Industry, innovation and infrastructure", "Reduced inequalities", "Sustainable cities and communities", "Responsible consumption and production", "Climate action", "Life below water", "Life on land", "Peace, justice and strong institutions", and "Partnerships for the goals".

The 17 SDGs were established in 2015 [7], when world leaders established them as a set of global goals to eradicate poverty, protect the planet, and ensure prosperity for all as part of the new sustainable development agenda. The deadline for achieving these goals was set at 15 years [8].

To introduce the historical context, it is essential to point out that concern for the environment began to emerge at the end of the Second World War [9], which is the period when concerns about the significant problems of that period became evident. At this stage, we should highlight the First Report of the Club of Rome, dated 1972, called "the limits of growth" [10], which concluded that the planet would reach the limits of its growth over the next one hundred years. It was in 1987 that the concept of sustainable development came into existence [11], which had international repercussions thanks to the Brundtland Report presented by the World Commission on Environment and Development [12]. The idea in question, defined in 1983 by the Commission, created by the United Nations (UN), was limited to "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*"[13]. Although this may be one of the broadest conceptions of sustainability to date, it can be refined by clearly distinguishing, for example, between development and sustainability, which is not entirely clear. While development is based on cultural uniformity and the destruction of natural resources [14], sustainability leans towards conservation and the rational use of the environment [15].

The above evolution shapes the so-called 2030 agenda [16], an initiative taken forward by UN country leaders. Previously, 189 leaders formed and signed the so-called Millennium Declaration [17], the objective of which was to be achieved by 2015 and was made up of the so-called Millennium Development Goals (MDGs) [18]. It should be noted that, at the end of the period, essential conclusions were drawn for the United Nations, and this led to a commitment by these leaders to the achievement of future goals to make global action work while at the same time pushing for the adoption of new ambitions to meet global needs better [19–21]. With 193 countries now signatories, the MDGs were replaced by the action plan "*Transforming our World: The 2030 Agenda for Sustainable Development*", which set out the 17 known SDGs and 169 associated targets [22].

Of the 17 SDGs, this article will focus on SDG 11. SDG 11 focuses on sustainable cities and communities in an increasingly urbanised world [23]. The article will link SDG 11 with the mathematical methodology of fuzzy logic [24,25], allowing us to take into account aspects of mainstreaming in the measurement given the characterisation of systems and society and the economy [26,27]. With the representation of the theoretical model to be introduced, the aim was to respond to the challenge posed by the fact that, since 2007, more of the world's population has been living in cities, a trend that is expected to reach 60 per cent by 2030 [28]. The importance of SDG 11 is evident in addressing challenges ranging from protecting cultural heritage to constructing sustainable and resilient buildings [29]. These challenges could also improve air quality or transport efficiency by expanding public transport services and enhancing their accessibility and safety. The targets of SDG 11, in concrete terms, are "11.1 Ensuring access to adequate, safe, affordable housing and essential services, and slum upgrading", "11.2 Providing access to safe, affordable, accessible, and sustainable transport systems for all and improving road safety", "11.3 Increasing inclusive and sustainable urbanisation and capacity for participatory planning and management", "11.4 Increased efforts to protect and safeguard the world's cultural and natural heritage", "11.5 Reducing the number of deaths caused by disasters, including water-related disasters", "11.6 Reducing the negative per capita environmental impact of cities", "11.7 Providing universal access to safe, inclusive and accessible green spaces and public spaces", "11.a Supporting positive economic, social and environmental linkages between urban, peri-urban and rural areas", "11.b Significantly increase the number of cities and human settlements adopting and implementing integrated policies and plans to promote inclusiveness, resource efficiency, climate change mitigation and adaptation, and disaster resilience", and "11.c Provide support to least developed countries for more efficient building construction".

As will be described when introducing the methodological framework and the theoretical model developed, fuzzy logic will also link measurable variables to each of the targets involved in the monitoring of SDG 11.

1.2. Fuzzy Systems for Decision Making

The theory of fuzzy logic based systems approximates the behaviour of a system when there are no analytical functions or numerical relations to define it. Social or political problems are complex systems for which it is often not possible to capture analytically the information required to represent them. The more complex a system is, the more imprecise or inaccurate the knowledge available to characterise it. The uncertainty surrounding a problem can be caused by its complexity, the lack of knowledge, the inability to make adequate measurements, or the inherent vagueness of natural language. Using vagueness to describe a system allows some intuitive information or inaccuracies to be incorporated, for example, by determining whether the biodiversity of an area is "adequate". Ragin's seminal work [30] critiqued the conventional approach to social research and proposed the use of set-theoretic methods to overcome its limitations. In his book, Ragin argues for the integration of fuzzy-set analysis, a set-theoretic method, as a means to strengthen the connection between qualitative researchers' deep case knowledge and quantitative researchers' exploration of cross-case patterns. Schneider and Wageman [31] provide an extensive guide to Qualitative Comparative Analysis (QCA), a set-theoretic method that has gained popularity in social science research. This book covers both basic and advanced issues in set-theoretic methods, equipping researchers with a comprehensive understanding of QCA. The authors also offer practical tips on software handling and exercises to facilitate the application of QCA in empirical research. Another article [32] highlights the use of Qualitative Comparative Analysis (QCA), encompassing crisp and fuzzy sets, in the field of business and management research. The authors emphasize the significance of incorporating contextual information and cognitive aspects into the analysis, which leads to a more comprehensive understanding of the subject matter. By utilizing QCA, researchers in business and management can gain valuable insights into complex phenomena. Pappas and Woodside's article [33] focuses on providing guidelines for using Fuzzy-set Qualitative Comparative Analysis (fsQCA) in Information Systems and marketing research. The authors discuss the distinctions between fsQCA and variance-based approaches, as well as structured equation modeling. Moreover, they offer a summary of thresholds and guidelines for practical implementation. The article also emphasizes how existing papers employing variance-based approaches can benefit from integrating fsQCA into their research.

In the case of the SDGs, many countries lack data and some variables cannot be measured accurately, suggesting that the assessment of the SDGs should be modelled assuming some uncertainty. The idea of thinking of this problem as a mathematical model based on fuzzy logic has been raised before to apply it to the study of human trafficking or to score test policies [34]. Establishing such frameworks provides great flexibility and allows for subsequent adaptation and continuous improvement. In decision-making, it is important to highlight the work of fuzzy logic in approximating complex assignments when the data set is to be decided upon, and the decision rules need to be clarified [35]. In addition to the examples mentioned earlier and the referenced handbook that evaluates the role of fuzzy logic in the field of decision-making, all of the above is reinforced due to the strong links in the field of medical sciences [36,37] and widely referenced fields such as engineering [38]or social sciences [39], specifically within business development [40].

2. The Current Implementation and Monitoring of the SDGs—The SDG 11 Case

As previously introduced, one of the main difficulties in approximating effective compliance with sustainability is the lack of robust and, above all, homogeneous criteria for follow-up and monitoring of the variables that give rise to knowing [41,42], for example, the position of each country or region concerning sustainability. There are even voices in favour of the scientific community considering whether the SDGs are suitable for measuring progress on the 2030 Agenda. In any case, they are also the ones that allow us to go beyond merely economic measurements.

Following Díaz-Sarachaga et al. (2017) [43], the indicators that already motivated, in one way or another, the provision of monitoring criteria important for humanity, were as follows:

- The Human Development Index (HDI) reflects three important human aspects: the pursuit of a long and healthy life, access to knowledge, and a good standard of living. This index, developed by the Human Development Report Office of the United Nations Development Programme (UNDP) in 2016, is calculated from the geometric mean of three normalised sub-indices representing the life expectancy index, the education index, and the gross national income index [44].
- The Ecological Footprint (EF) is an indicator that aims to determine the area of land required to cover the consumption of natural resources by a defined population [45]. It is a helpful measure developed by the University of British Columbia to quickly compare the demand for nature required to meet the needs of a given human settlement. Another indicator motivated by environmental sustainability monitoring is the Living Planet Index developed by the Worldwide Wildlife Foundation (WWF) and the Zoological Society of London (ZSL) [46].
- Another key indicator that has accompanied society in its well-being assessment is the result of collaboration between the International Union for Conservation of Nature (IUCN) and the International Development Research Centre (IDRC). It began with the birth of the Sustainability Barometer tool [47]. It led to what is known as the Well-being Assessment Method [48], which has been applied in 180 countries as the first global assessment of sustainability. Importantly, sustainable development is measured by combining four indices: the Human Well-being Index (HWI), the Ecosystem Well-being Index (EWI), the Well-being Index (WI), and the Well-being Stress Index (WSI).
- Focusing on current research, there are also indices and indicators related to the concern for the advancement of cities. The so-called Urban Development Index (UDI) classifies cities according to their urban development based on criteria of liveability, poverty, traffic congestion, inclusion and different sustainability factors. Also noteworthy is the emergence, in 2012, of City Prosperity. This indicator promotes and integrates other elements such as those supporting local, regional, and national decision-makers

in productivity, infrastructure, quality of life, equity, and inclusion, environmental sustainability and factors related to governance and legislation. It is divided into four scenarios:

1. Global City Ranking for global and regional monitoring.
2. Basic CPI provides the first internationally comparable diagnosis.
3. Extended CPI, consisting of a comparable in-depth analysis within the country.
4. Contextual CPI serves as an urban monitoring tool that includes national urban policies.

- In addition to the above, and already related to purely economic criteria, there are indices of a financial nature such as the Gross Domestic Product (GDP) [49], which evaluates economic well-being and for which alternatives emerged, such as the Economic Well-being Measure, which adjusted GDP by adding values relating to leisure time, unpaid work, and subtracting the importance of environmental damage due to industrial production and consumption. Another alternative is the Genuine Progress Indicator (GPI) [50], which considers income inequality, crime costs, environmental damage, and reduced leisure time. Finally, another of the highlights is the Adjusted Net Savings Index (ANSI), also known as the Genuine Savings Index (GSI) [51], which measures the change in annual net national wealth, taking into account the human, natural and economic dimensions. The latter indicator is also concerned with the wealth that future generations may receive; otherwise, sustainability would not be guaranteed.

In addition to the above indicators, the so-called SDG index describes the progress towards the SDGs of different countries, i.e., it works at the aggregate country level, establishing critical points where progress may be considered insufficient. This is an optimal representation of development represented through percentages in what is indicated as an SDG index. This index works by establishing a series of differences between any given country's score and the maximum value given, 100, and establishing this as the distance in percentage points that each country is from the development optimum. Of course, the SDG index uses the same indicators for all countries and tracks them by ranking against the particular index. Details on the applied statistics can be found in Papadimitriou et al. (2019) [52], within their studies conducted at the Joint Research Centre of the European Commission (EU JCR), and the methodology developed in the latest report can be found in Lafortune et al. (2018) [53], also developed within the EU JCR. All of the above was developed and can be visualised in the dashboard, which allows the development of the different countries concerning the 17 SDGs to be visualised by colour. The index in question has limitations that have been observed and expressed in the different annual reports that have been developed, among which we would highlight the following:

- The change in some of the metrics or the indicators developed annually may cause the indicator to be affected by a lack of complete comparability concerning the previous year.
- The index incorporates data from official and non-official sources. Official sources include FAO, ILO, OECD, UNICEF, WHO, and The World Bank. At this point, what is noteworthy as a possible gap is the non-availability of weights and aggregation criteria by experts, as there is no consensus, given the disaggregation and idiosyncrasies of each area at the global level. In this sense, the index favours the existence of equal weights for each of the variables mentioned.

After the first strategic step, where a five-step decision tree is established, the normalisation criterion is followed by the equation

$$x' = \frac{x - \min.(x)}{\max.(x) - \min.(x)} 100, \quad (1)$$

where x is the raw data value, the $\min.$ and $\max.$ denote the lower and upper bounds, respectively and, therefore, x' is the normalized value. The requirements already mentioned for the weights and rankings are then selected and the dashboard is generated, where the different trends in the measurement of the SDGs can be observed. Specifically, concerning SDG 11, which is the one we worked on in this theoretical study, the indicators included in the latest Sustainable Development Report are as follows [54]:

- Proportion of urban population living in a slum, in percentage terms.
- Annual mean concentration of particulate matter of less than 2.5 microns in diameter (PM2.5) (mg/m^3).
- Access to improved water source, in percentage terms of urban population.
- Satisfaction with public transport, in percentage.
- Population with rent overburden, in percentage.

In order, each of the above corresponds to the following optimal criteria:

- Proportion of urban population living in a slum. Zero is the optimum and is justified by the premise "leave no one behind".
- Annual mean concentration of particulate matter of less than 2.5 microns in diameter (PM2.5) (mg/m^3); 6.3 is the optimum and is justified on the premise "average of five best performers".
- Access to improved water source. One hundred is the optimum and is justified by the premise "leave no one behind".
- Satisfaction with public transport; 82.6 is the optimum and is justified by the premise "average of five best performers".
- Population with rent overburden; 4.6 is the optimum and is justified by the premise "average of three best OECD performers".

With all of the above, and as has been introduced, we will work on optimising the incorporation of fuzzy logic systems which, for cities, as units of vital development, favour the incorporation of expert criteria. Furthermore, the automation in the homogenisation of the process will allow for agility in compiling different sources in different cities.

3. The Proposed Fuzzy Assessment System

The diagram in the Figure 1 represents the steps to be followed to define the fuzzy logic system [55]. The first phase consists of identifying the variables that govern the system (input and output) and set criteria indicating the interaction between them. In a fuzzy logic system, the association between input and output variables is determined by a collection of fuzzy rules. These rules delineate the manner in which inputs are linked to outputs, taking into account their linguistic terms and accompanying membership functions. Input variables are commonly characterized by fuzzy sets, representing varying degrees of membership for each linguistic term. Likewise, output variables are also defined by fuzzy sets that encompass linguistic terms and their respective membership functions. Fuzzy rules elucidate the behavior of the system by establishing logical connections between input and output variables. Each rule comprises an antecedent (input) and a consequent (output). The antecedent evaluates the extent to which the input variables fulfill the conditions specified by linguistic terms and membership functions. The consequent determines the degree to which output variables are assigned to specific linguistic terms and their corresponding membership functions. The process of mapping inputs to outputs in a fuzzy logic system entails fuzzification, rule evaluation, aggregation, and defuzzification. Fuzzification converts precise input values into fuzzy sets, associating them with appropriate linguistic terms and membership degrees. Rule evaluation quantifies the degree of activation for each rule based on the membership values of the input variables. Aggregation combines the activated rules to ascertain the overall output membership functions. Finally, defuzzification converts the fuzzy output sets into precise output values by calculating a representative value, such as the centroid or maximum membership, derived from the aggregated membership functions. Finally, if data are available, they are fed into the system to obtain output values. The last phase consists of the interpretation and validation by experts of the results obtained. Each of these steps is detailed below as applied to the particular case of defining a fuzzy logic system that assesses compliance with SDG 11.

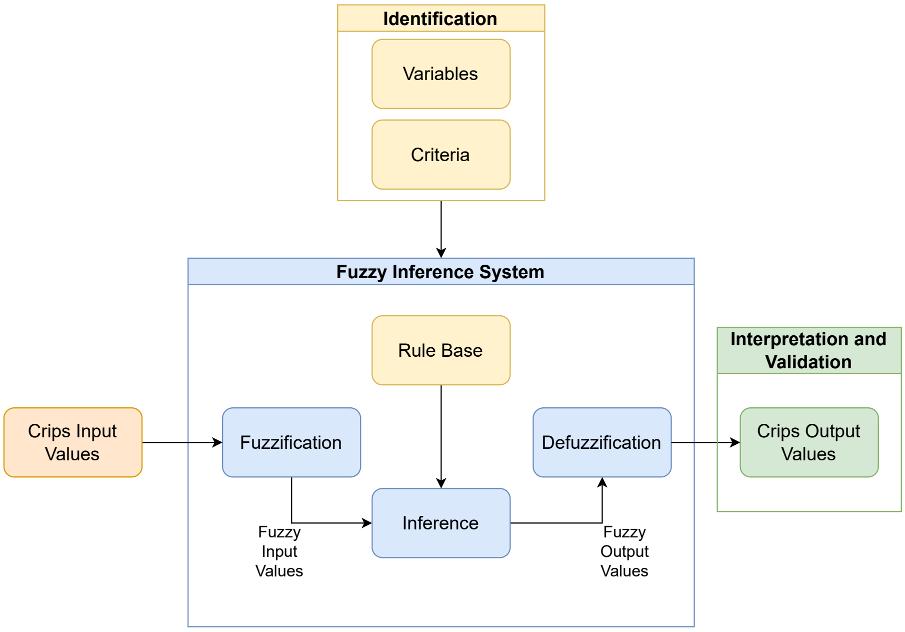

Figure 1. Fuzzy logic evaluation system architecture.

First, the system must be defined by identifying the variables governing the system and how the input variables are related to each other and to the output variable. In this study, the indicators included in the Sustainable Development Report 2022 for SDG 11 (Table A.5) [54], which will be described in detail below, are taken as input variables and mathematically denoted as follows.Let $\{v_i\}_{i=1}^{5}$ be the set of the fuzzy input variables, where v_1 is the proportion of urban population living in slums (%); v_2 is the annual mean concentration of particulate matter of less than 2.5 microns in diameter (PM2.5) ($\mu g/m^3$); v_3 is the access to improved source, piped (% of urban population); v_4 is the satisfaction with public transport (%); and v_5 is the population with rent overburden (%). Each fuzzy variable is fully characterised in the following paragraphs in terms of its universe of discourse and fuzzy subsets.

Let X_i be the universe of discourse, that is, the set of real values $x \in X_i$ for which a variable v_i, $\forall i \in \{1, ..., 5\}$ is defined. In practice, it could be defined by giving the minimum a_i, maximum b_i and number of points contained between these two extremes s_i (in theory it is possible to define a real interval with infinite values between the points defining an interval but in any practical implementation it is necessary to define some way to discretise the domain, in this case, it is proposed to fix the number of intermediate points contained between extremes). The universe of discourse for the indicators measured in percentages will be $[0, 100]$ by definition of percentage and we take $X_2 = [5, 107]$ as these are the floor of the minimum and ceiling of the maximum values for v_2 found by studying the available data per country obtained from the Sustainable Development Report 2022. For example, the annual mean concentration of particulate matter of less than 2.5 microns in diameter (v_2) for a country could be any value between 5 and 107, including both.

Currently, each variable is divided exactly into subsets defined by quantitative thresholds that map each value of an indicator to a colour code (green, yellow, orange, red, or grey). These colour codes represent how far a country is from meeting a given SDG [54]. The colour legend used is illustrated in Figure 2 and associates a colour with a linguistic description of the progress of a country towards achieving an SDG [56].

Figure 2. Colour scales to benchmark progress towards achieving the SDGs.

The colour green should not be taken to mean that the state has achieved the SDG indicator but rather that it is on track to do so by 2030 [56]. A range is associated with each colour so that, if an indicator takes values in that range, the corresponding colour is associated with it. The limits of each interval have been defined by experts, scientifically determined levels, or using summary statistics of data when the previous options are not possible [56]. This definition of the ranges suggests that the fuzzy logic approach to the problem may be more suitable due to factors such as possible discrepancies between expert judgement or future changes in the data that would shift the thresholds. For SDG 11 indicators, the current ranges A_j^i associated with each variable ν_i are shown in the Table 1. For example, if the proportion of the urban population living in slums (ν_1) is 3% for a country, then it is considered as SDG-achieved or green (A_1^1).

Table 1. Defined bounds per indicator for SDG 11.

	ν_1	ν_2	ν_3	ν_4	ν_5
Universe of discourse (X_i)	[0, 100]	[5, 107]	[0, 100]	[0, 100]	[0, 100]
SDG achieved—Green—(A_1^i)	[0, 5]	[5, 10]	[98, 100)	[72, 100]	[0, 7]
Challenges remain—Yellow—(A_2^i)	(5, 15]	(10, 17.5]	[86.5, 98)	[57.5, 72)	(7, 12]
Significant challenges remain—Orange—(A_3^i)	(15, 25]	(17.5, 25]	[75, 86.5)	[43, 57.5)	(12, 17]
Major challenges remain—Red—(A_4^i)	(25, 100]	(25, 107]	[0, 75)	[0, 43)	(17, 100]

At this point, it is important to mention a drawback related to data availability: some countries are not fully characterised, this is, the corresponding value of ν_i is not available for one or more $i \in \{1, ..., 5\}$. Therefore, to deal with this, we proposed to create the system dynamically according to the input variables for which information is available, provided that the number of available input variables is equal to or greater than two. In case a country has no information for any variable or has information for only one, the current criterion—identifying SDG 11 compliance with grey as information not available—is maintained. As a consequence, it will not be possible to define a single system but there will be as many as there are combinations of two or more variables. This is equivalent to saying that the number of fuzzy logic systems, #FLS, resulting from this approach are the number of possible combinations formed by two or more unordered and non-repeating variables:

$$\#\text{FLS} \leq \sum_{k=2}^{5} C_k(n) = 26, \quad C_k(n) = \binom{n}{k} = \frac{n!}{k!(n-k)!}, \tag{2}$$

where $n = 5$ is the maximum number of variables.

To conclude with the identification of variables, we define the output variable, η, as the degree of SDG compliance, measured as a percentage. The universe of discourse and the ranges we have considered for the output variable are shown in Table 2.

Table 2. Crisp bounds for the output variable.

	η
Universe of discourse (X_6)	[0, 100]
SDG achieved—Green—(A_1^6)	(80, 100]
Challenges remain—Yellow—(A_2^6)	(50, 80]
Significant challenges remain—Orange—(A_3^6)	(20, 50]
Major challenges remain—Red—(A_4^6)	[0, 20]

Finally, the relationships of the input variables to each other and to the output variable must be established. One simple rule block is defined per variable present in the system plus two additional rules combining multiple variables. Each simple block consists of four rules—one for each interval of values defined in each input variable—and each rule relates each interval of an input variable to an interval of those of the output variable following a relationship of direct proportionality. Let ξ_j, $j = \{1,2,3,4\}$ denote each qualitative range of values that defines a variable, such that $\xi_1 :=$ SDG achieved (Green), $\xi_2 :=$ Challenges remain (Yellow), $\xi_3 :=$ Significant challenges remain (Orange), and $\xi_4 :=$ Major challenges remain (Red). Then ,a simple block of rules for a variable ν_i is given by:

$$\text{If } (\nu_i = \xi_j), \text{ then } (\eta = \xi_j), \forall j = 1, .., 4. \tag{3}$$

Examples of these rules inside a block in natural language include "if slum population is SDG-achieved, then compliance degree is SDG-achieved" or "if matter concentration is that significant challenges remain, then compliance degree is that significant challenges remain". These rule blocks establish the relationships between the input variables and the output variable based on the defined qualitative ranges (Green, Yellow, Orange, Red). Each input variable's interval is mapped to an interval of the output variable, maintaining a direct proportionality relationship.

The other two additional rules can be deduced from the following extract:

"*Averaging across all indicators for an SDG might hide areas of policy concern if a country performs well on most indicators but faces serious shortfalls on one or two metrics within the same SDG (often called the "substitutability" or "compensation" issue). [...] We applied the added rule that a red rating is given only if the country scores red on both of its worst-performing indicators for that goal. Similarly, to score green, both of these indicators had to be green [54].*"

This implies that $\eta = \xi_4$ for a country if at least two of its indicators are red and that it is green if and only if all its indicators are green. These rules are transformed into implication type for inclusion in the rule base:

$$\begin{aligned} \text{If } \Big(& ((\nu_1 = \xi_4) \text{ and } (\nu_2 = \xi_4)) \text{ or } ((\nu_1 = \xi_4) \text{ and } (\nu_3 = \xi_4)) \text{ or} \\ & ((\nu_1 = \xi_4) \text{ and } (\nu_4 = \xi_4)) \text{ or } ((\nu_2 = \xi_4) \text{ and } (\nu_3 = \xi_4)) \text{ or} \\ & ((\nu_2 = \xi_4) \text{ and } (\nu_4 = \xi_4)) \text{ or } ((\nu_3 = \xi_4) \text{ and } (\nu_4 = \xi_4))\Big), \text{ then } (\eta = \xi_4) \end{aligned} \tag{4}$$

$$\text{If } \Big((\nu_1 = \xi_1) \text{ and } (\nu_2 = \xi_1) \text{ and } (\nu_3 = \xi_1) \text{ and } (\nu_4 = \xi_1)\Big), \text{ then } (\eta = \xi_1). \tag{5}$$

That is: "If (((((((((slum population is Major challenges remain) and (matter concentration is Major challenges remain)) or ((slum population is Major challenges remain) and (water access is Major challenges remain))) or ((slum population is Major challenges remain) and (public transport satisfaction is Major challenges remain))) or ((slum population is Major challenges remain) and (rent overburden population is Major challenges remain))) or ((matter concentration is Major challenges remain) and (water access is Major challenges remain))) or ((matter concentration is Major challenges remain) and (public transport satisfaction is Major challenges remain))) or ((matter concentration is Major challenges remain) and (rent overburden population is Major challenges remain))) or ((water access is Major challenges remain) and (public transport satisfaction is Major challenges remain))) or ((water access is Major challenges remain) and (rent overburden population is Major challenges remain))) or ((public transport satisfaction is Major challenges remain) and (rent overburden population is Major challenges remain)), then compliance degree is Major challenges remain"; and "If ((((slum population is SDG achieved) and (matter concentration is SDG achieved)) and (water access is SDG achieved)) and (public transport satisfaction is SDG achieved)) and (rent overburden population is SDG achieved), then compliance degree is SDG achieved". In what follows, we will refer to these rules as "red rule" and "green rule".

By incorporating these two additional rules along with the previous rule blocks for each input variable, a complete set of rules is defined to evaluate the degree of compliance (output variable) based on the given input variables. This concludes the identification phase and leads to the construction of a fuzzy logic system.

Fuzzification can be described as the process of transforming crisp input values into fuzzy sets, which are completely characterized by the set of pairs:

$$\tilde{\xi}^i_j = \left\{ \left(x, \mu_{\tilde{\xi}^i_j}(x) \right), x \in X_i \right\}, \quad i = \{1, ..., 6\}, j = \{1, ..., 4\}, \tag{6}$$

where $\mu_{\tilde{\xi}^i_j}$ denotes the membership function that associates a degree of membership to each $x \in \xi^i_j$ such that $\mu_{\tilde{\xi}^i_j}(x) \in [0, 1]$. The membership functions are intended to describe vagueness and ambiguity: if the degree of membership is one, $x \in \xi^i_j$; if it is zero, $x \notin \xi^i_j$; any value between zero and one indicates the degree of uncertainty associated with the value being in a given set.

For this phase, we have taken the limits defined in Tables 1 and 2 and blurred their boundaries to incorporate uncertainty. This is justified by the difficulty of defining precise upper and lower limits in practice. We chos S-shaped, Z-shaped, and bell-shaped membership functions as shown in the Figure 3. However, this choice is not unique and other types of functions, such as trapezoidal or triangular, can be considered. Each fuzzy set has an associated description in linguistic terms, as described above. For example, the membership functions for the slum population variable can be defined formally as follows:

$$\mu_{\tilde{\xi}^1_1}(x) = \begin{cases} 0 & \text{if } x \leq 3 \\ 1 - 2\left(\frac{x-3}{5-3}\right)^2 & \text{if } 3 \leq x \leq 4 \\ 1 & \text{if } x \geq 5 \end{cases} \tag{7}$$

$$\mu_{\tilde{\xi}^1_2}(x) = \frac{1}{1 + \left|\frac{x-10}{5}\right|^{10}} \tag{8}$$

$$\mu_{\tilde{\xi}^1_3}(x) = \frac{1}{1 + \left|\frac{x-20}{5}\right|^{10}} \tag{9}$$

$$\mu_{\tilde{\xi}^1_4}(x) = \begin{cases} 0 & \text{if } x \leq 23 \\ 2\left(\frac{x-23}{30-23}\right)^2 & \text{if } 23 \leq x \leq 26.5 \\ 1 - 2\left(\frac{x-30}{30-23}\right)^2 & \text{if } 26.5 \leq x \leq 30 \\ 1 & \text{if } x \geq 30 \end{cases}. \tag{10}$$

These equations represent the membership functions that associate a degree of membership $\mu_{\tilde{\xi^i}_j}(x)$ to each value x. The membership functions of the other variables are defined analogously.

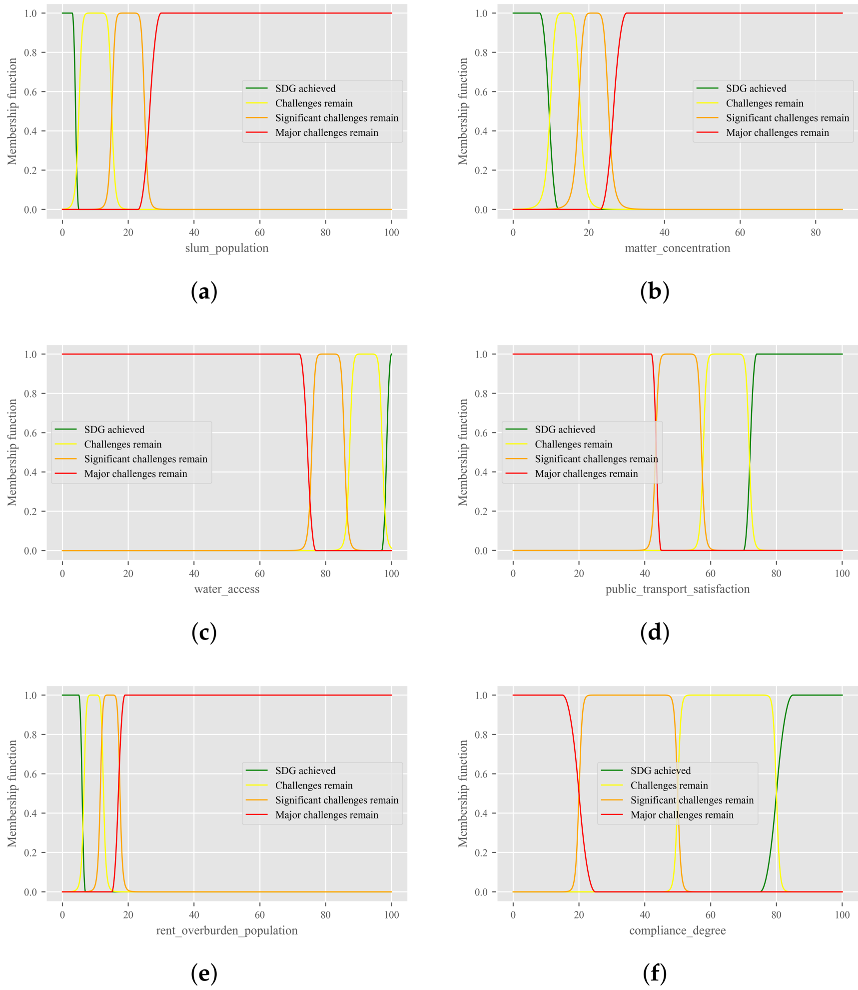

Figure 3. Fuzzy membership functions per variable. (**a**) $\tilde{\xi}_j^1$; (**b**) $\tilde{\xi}_j^2$; (**c**) $\tilde{\xi}_j^3$; (**d**) $\tilde{\xi}_j^4$; (**e**) $\tilde{\xi}_j^5$; (**f**) $\tilde{\xi}_j^6$.

The rule set in the identification phase indicates how to relate the input variables to the output variable. In terms of fuzzy logic, each block of simple rules is converted into:

$$\text{If } (\nu_i = \tilde{\xi}_j^i), \text{ then } (\eta = \tilde{\xi}_j^6), \forall j = 1, .., 4, \quad (11)$$

where ν_i and η are now fuzzy variables, $\tilde{\xi}_j^i$ is the j-th fuzzy set of the variable ν_i, and $\tilde{\xi}_j^6$ is the j-th fuzzy set of the variable η. The remaining two rules (4) and (5) are translated analogously. The operations of *or* and *and* of the last two rules are the Zadeh logical operators of fuzzy logic, where $(x \text{ or } y) := \max(x, y)$ and $(x \text{ and } y) := \min(x, y)$. In addition, each rule is weighted with a $\omega_k \in (0, 1]$, $k \in \{1, ..., 22\}$, according to the importance assigned to it in relation to the other rules. Note that if the current approach is to be respected, the last two rules should have considerably more weight than the other simple rules. Consequently, we tentatively assign $\omega_k = 0.1$ for each simple rule and $\omega_k = 1$ for red and green rules.

After evaluating each rule in a fuzzy inference system, a fuzzy set is obtained as output. These outputs are aggregated using the maximum aggregation function to produce another fuzzy set. Defuzzification converts this aggregate fuzzy set into a single number by selecting the best possible crisp value. For this, the centroid method was applied, which gives the value of the centre of the area under the curve.

The output is precisely the degree of compliance with SDG 11 for each country, obtained after combining the values of the input variables collected with the rule base.

The current implementation of the method can be found in the following repository: https://github.com/marialonsogar/fuzzy-compliance-SDG11, (accessed on 20 May 2023).

4. Results

The results of the previous research are now presented. The first outcome of the research is the identification of the lack of data and the limitations this places on any further analysis or modelling.

Ideally, all countries covered by the report should have values for each of the five indicators. However, in the data used for the report, only 28 countries (14.51%) have complete information. On the other hand, there are 11 countries (5.7%) that have only one non-missing value—marked as grey, meaning information unavailable.

As indicated by Equation (2), there is one model for each possible combination of indicators available. Theoretically, there are 26 possible combinations but in practice this dataset contains only eight of them. Therefore, the same number of fuzzy logic-based models is defined. After applying this method, the best and worst ranked countries are collected in Tables 3 and 4, respectively, along with their corresponding input values.

Table 3. Best ranked countries for SDG 11.

Country	v_1	v_2	v_3	v_4	v_5	FIS Evaluation
Brunei Darussalam	-	5.102	99.60	-	-	89.771
Tonga	-	10.117	99.75	-	-	83.243
Tuvalu	-	10.251	100.00	-	-	82.202
Andorra	-	11.189	100.00	-	-	75.114
Netherlands	0	11.411	100.00	78.0	6.144	74.950

Table 4. Worst ranked countries for SDG 11.

Country	v_1	v_2	v_3	v_4	v_5	FIS Evaluation
Togo	53.3	41.082	41.827	29.0	-	10.079
South Sudan	97.3	46.141	10.489	18.0	-	10.079
Afghanistan	73.5	54.950	41.859	34.0	-	10.078
Equatorial Guinea	66.1	59.020	48.115	-	-	10.078
Central African Republic	98.5	61.733	32.291	25.0	-	10.078

Brunei Darussalam, the country with the highest score, aligns with the current report's classification and has been assigned a green colour. This country is the only one to receive a green colour designation within the report. It is crucial to note that this evaluation came from having only some green indicators but rather from having two green ones and the rest not reported. This could suggest that the model might favour information gaps, a trend in other top-ranking countries. On the other hand, countries with the lowest scores correspond with those assigned a red colour in the report, indicating their two worst indicators as red. A clear pattern emerged in the analysis, showing a superior overall performance from countries in Asia, Oceania, and Europe. At the same time, Africa and the notable outlier, Afghanistan in Asia, demonstrate comparatively unfavourable results. Sustainable Development Goal 11 (SDG 11) currently focuses on cities as unique units within countries and continents. As cities are a significant driving force for societal progression, they play a critical role in fostering social development. Therefore, adopting a holistic perspective and actively engaging in discussions regarding this indicator is vital, as it provides an all-encompassing evaluation of sustainability progress.

5. Discussion

In this paper, a dynamic method based on fuzzy logic was proposed to translate human criteria involving some uncertainty into technical and computational language in order to define a robust evaluation system for SDGs accomplishment degree. This approach should be understood as an initial proposal for understanding and automating the evaluation of policies where human reasoning is involved in some way. Several limitations have been identified herein, primarily stemming from the availability of data. In this particular instance, the absence of certain indicators may potentially yield overly optimistic scores for certain countries. Furthermore, the comparison between countries lacks complete precision, as not all cases consider identical information, despite being a commendable approximation. Consequently, the scarcity of information necessitates a penalization mechanism, either through the inclusion of a new rule or by subsequent adjustment of the results. Moreover, all rules pertaining to individual indicators were regarded as equally significant in this study, implying that each indicator carries the same weightage in the final evaluation. To address this, it is imperative to incorporate expert judgment in order to discern the relative importance of various indicators. For instance, prioritizing the minimization of the population residing in suburban areas may be deemed more significant than evaluating satisfaction with public transportation.

On the other hand, fuzzy logic, despite its usefulness in handling imprecision and uncertainty, faces several limitations that need to be considered. Firstly, the subjectivity involved in designing membership functions introduces inconsistencies and potential bias in the system, as different experts may have varying opinions. Additionally, fuzzy logic systems can be sensitive to small changes in input values, leading to unexpected outputs. Furthermore, the absence of universally accepted standards for system design, rule formulation, and performance evaluation makes it challenging to compare and benchmark different fuzzy logic systems, hindering widespread adoption. Addressing these limitations by experts is crucial for ensuring the effective and reliable use of fuzzy logic systems.

Beyond the possible future lines of work in mathematics, future studies must move forward in transferring this study to other SDGs by generating a monitoring system to support decision-making that acquires the operation for complex fields of fuzzy logic. Furthermore, in the work of the cities themselves, it is also possible to observe the scope of the measurements, not only in terms of a specific indicator such as SDG 11 but also because the activity in the cities can affect the following SDGs:

- Good health and well-being;
- Clean water and sanitation;
- Affordable and clean energy;
- Industry, innovation, and infrastructure;
- Sustainable cities and communities;
- Responsible consumption and production;
- Climate action;
- Life on land.

In addition to the application to other SDGs as future lines, future research may benefit from exploring extensions to research more complex types of fuzzy subsets, allowing for further deepening of the analysis. Still, it is essential to note that using more complex types requires more parameter tuning, which may result in a more parsimonious analysis.

6. Conclusions

Several international organisations and institutions are concerned about sustainable development and its consequences. In addition to the different organisations and institutions, there is a notable concern on the part of experts and academics in the sense of accompanying and monitoring this sustainable development. The primary motivation for our study lies precisely in the capacity of governments and institutions to generate sustainability reports based on the necessary expert judgement. Sustainability must comply with the premises observed in the 2030 Agenda, which, disaggregated, can be found in the different Sustainable Development Goals that currently exist. With this research, working on an already completed "Sustainable Development Report" (in its 2022 edition), it is possible to incorporate the field of fuzzy logic to the necessary progress in the marking of sustainability criteria that robustly make the systems ready not only to issue reporting information but also to take this information as information that can be monitored and can be subjected to comparability criteria.

This study highlights some of the current limitations in assessing compliance with the SDGs and, in particular, with SDG 11. The lack of data for some indicators makes it impossible to provide a fully objective and comparable assessment. In addition, the information collected is not necessarily up to date: the reference years may be earlier than 2022. However, the approach presented here provides a way of assessing a country's performance while respecting the current reporting guidelines and is intended to serve as a basis for evaluating future policies. As the Sustainable Development Report (2022) sets out certain rules for evaluating an SDG, it seems natural to provide a fuzzy logic-based system that incorporates precisely this rule engine. As indicated above, the importance assigned to each defined rule must be refined by experts.

As a result, a ranking of countries was obtained, where the best rated country with our method—Brunei Darussalam—coincides with the best rated country with the current evaluation method and analogously for the worst scoring countries. Some results change as all available information is incorporated into this system and not only the information from the two worst indicators, as had been the case in the past. We have also highlighted some limitations of the system, caused mainly by the quality of the data collected so far. The technical limitations encountered are in line with the current monitoring system. A greater homogenisation of criteria through techniques such as fuzzy logic will allow the correct monitoring so that, in later phases such as verification, cities can make use of it in their progress concerning key factors such as:

- Mobility
  1. Air quality;
  2. Noise measurement;
  3. Parking and access;
  4. Low emission zone;
- Environment
  1. Intelligent irrigation;
  2. Waste monitoring;
- Energy
  1. Renewable energy;
  2. Smart lighting;
  3. Energy efficiency;
- Water
  1. Remote meter reading;
  2. Industrial water management.

Author Contributions: Conceptualization, J.P.-D.; methodology, J.P.-D., M.A.-G. and J.M.C.; software, M.A.-G. and J.M.C.; validation, J.P.-D., M.A.-G. and J.M.C.; formal analysis, J.P.-D., M.A.-G. and J.M.C.; investigation, J.P.-D., M.A.-G. and J.M.C.; resources, M.A.-G. and J.M.C.; data curation, M.A.-G. and J.M.C.; writing—original draft preparation, J.P.-D., M.A.-G. and J.M.C.; writing—review and editing, J.P.-D.; visualization, M.A.-G. and J.M.C.; supervision, J.P.-D.; project administration, J.P.-D.; funding acquisition, J.M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been partially supported by the project FARMS4CLIMATE (PRIMA S1 2021 FARMING SYSTEMS): Smart governance and operational models for agroecological carbon farming.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Deep Intelligence for the willingness and freedom to use the deepint software.

Conflicts of Interest: The authors declare no conflict of interest.

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