We Put the "UN" in FUN: The Mathematical Guide to Saving the World

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Abstract

Imagine a world without hunger, without poverty, with equality and education. Could this ever truly be a worldwide possibility? While some of these goals may appear distant, the *United Nations (UN)*, with their *Sustainable Development Goals (SDGs)*, aims to create change across seventeen different categories by 2030. These goals focus on various contemporary challenges that can improve the quality of life for people across the globe. However, with such a broad range of topics and the short time frame, it becomes necessary to prioritize some goals over others in order to have the greatest chance of success and impact.

In searching for a method to prioritize a subsection of the seventeen different goals, our team used a *weighted graph model* with nodes and edges as a method to represent some set of elements and relationships between them. For our model, we constructed a network of connections with each node representing one of the SDGs. The edges between the nodes are weighted, representing the positive or negative impact correlation between two goals. Each node is connected to every other node in the graph. To determine the proper weighting between each node, we analyzed data from a 2017 study which utilized Spearman's correlation ranking to determine interactions between different goals [Pradhan et al., 2017]. Another popular metric for measuring correlation between SDGs is the 7-point scale, where correlations are ranked from -3 to +3, where -3 represents the most negative correlation and +3 represents the most positive (Pradhan et al., 2017). However, there are no current global values measured with this scale, so we combined both approaches to scale the Spearman's correlation rankings and the 7-point scale to create our scale, which ranges from -1 to +1.

As a metric to model the synergy between the SDGs, we used an *achievement score*, a value between 0 and 1, where 1 indicates complete achievement and 0 indicates no progress. The achievement scores can be propagated through the network as a function of the weights and distance from the parent vertex. Using our model, we experimented with various connection weights and initial achievement values to determine the most interconnected and most influential goals. From this analysis, we determined that SDG 1: *No Poverty* holds the highest positive priority, while SDG 12: *Responsible Consumption and Production* holds the greatest negative priority. This indicates that SDG 1 holds the most positive correlations with the other goals and SDG 12 holds the most negative correlations. This model was also used as a foundation for what we might expect to be accomplished in 10 years if actions based on our priorities were enacted. We believe that while focusing on SDG 1 would allow the UN to better meet the holistic needs of people worldwide, the initial value for SDG 1 is not high enough to expect completion by 2030.

We also included *constant multipliers* within each node to represent the probable impact that certain worldwide events could have on the achievement level of each goal. Constant multipliers represent a percentage change in the achievement levels of each of the SDGs and are calculated for each potential event separately. The COVID-19 pandemic, which erased four years' worth of progress towards ending poverty, is one example (United Nations, 2015). Statistics like this impacted the relative values of our multipliers for war, technological advancements, pandemics, climate change, and refugee movements. From implementing the multipliers, we determined that SDG 1: *No Poverty*, SDG 2: *Zero Hunger*, SDG 4: *Quality Education*, SDG 10: *Reduced Inequalities*, and SDG 16: *Peace, Justice, and Strong Infrastructure* would be most impacted by a variety of possible future events.

1 Introduction

1.1 *Overview of the Problem*

The 17 SDGs, as laid out by the UN's Department of Economic and Social Affairs, aim to improve life for people across the globe. Many goals have the potential to influence others, meaning that implementing one goal may have a desirable or undesirable impact on the other goals. Implementing one goal can also lead to indirect changes among other goals alongside the direct changes caused through immediate connections. Additionally, technological advances, global pandemics, climate change, and other international factors have led to changes in the ability to enact certain goals. Therefore, this intertwining of the goals and numerous external factors leads to the necessity of prioritizing certain goals and creating a viable network of the relationships between them.

1.2 *Assumptions*

Our analysis aggregates the currently existing data for all countries to determine net correlation and does not depend on any singular geographic region. Thus, this analysis is purely conducted on a global scope and represents the impact of certain policies on the entire world, not on any specific country or region. Therefore, our model relies on the following assumptions:

- The goals are implemented and impacted uniformly across the globe.
- International crises have a net uniform impact across the globe
- The impacts between achievement values and from global crises are time independent.
- Goals feel the full influence of each other's achievement before feeling the impact of external influences.

1.3 *Existing Models*

Currently, there exist a few models which attempt to inform policy-making through a simulation of the SDGs. The most prominent, the iSDG, simulates the effects of changing policies on each Sustainable Development Goal in specific countries with established infrastructure [Millennium Institute, 2016]. In order to produce more widespread conclusions and address a current gap in the available models, our model seeks to understand the impact on a much broader scale.

2 Background

2.1 *The Sustainable Development Goals*

In 2015, the UN adopted the 2030 Agenda for Sustainable Development. Their hope was to enact a plan to increase peace and prosperity across the planet. The SDGs originated from this agenda, which leans on global partnership to develop strategies to increase quality of life in both developed and undeveloped countries. The SDGs also focus on mitigating the impacts of climate change. [United Nations, 2015]

1. No Poverty
2. Zero Hunger
3. Good Health and Well-Being
4. Quality Education

5. Gender Equality

6. Clean Water and Sanitation

7. Affordable and Clean Energy

8. Decent Work and Economic Growth

9. Industry, Innovation, and Infrastructure

10. Reduced Inequalities

11. Sustainable Cities and Communities

12. Responsible Consumption and Production

13. Climate Action

14. Life Below Water

15. Life On Land

16. Peace, Justice, and Strong Institution

17. Partnership for the Goals

2.2 *Relations Between Goals*

[United Nations, 2015]

Each goal is defined in terms of its targets and indicators, many of which align. We extrapolated the relationships between these targets and contemporary affairs onto our scaled version of the standard metric for measuring goal synergy. A highly synergistic relation can be seen through common indicators, such as is the case with SDG 1: *No Poverty*, SDG 11: *Sustainable Cities and Communities*, and SDG 13: *Climate Action*, which all contain the indicator "number of deaths, missing persons, and persons affected by disaster". [Pradhan et al., 2017] Furthermore, it has been determined that SDG 8: *Decent Work and Economic Growth* and SDG 9: *Industry, Innovation, and Infrastructure* are negatively correlated with twelve other goals. [Pradhan et al., 2017]

3 Variables and Definitions

Variable	Meaning
	Achievement Score of a Vertex
P	Priority of a Vertex
L	Chosen Layer Depth
$A_{i\,j}$	Achievement Score of a Vertex at a Given Depth
$w_{i\,j}$	Weight of a Given Connection on a Layer
k	Experimentally Determined Decay Coefficient
$i\,,\ j$	Summation Variables
S	Number of Vertices in the Network

Some of these values are consistent throughout this paper but could be modified depending on the network. These are as follows:

Variable	Chosen Value
L	3
k	2.56
S	17

Commonly Used Terms:

Achievement - a measure of the "percent completion" of a given goal

Priority - a measure of the "connectedness" of a goal to others, based on the weights of its neighbors

Vertex/Node - a data type symbolizing one goal and containing its achievement score

Layer - a set of vertices a given number of connections away from a central vertex (*i.e.*, layer 0 is the central node, layer 1 is every node connected to it, layer 2 is every node connected to a node in layer 1 [including repeats from layer 1], *etc.*)

4 Methodology

4.1 *Model Overview*

The core of the model is a *weighted undirected graph*, with each *vertex* corresponding to one of the 17 UN SDGs and each *edge* corresponding to a correlation between two goals. The edges are weighted from 1 to -1, with goals having positive influence on one another (*i.e.*, helping climate change and preserving ocean life) being weighted positively and goals having negative influence on one another (*i.e.*, no poverty and responsible production/consumption) being weighted negatively. Each vertex is connected to every other in the model, although some weights are given a value of zero, corresponding to having little to no influence on one another.

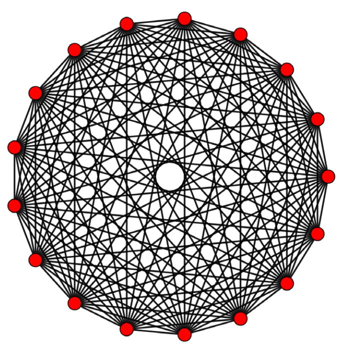

Figure 1: The system can be represented as the connections of a graph with 17 vertices, each connecting to all others. [Public Domain]

Each vertex has associated with it a certain achievement score between 0 and 1, where 1 means that the goal has been completely achieved and 0 means that no progress has been made towards it. The achievement scores can be propagated through the network as a function of the weights and distance from the parent vertex; this propagation is given by an equation that we derived based on the idea of constructive and destructive interference of waves. Each vertex also has a priority score based on the weights of its connections; this score determines the importance of accomplishing a given goal.

The values of the weights and initial achievement scores were derived from recent data from the UN and other organizations; these data were then used to calibrate the model and determine how the success rates of certain goals will propagate into the future. Subsequently, these "idealized" models were contrasted with models that took into account external effects such as war and pandemic.

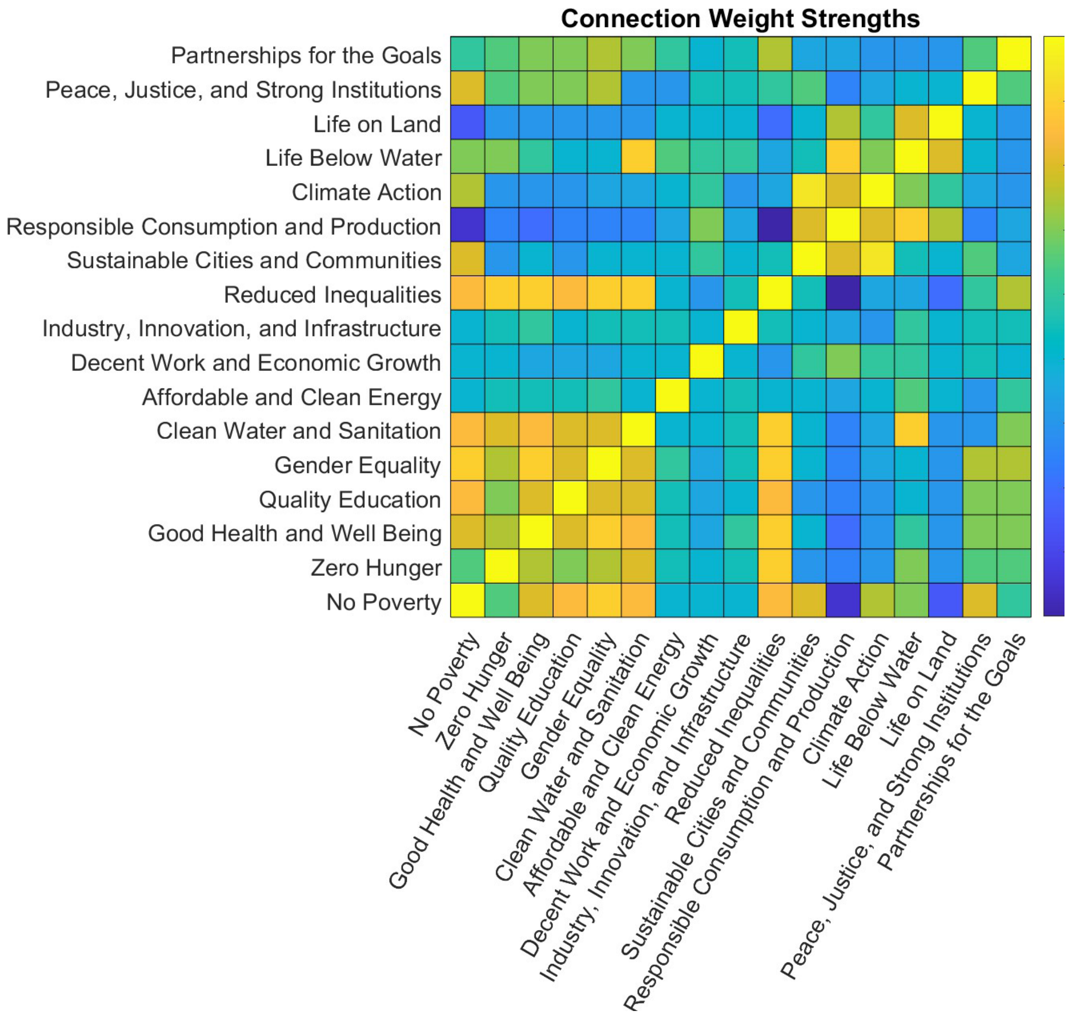

Figure 2: The weights of the connections are represented in this grid, where each box represents the connection between two goals given along the axes. The symmetry over the line $y = x$ is a byproduct of the undirected nature of the graph. All vertices are set to have a connection of weight 1 with themselves.

4.2 *Basis and Derivation of Model*

The weighted graph network used to calculate the achievement and priority scores for each goal are based off David Kopec's generic WeightedGraph from his book *Classic Computer Science Problems in Java* [Kopec, 2018]. This weighted graph was implemented using generics for greater flexibility; therefore, we created our own Vertex data type, with properties corresponding to effect multipliers for outside influences and achievement score. Using this new data type, we implemented a recursive breadth-first algorithm to get the weights and achievement scores of vertices in a wavelike fashion from a central node. Due to the graph being fully connected (every node connects to every other), these "waves" propagate very quickly through the system, and it became necessary to include associated damping factors. These damping factors came in two facets: *direct* factors were inversely proportional to some factor of the "distance" between nodes, and *indirect* factors were coefficients derived to calibrate the model according to current data.

The equations were derived from a need to be able to associate a given vertex with others around it. Since the impacts of one goal on others depend on how strongly correlated they are, both the achievement and priority equations are inversely related to the distance from the center node. Although these equations were not directly based on any one prior formula, they make use of the idea of *weighted averages* to calculate the important factors that must later be visualized and analyzed.

The values of L and k were chosen to balance efficiency and accuracy of results; since the algorithms used to determine the achievement and priority scores are recursive, they have high associated time costs. This selection of values allows for enough interplay between vertices that the complex interactions associated with the goals is accurately portrayed while also ensuring that the feedback loops caused by the interconnectedness of the network do not generate unnecessary noise and/or false results at a high time cost.

We chose to visualize the data using bar graphs with different bars corresponding to different conditions (*i.e.*, the effects of completing one goal, the effects of war, *etc.*). This visualization style allows for a more comprehensive and accurate analysis of the data, as well as a simpler way to compare the effectiveness of a certain plan. Additionally, we chose to visualize the graph itself as a colormap with the color corresponding to edge weights; this provides a very simple way to see the structure of the network without needing to visualize every vertex individually. Combined, these two visualization sets allow for a holistic view of the workings of the model and make it easier to interpret and analyze its results.

4.3 *Equations*

The achievement metric of each node (a bounded value between 0 and 1) can be calculated based on the achievements of the surrounding vertices and weights of their connections. The influences of other vertices fall off exponentially with distance from the center node according to the following equation:

$$A = A_0 + \frac{\sum_{j=1}^{S-1}(A_{1j}w_{1j})}{k(S-1)} + \frac{\sum_{j=1}^{(S-1)^2}(A_{2j}w_{2j})}{k^2(S-1)^2} + \cdots + \frac{\sum_{j=1}^{(S-1)^L}(A_{Lj}w_{Lj})}{k^L(S-1)^L}$$
$$= \sum_{i=1}^{L}\left(\frac{\sum_{j=1}^{(S-1)^i}(A_{ij}w_{ij})}{k^i(S-1)^i}\right)$$

(Equation 1)

where A_0 is the achievement score of the vertex in question before propagation. Other values are the same as those given in Table 3.

Variables and Definitions.

At each layer, all $(S-1)^i$ vertices connected to the previous layer of parent vertices (where i is the current layer depth) will be counted and their weights and achievement scores multiplied; these will then be summed and divided by an amount proportional to their distance from the vertex for which A is the achievement (the "center" of the measurement, in a sense).

This equation was derived with the idea of achievement propagating outwards similarly to a wave in a closed region; some achievement-weight combinations will interfere constructively, and some will interfere destructively, with the *superposition* of these leading to the final achievement score.

The priority of each node is based on the weights of its connections without taking into consideration the achievement scores of it or its neighbors. This is calculated through propagation in a similar fashion to the achievement values, according to the following equation:

$$P = e^{\frac{\frac{\sum_{j=1}^{S-1} w_{1j}}{\left|\sum_{j=1}^{S-1} w_{1j}\right|}}{1-\frac{\left|\sum_{j=1}^{S-1} w_{1j}\right|}{S-1}} + \frac{\frac{\sum_{j=1}^{S-1} w_{2j}}{\left|\sum_{j=1}^{S-1} w_{2j}\right|}}{\sqrt{2}\left(1-\frac{\left|\sum_{j=1}^{S-1} w_{2j}\right|}{(S-1)^2}\right)^2} + \cdots + \frac{\frac{\sum_{j=1}^{S-1} w_{Lj}}{\left|\sum_{j=1}^{S-1} w_{Lj}\right|}}{\sqrt{L}\left(1-\frac{\left|\sum_{j=1}^{S-1} w_{Lj}\right|}{(S-1)^L}\right)^L}}$$

$$= e^{\sum_{i=1}^{L}\left(\frac{\frac{\sum_{j=1}^{S-1} w_{ij}}{\left|\sum_{j=1}^{S-1} w_{ij}\right|}}{\sqrt{i}\left(1-\frac{\left|\sum_{j=1}^{S-1} w_{ij}\right|}{(S-1)^i}\right)^i}\right)}$$

(Equation 2)

The top term of this summation evaluates to 1 if the sum of the layer weights is positive and -1 otherwise; this preserves the sign of the weights to ensure that the priority is not calculated as positive where it should be negative. The priorities fall off both with an exponential term and with a term proportional to the square root of the layer depth; this ensures that distant connections do not significantly influence the priority of a given vertex.

The entire summation term is used as an exponent in order to sure that all priorities remain positive while preserving the fact that negative sums should have smaller priority values than positive ones. Note that it does not matter what the base of the exponent is as long as it is greater than 1; here, e is simply used for convenience and simplification properties.

It is immediately evident that both these equations are highly summation-dependent. Therefore, they can both be written in the following compressed (and far more legible) forms:

$$A = \sum\left(\frac{\sum(A_i w_i)}{k^i (S-1)^i}\right)$$

(Equation 3)

$$P = e^{\sum\left(\frac{\sum w_i}{\left|\sum w_i\right|\sqrt{i}\left(1-\frac{\left|\sum w_i\right|}{(S-i)^i}\right)^i}\right)}$$

(Equation 4)

Equation (4) can alternatively be written in the form

$$\ln(P) = \sum \left(\frac{\sum w_i}{|\sum w_i|\sqrt{i}\left(1 - \frac{|\sum w_i|}{(S-i)^i}\right)^i} \right)$$

(Equation 5)

Note how much faster the achievement falls off than the priority; this is to prevent interference from other vertices at high depths. The domain of priority starts at a layer depth of one since all weights begin on the first layer.

Figure 3: The decay rates of achievement and priority with respect to layer depth. In both these cases, the sum of the achievements and weights is set to 1 to focus only on the trends.

In order to account for both independent and overlapping effects from multiple global events, we used the following equation to combine the Multiplier values from all events:

$$\frac{\sqrt{W^2 + R^2 + C^2 + T^2 + P^2}}{5}$$

(Equation 6)

where W is the War Multiplier, R is the Refugee Multiplier, C is the Climate Change Multiplier, T is the Technological Advancement Multiplier, and P is the Pandemic Multiplier. This formula can be generalized for any combination of events in the form:

$$\frac{\sqrt{\sum_{i=1}^{n} E_i^2}}{n}$$

(Equation 7)

where E is the nth Event Multiplier value.

4.3.1 *Derivation of k*

The constant k represents the amount of influence from more distant connections on the current node's achievement score. k varies depending on the layer depth search and so, for each depth, k was experimentally determined. In order to find the precise value for k, we compared the current trend in SDG progress to the result our model achieved when only considering the initial values. This resulted in the following values:

$k(1) \approx 1.88$
$k(2) \approx 2.39$
$k(3) \approx 2.56$
$k(4) \approx 2.61$
$k(5) \approx 2.62$

From this analysis, we conclude that k is logarithmic, and can be related to the search depth D by the following equation

$$k(D) \approx -0.85D^{-\frac{1}{0.72}} + 2.72$$

(Equation 8)

The significance of the asymptotic approach of k to 2.72 is unclear; further tests were inhibited by the time cost of running the recursive algorithm for high search depths. It is unknown if this is at all related to Euler's number or if the similarity is purely coincidental; the R^2 value of the regression is .998, and the percentage difference between the asymptotic value and e is only .063%. Further experimentation using different calibration values seems to suggest a coincidence, but more testing is needed.

4.4 *Vertex Connection Weights*

Each node in the graph is connected to the others through a weighted connection, with each connection measuring the synergy between the goals.

These connections are undirected since the current data between improvements in goals is correlational. An improvement in one goal is a reflection in the improvement in one or more of its UN defined targets [United Nations, 2015], and many SDGs share these targets. For example, reducing the number of deaths from natural disasters coincides with implementing policies to mitigate climate disaster, resulting in a strong connection between SDG 11: *Sustainable Cities and Communities* and SDG 13: *Climate Policy*.

We modeled our ranking after two currently existing standards: a study based on Spearman's rank correlation analysis between indicators of two goals and the 7-point SDG interaction scoring scale [Pradhan et al., 2017]. Spearman's rank correlation was used due to its ability to reliably detect correlation while avoiding excessive influence from outlier data points. This analysis was performed on targets and indicators of each

SDG. Many of these targets overlap, accounting for the observed positive correlation, and others are inversely proportional, resulting in negative correlation. The 7-point scoring system aligns nicely with our intended model, since both this metric and ours measure achievement linearly, but it requires modification in order to scale to our current system.

Our connection weights span from -1 to 1 in increments of 0.1, and in order to achieve this, we combined the approach of the 7-point system with the synergy analysis [Pradhan et al., 2017]. By measuring the positive and negative correlations, we scaled the 7-point system down and used these values to weigh each connection. The choice of the -1 to 1 scale was made for simplifying the equations. Negative values represent negative correlation, or when a positive development towards one goal leads to a negative development in another. Positive values represent improvements on both ends of the connection, where a net positive impact is achieved. Values larger in magnitude correspond to a stronger connection between two goals, either beneficial or detrimental.

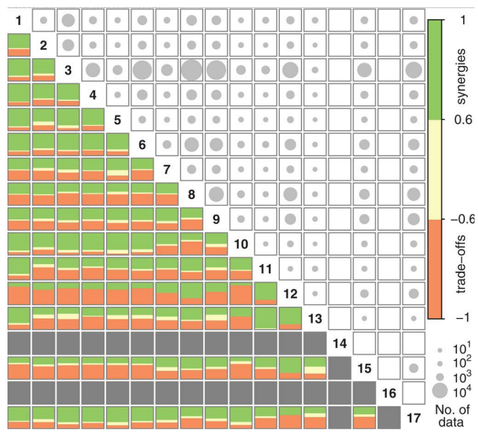

Figure 4: Synergistic and Trade-Off Relationships Between the Goals [Pradhan et al., 2017]

4.5 *Initial Achievement Values*

In order to provide an accurate representation of future trends, our model must be up to date with the current state of affairs as it pertains to all goals. To ensure as much accuracy as possible, we used the UN 2022 SGD Progress Report [United Nations, 2022a], which evaluates the goals in terms of their indicators. There are a total of 248 indicators, and of these, 13 repeat. This repetition can happen for multiple targets, and consequently, there are 231 unique indicators [United Nations, 2017a]. For each goal, we averaged the data for all of its indicators to produce a reliable metric by which the current level of progress can be evaluated and utilized in our model.

The table below outlines the initial values used from 0 to 1:

Goal	Initial Value
No Poverty	0.6
Zero Hunger	0.4
Good Health and Well-Being	0.6
Quality Education	0.6
Gender Equality	0.6
Clean Water and Sanitation	0.6
Affordable and Clean Energy	0.7
Decent Work and Economic Growth	0.3
Industry, Innovation, and Infrastructure	0.8
Reduced Inequalities	0.6

Sustainable Cities and Communities	0.4
Responsible Consumption and Production	0.7
Climate Action	0.3
Life Below Water	0.3
Life on Land	0.6
Peace, Justice, and Strong Institutions	0.5
Partnerships for the Goals	0.5

4.6 *Model of Instance 1 - Network of Relationships*

This model represents the control. Using current data, this graph demonstrates the relationships between the SDGs. We noted that despite some negative correlations, most saw an overall positive change in the achievement of goals when the relationships between them were considered and the achievement propagation algorithm was used. For example, if SDG 1: *No Poverty* experiences a significant growth, we would expect to see a similar impact on SDG 2: *Zero Hunger*. However, we might also expect to see a slight decrease in the progress towards SDG 12: *Responsible Consumption and Production*. However, SDG 12 is also positively influenced by other goals, such as SDG 11: *Sustainable Cities and Communities* and SDG 13: *Climate Action*; since SDG 11 and SDG 13 both have positive correlations with SDG 1, there will be an increase in progress in both of these goals, and they will in turn augment the progress of SDG 12. Our propagation algorithm accounts for the multi-dimensional connections within our network. Therefore, we analyze not only the impacts of a primary layer, but also the impacts from the secondary and tertiary layers with respect to one node within this model.

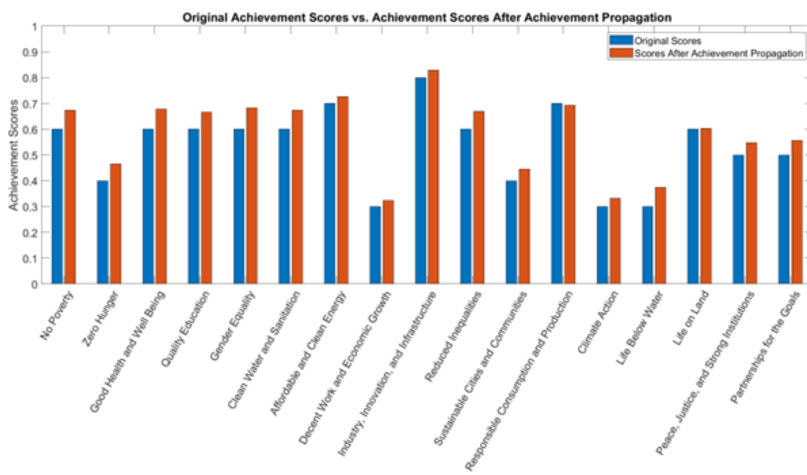

Figure 5: This model demonstrates the initial values of the achievement of the SDGs as they currently exist as seen by the blue bars. It also demonstrates the values as they are impacted by the other SDGs.

Note that no value experiences a substantial decrease in its achievement metric (with only one decreasing at all), meaning that all goals can theoretically be accomplished simultaneously.

4.7 *Model of Instance 2 - Influences of Goals on Another*

In order to determine which goals were the most influential on all other goals, we modified the initial achievement values to reflect the circumstance in which one goal reached full achievement. After analyzing the results for each goal, in combination with our formula representing the priority for each goal, we determined that SDG 1: *No Poverty* had the largest positive impact, whereas SDG 12: *Responsible Consumption and Production* had the largest negative impact. Note that the differences may appear small; however, this is due to the synergy between other goals simultaneously affecting achievement values.

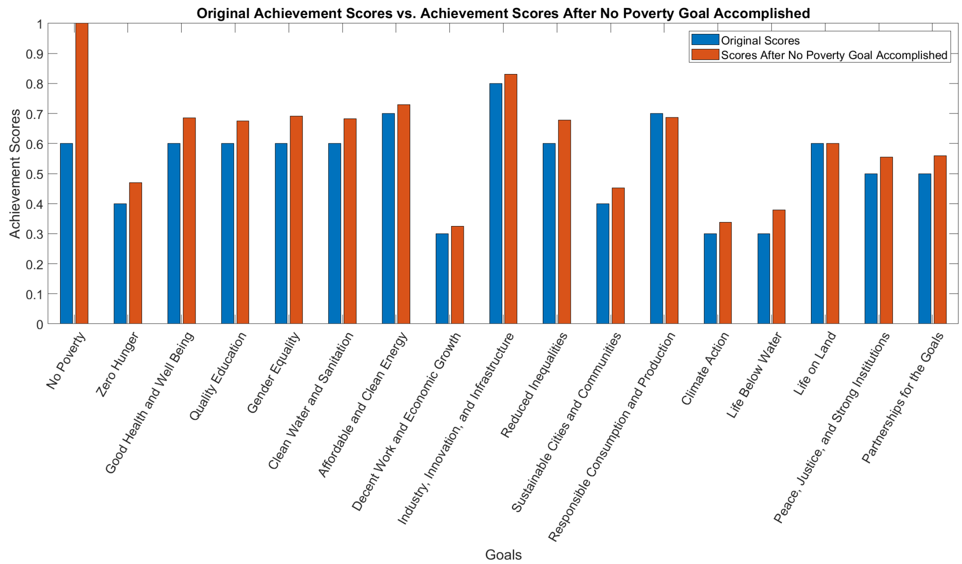

Figure 6: The achievement with the largest positive impact on the other goals is SDG 1: *No Poverty*

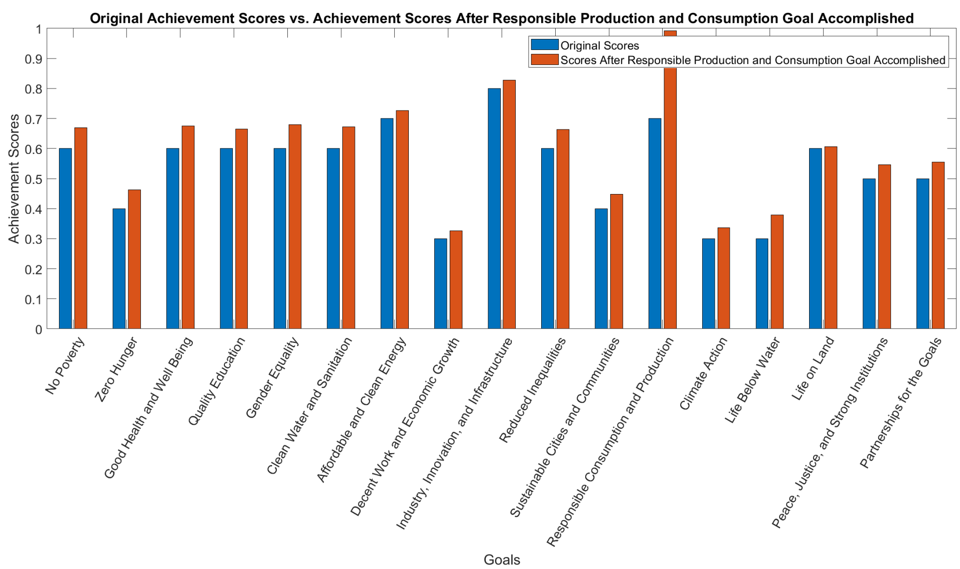

Figure 7: The achievement with the largest negative impact on the other goals is SDG 12: *Responsible Consumption and Production*

4.8 *Model of Instance 3 - International Impacts*

4.8.1 *Multiplier Scale*

To analyze the impact that international crises cause on the SDGs, our team created a multiplier system for each crisis. The multipliers are set at a constant value per each SDG extrapolated from data discovered in our research. These constant values represent a percentage change in the achievement levels of each of the SDGs. In applying the multiplier scale to our weighted graph model, we first calculate the change in achievement levels based on the interactions between the SDGs as determined above. Afterwards, we apply the multiplier for the international event to determine how the achievement levels are impacted. We performed the calculations in this order to allow for the SDGs with high positive correlations to propagate their achievements despite the devastating impacts of wars or pandemics.

War

Multiplier Values

When looking to analyze the impact of wars on the SDGs from a global perspective, our team needed to obtain worldwide data to reflect our model design. In researching the impact of wars on the SDGs, our team discovered data from both the war in Yemen [Moyer et al., 2019] and the war in Ukraine [Bin-Nashwan et al., 2022]. While we recognize that each war holds its own unique circumstances, we found common impacts between the two wars. From the data acquired, we were able to extrapolate values to use for a multiplier scale. Regarding the war in Yemen, the UN compiled a report of the indicators based on four different SDGs that were impacted by the war. Using a conflict vs. no conflict analysis, the UN determined what the "*Conflict-Attributable Difference*" was for each of the four goals [Moyer et al., 2019]. From this data, we also looked at the impacts of the war in Ukraine to fill in the gaps and refine data from the war in Yemen. The UN also compiled a report regarding the impacts of the war in Ukraine on sustainable development in Africa [United Nations, 2022c], which we used to help understand long-distance effects and global trends. The information from this report in combination with other sources allowed us to determine the devastating impacts of war on most of the SDGs.

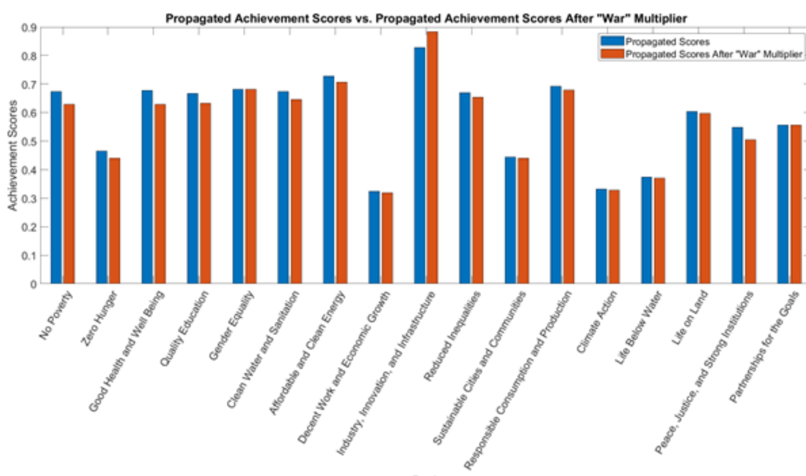

Figure 8: The impacts of war on the SDGs

Technological Advancements

Multiplier Values

Technological advancement is an extremely broad metric, and to best understand the impact of potential technological improvements, we researched the technology predicted to have the greatest positive impact on each of the SDGs [Capon et al., 2017] [ITU, 2021] and chose to study the effects of this most prominent technology. We then defined a set of specific advancements that would be simulated, denoted in the table below:

Advancement	SDGs Impacted
Widespread Access to Bank Accounts	1, 2
Boost Agricultural, Water Management, and Energy Research	2, 3, 6, 7, 8, 9, 11, 13
Enhance Internet Accessibility	4, 5, 9, 10, 16, 17
Strengthen Communication Networks	9, 11, 12, 16, 17
Minimize E-Waste	7, 8, 9, 11

Next, we scaled our multiplier metric according to the number and strength of these impacts. This scale was then propagated across our achievement values to produce the following results.

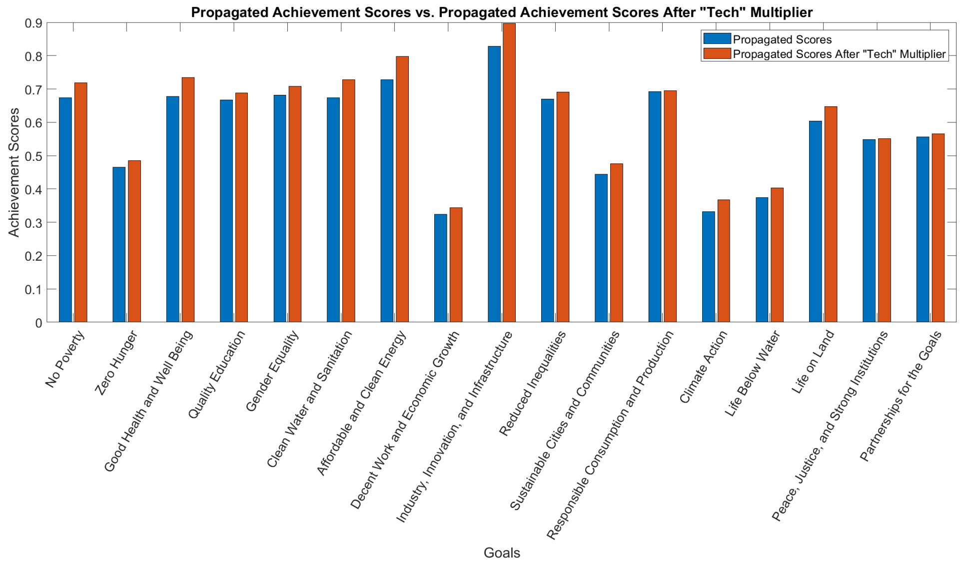

Figure 9: The impacts of technological advancements on the SDGs

Pandemic

Multiplier Values

In order to assess the impact of a global pandemic, we studied the effects of the COVID-19 pandemic and extrapolated these effects to a general multiplier scale for the impact of a future pandemic [Richter, 2021] [United Nations, 2020a]. We looked at current trend lines and extrapolated these results to the rate of change in the projected values without a pandemic using the current values [Mahler et al., 2021]. The figure below illustrates this process for SDG 1: *No Poverty*:

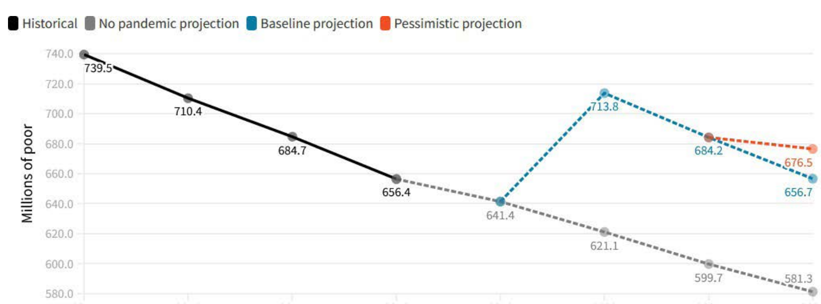

Figure 10: Projected effect of COVID-19 pandemic on global poverty rates [Mahler et al., 2021]

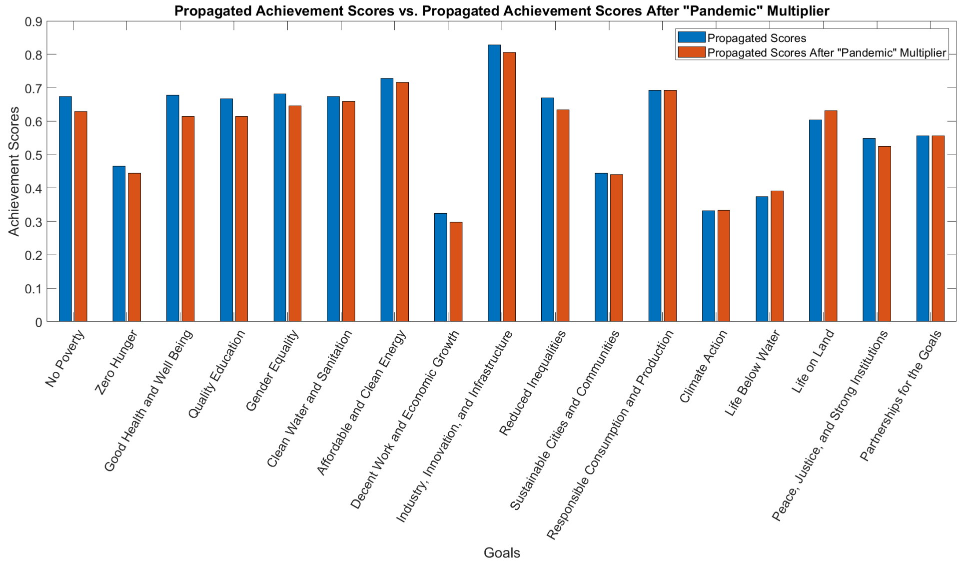

Figure 11: The impacts of a pandemic on the SDGs

This process was repeated for each separate SDG to determine the relationship between the goals and the effects were experimentally calibrated by configuring the constant k to reflect the real-world changes.

Climate Change

Multiplier Values

We compiled available data for each SDG based on the current and projected impacts of climate change on each goal [United Nations, 2022b] [United Nations, 2019]. This model analyzes the expected impacts on each goal with no current change in policy. This model will not change the current achievement levels of goals directly related to mitigating the problem of climate change, but rather focuses on the goals climate change would impact.

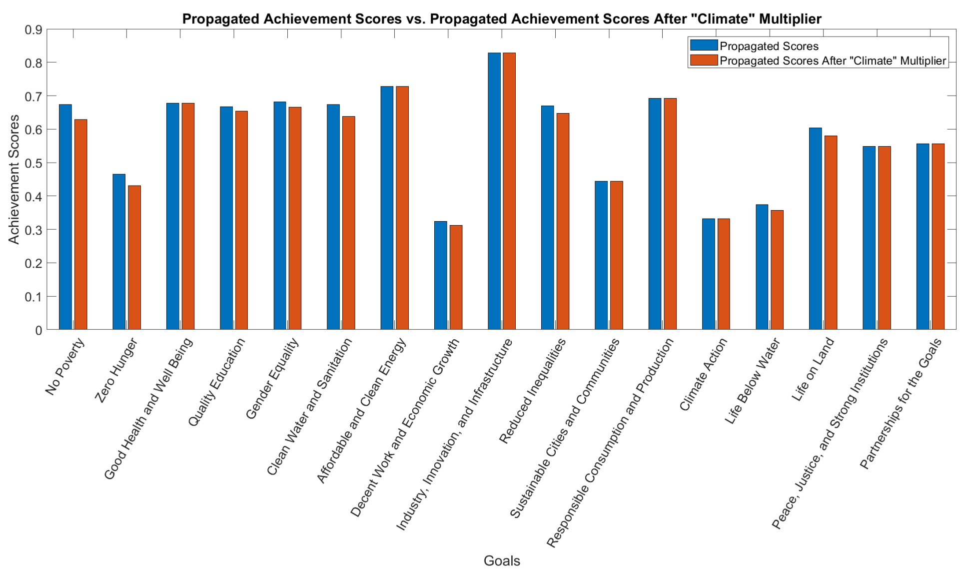

Figure 12: The Impacts of Climate Change on the SDGs

Refugee Movements

Multiplier Values

To determine the impacts of refugee movements, we analyzed the results of historical refugee crises and projected their impacts onto the SDGs [United Nations, 2017b]. We chose to focus our research on Syria, Venezuela, and Afghanistan due to their large impact on contemporary statelessness and the diverse situations they represent [Denaro and Giuffré, 2021]. We combined these factors to produce scaling multipliers which, as we have done for each potential global event, were applied to the achievement scores for each SDG.

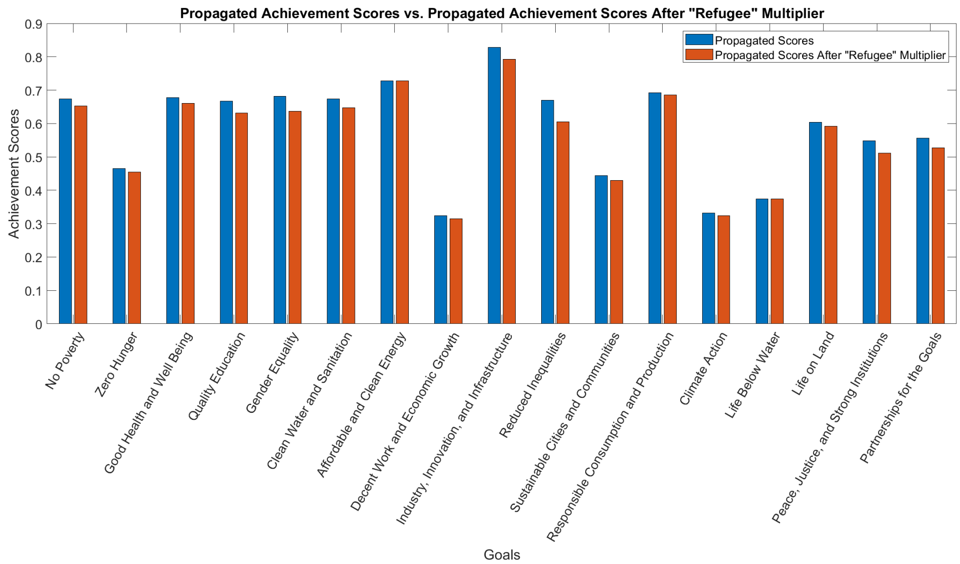

Figure 13: The Impacts of Refugee Movements on the SDGs

Combinations of Global Events

In order to understand the effects of multiple events occurring together, we accounted for the different ways in which each global event impacts the achievement scores of all goals. For example, while both war and climate change have a deleterious effect on SDG 2: *Zero Hunger*, they do so in different ways. Climate change might reduce the amount of fertile land, while war might decrease the number of people available to manage the harvest. Yet these two impacts are not entirely independent; for example, war might also destroy plots of agricultural land, thus overlapping with the effects of climate change. In order to account for both the overlap and individual effects, we took the square root of all multiplier values squared before calculating the combined effect on the SDG's achievement scores using Equation (6). Our results followed expected patterns and we noticed more dramatic changes when the effects of multiple catastrophes or developments were superimposed.

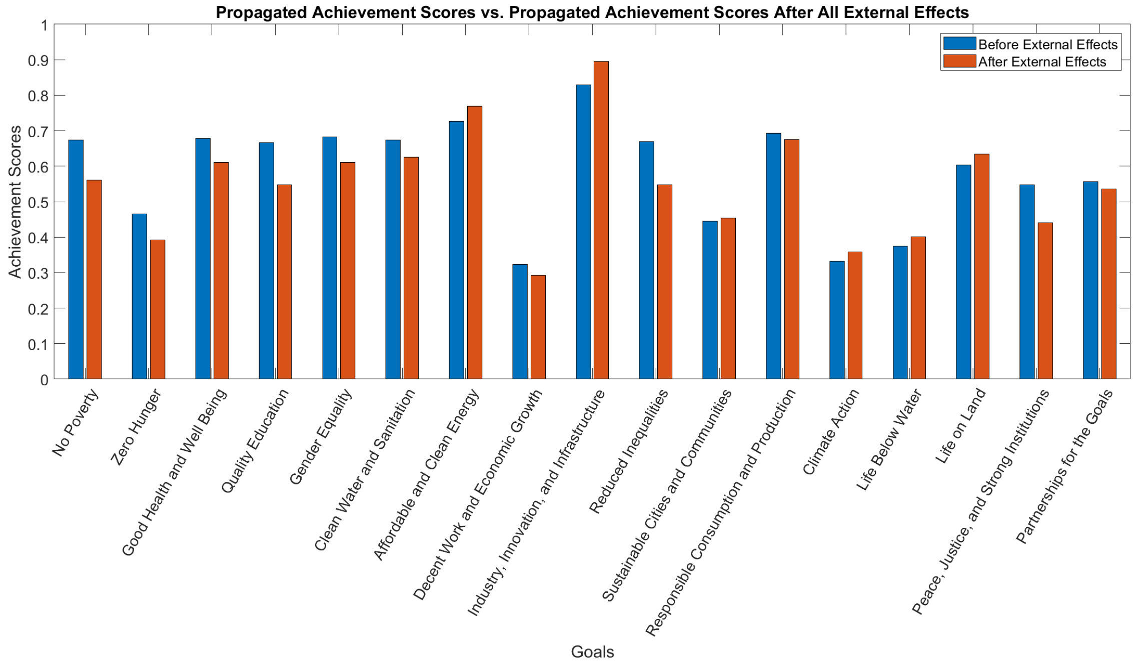

Figure 14: The impacts of all multipliers combined on the SDGs

4.9 *Sensitivity Analysis*

Our sensitivity analysis was conducted by rerunning the model with variations of the weight parameters to quantify how the propagation changes with variations in inputs. We used several different multipliers with our weights to determine how achievement propagation differs; specifically, we multiplied the weights by 0.25, 0.5, 1.25, and 1.5. We then propagated the achievement scores using these modified weights and compared them to the control data set to see if our model responded chaotically. The results below conclude that they do not; the propagation of achievement varies in a linear fashion compared to the weights, with the intensity of the variation being directly correlated to the priority score of a given node. The linearity is evident in the output data when tests of various sensitivities are run side-by-side.

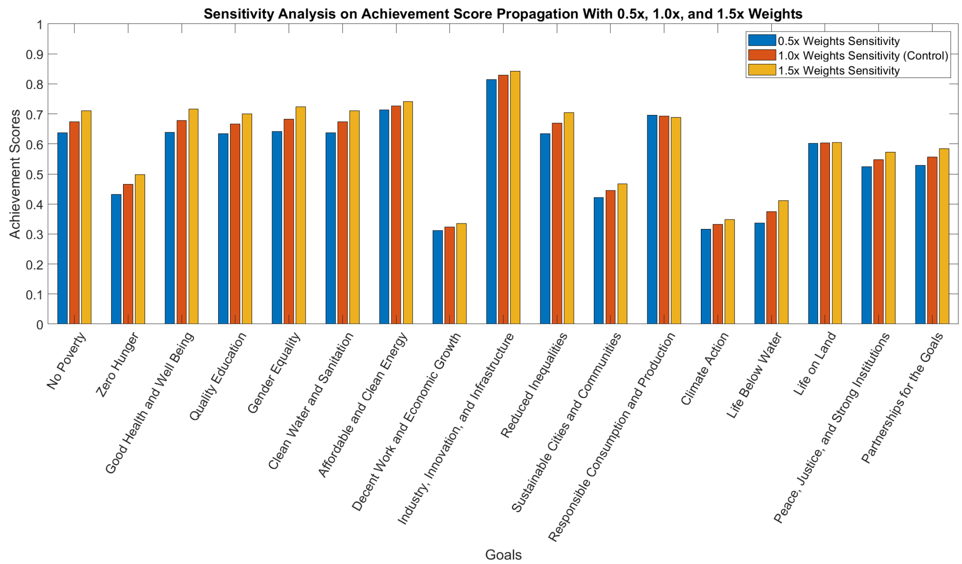

Figure 15: Sensitivity analysis run with 0.5x, 1.0x, and 1.5x weight data sets. The variance in the propagated achievement scores appears to correlate linearly to the input weights.

We only tested our model on the weight distribution corresponding to reasonable values for the UN SDGs, since the model is based around this data set. Although the model could theoretically be implemented generically, we calibrated values (specifically the value of *k*) based on data relevant to only the UN goal data set (relationships between the goals, current achievement of the goals, *etc.*). Therefore, although we have proven that the model is not chaotic when used to analyze relevant data, we are unsure of its effectiveness in analyzing similar data sets with different relationships and parameters. Such "similar" data sets could include, for instance, relationships between populations of different species or trade-offs in economic systems; such examples center around data with components that are intrinsically connected to each other and vary with respect to one another. Mathematically, such data sets could be represented with coupled systems of equations. We are, however, confident in our model's ability to represent relationships between the goals given here, even with varied inputs; additionally, with specification based on the data set, this model could likely be expanded to further unrelated cases. The fact that priority and sensitivity are directly correlated follows from the fact that a node with a higher priority has more significant connections, which in turn means a greater change in achievement score. It is important to note that the correlation scores can be negative (such as is the case for SDG 12: *Responsible Consumption and Production*); this simply means that the given goal correlates negatively with most other goals, so increasing these weights results in a decreased achievement score.

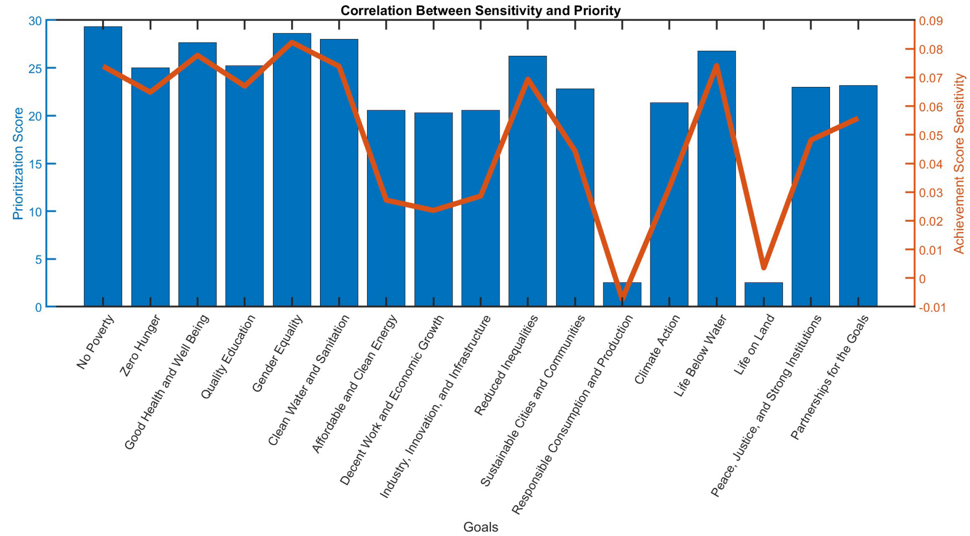

Figure 16: Correlation between goal priority and change in propagated achievement score.

5 Results

5.1 *Priority Rankings*

As demonstrated in the model, many of the SDGs have high priority scores, with the two outliers of SDG 12: *Responsible Consumption and Production* and SDG 15: *Life on Land*. With many of them maintaining a high priority, this indicates that there are different options when exploring which goal should be implemented first. However, SDG 1: *No Poverty* holds the highest priority in accordance with our model and formula utilized.

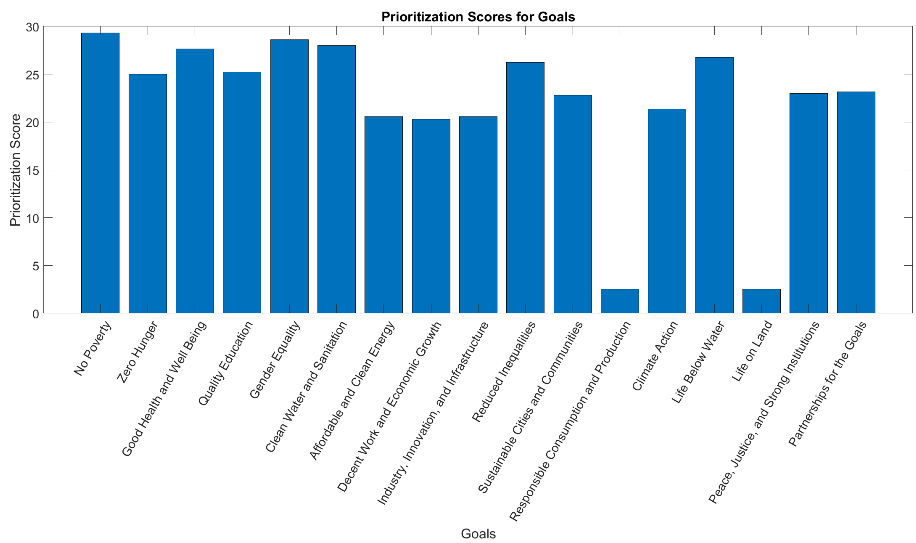

Figure 17: The prioritization values of each goal. The numerical values of the scores themselves are somewhat arbitrary; only the relative priorities matter.

Using our priority model, if SDG 1 was chosen as a focus in the next 10 years, we would expect to see the greatest net increase in the achievement levels of the other SDGs, especially with SDG 2: *Zero Hunger*, SDG 3: *Good Health and Well-Being*, SDG 4: *Quality Education*, and SDG 10: *Reduced Inequalities*. With current policy and the potential for continuing international crises, we do not expect SDG 1 to become fully achieved; however, we can expect many positive changes across other goals if a focus on SDG 1 is implemented.

5.2 *Impacts of Goals on One Another*

The majority of the goals, when fully achieved, had a positive impact on all other goals. Oftentimes however, when one goal is achieved, a different goal is left behind. For example, when the most impactful goal, SDG 1: *No Poverty*, was achieved, SDG 15: *Life on Land* would see little to no progress as a direct result. Thus, SDG 15 would require action and would become a new priority. The results from the current analysis, therefore, would not be effective indefinitely; the model would have to be rerun (most likely every year or whenever there is a significant international event) to determine the new most urgent priority. Acting on the goal of highest current urgency ensures a well-distributed beneficial effect from the work towards achieving all SDGs.

5.3 *Impact of Global Events*

5.3.1 *War*

War most negatively impacted SDG 1: *No Poverty*, SDG 3: *Good Health and Well-Being*, and SDG 16: *Peace, Justice, and Strong Institutions*. All three of these metrics have a positive correlation with each other, with the strongest correlation between SDG 1 and SDG 3 and a strong correlation between SDG 1 and SDG 16. It is therefore understandable that these three SDGs would have the highest impact in relation to each other. Therefore, the best strategy for addressing the impacts of war is to focus efforts on poverty mitigation and utilize the synergy between the goals to continue progress. As noted in our model, SDG 5: *Gender Equality* and SDG 17: *Partnerships for the Goals* have very little correlation with war. SDG 9: *Industry, Innovation, and Infrastructure* was noted to have a positive correlation with war. Therefore, we can assume that emphasizing the betterment of any of these three goals (SDGs 5, 9, 17) would not have a large impact during a time of war and should not be focused on.

5.3.2 *Technological Advancement*

Technological advancement, produced a net positive impact on all 17 SDGs. Most notably, the impacts on SDG 3: *Good Health and Well-Being* and SDG 9: *Industry, Innovation, and Infrastructure* were especially pronounced. Technological advancement has the most minimal impact on SDG 16: *Peace, Justice, and Strong Institutions* and SDG 12: *Responsible Production and Consumption*. Therefore, in combination with increased efforts to develop new technologies, it is imperative to also take steps to ensure that SDGs 12 and 16 are not left behind. SDG 12 has a positive correlation with SDG 8: *Decent Work and Economic Growth* and SDG 11: Sustainable Cities and Communities. A potential method to ensure that SDGs 12 and 16 are not abandoned would include ensuring that the goals with positive correlations to these goals are being increased through other actions.

5.3.3 *Pandemic*

A global pandemic is devastating for progress towards the goals, and in particular, it has detrimental impacts on SDG 3: *Good Health and Well-Being*, SDG 4: *Quality Education*, and SDG 8: *Decent Work and Economic Growth*. SDGs 3 and 4 have a strong positive correlation with each other and both SDGs 3 and 4 have a slight negative correlation with SGD 8. Therefore, a pandemic will require a widespread holistic approach that addresses its myriad of detriments on the SDGs.

While the effect of a pandemic may lead to progress towards SDG 14: *Life Below Water* and SDG 15: *Life on Land*, it is important to note that these effects are not usually sustainable without additional progress in SDG 13: *Climate Action* [United Nations, 2020b], and thus, SDG 13 still retains its importance among the goals.

5.3.4 *Climate Change*

Compared to war and pandemics, the effect of climate change appears deceptively small, but contrary to most other events, climate change's impacts happen gradually over a longer period of time, which must be taken into consideration when evaluating these results. Climate change is predicted to have the most deleterious impacts on SDG 1: *No Poverty*, SDG 2: *Zero Hunger*, and SDG 6: *Clean Water and Sanitation*. Additionally, climate change is not set to impact SDG 13: *Climate Action* or SDG 7: *Affordable and Clean Energy*, since this model analyzes the impacts of climate change without any changes to current policy. Of course, focusing on SDGs 7 and 13 would abate the inimical effects predicted by the model, but if no progress is made, the best strategy to combat climate change and augment sustainability is to focus on SDG 6. Since the correlations between SDGs 6 and 1 and between SDGs 6 and 2 are heavily positive and the correlation between SDGs 1 and 2 is moderately positive, achieving SDG 6 would be beneficial for both SDGs 1 and 2.

5.3.5 *Refugee Movement*

While refugee movement is a complex phenomenon highly dependent on location, motivation, and other specific factors, the most common impacts of refugee movement are harmful to most SDGs. In particular, SDG 4 *Quality Education*, SDG 5: *Gender Equality*, and SDG 6: *Reduced Inequalities* are highly susceptible to refugee crises. The correlation between these 3 goals is strongly positive and, consequently, working to advance these goals will help limit the negative effects of future mass refugee movement.

5.3.6 *Combinations of Global Events*

When all global events are analyzed together, there are mixed results. Strong positive effects are seen in SDG 9: *Industry, Innovation, and Infrastructure* and SDG 6: *Affordable and Clean Energy*. On the other hand, strong negative effects are observed in SDG 1: *No Poverty*, SDG 2: *Zero Hunger*, SDG 4: *Quality Education*, SDG 10: *Reduced Inequalities*, and SDG 16: *Peace, Justice, and Strong Infrastructure*. This indicates that the biggest challenges are expected to align with SDGs 1, 2, 4, 10, and 16, and thus, policy should be most focused on these goals.

The biggest threat to achieving the SGDs is the threat of war or a pandemic because these possess the capability to erase years of progress in a very short period of time and are particularly difficult to predict. Our recommendation is to focus on conflict prevention strategies and build a strong healthcare foundation that is adequately equipped to combat new diseases, and thereby minimize the consequences from a pandemic on sustainable development.

5.4 *Prioritization With 3rd Party Entities*

Due to our network's multi-layered approach in determining priorities, we believe that this model would be useful in assisting third-party companies with their prioritization needs and company goals. The weighted graph structure of our model can be widely utilized in a variety of different situations given thorough research into the connections between aspects of the data being modeled. Our model is also highly adaptable; the only necessary changes to a new set of initial conditions would be the differences in edge weight, the initial values, and the values of multipliers (if any), which can be easily inputted into the model. Therefore, with the modification of values, companies could accurately compare how different goals would impact one another. The implementation of our priority formula would also assist in creating a standardized measure for what is the most useful to implement.

6 Conclusion

6.1 *Model Strengths*

One major strength of our model was its versatility. Our model not only has the capacity to measure and predict the impact of a variety of global events, but it can also analyze the impact of two or more events occurring together. This allows for a multifaceted future-orientated model capable of adapting to various scenarios.

Another advantage of our approach was our model's consideration of secondary and tertiary impacts. When changing one value, our model initially updates all of the other goals accordingly; through our recursive approach, it will then consider how these initial changes affect each other. As in real life, one goal cannot be achieved instantly and without impact on any others. As progress is made towards a goal, its impacts propagate to other goals, which change according to their respective synergies and trade-offs, and our model adequately accounts for this effect.

6.2 *Model Weaknesses*

Although our model had many strengths, some weaknesses severely limited our model and analysis. Within our collection of data, many sources were incomplete in regard to all 17 SDGs. This led to a necessity to extrapolate and compare data from different sources, decreasing the reliability and strength of our model; this especially impacted the standardization of weights and multipliers values.

Another weakness we encountered originated from one of our assumptions stated at the beginning: we decided to create our model utilizing a global perspective. This, while increasing our ability to perform calculations, meant that we could not analyze separate municipalities or the impact on a specific location based on an international crisis. For example, when a war breaks out in one part of the world, it impacts that region much more than others, but our model structure does not allow us to analyze impacts to that extent. Our time independence assumption also creates the disparity in the ability to use our model for a prolonged period of time; rather, it would need to be updated frequently based on current achievement scores.

6.3 *Final Statements*

The UN Sustainable Development Goals will not be easy to accomplish, but through careful analysis and the implementation of an informed mathematical model, we can take the next step towards a sustainable future. By understanding the relationships between the goals and the effects of global events, we can lay the foundations necessary to build a better world, one goal at a time.

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