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2019

The International Mathematical Modeling Challenge (IM²C) Summary Sheet

(Your team's summary should be included as the first page of your electronic submission.)

Summary

With rapid growth of human population comes growth of human impact on Earth. It is predicted that in the next 30 years, our population may increase by 2 billion people. Although, human population seems to have no limits, Earth's resources are finite and may soon be depleted. Without said resources, people cannot satisfy their basic needs. This is why the notion of carrying capacity is of such importance and understanding it is key for future development. Our goal was to create models which can estimate current Earth's carrying capacity as well as propose a sensible solution to raising this number in the future.

We understand carrying capacity as maximum population that can both be environmentally sustainable and provide a decent life for all. The same idea was incorporated in Safe and Just Space Framework defined as doughnut-shaped "safe operating space" restrained by planetary and social boundaries. Based on SJS we selected 5 biophysical and 5 social factors that impact the carrying capacity the most.

Our base model was based on 2 methods used in the past. The first calculates carrying capacity by estimating how many people can live on Earth based on space they need. The result that we got using this method was 12 billion. The other method focuses on choosing one natural resource and estimating how many people it can satisfy indefinitely. In this model we used the most commonly analysed resources - water and food and arrived at 31 billion and 13 billion respectively.

Our main, Dynamic model was based on Safe and Just Space framework and used System Dynamics approach to calculate carrying capacity. The first one provided us with a conceptualization of the problem while the latter enabled us to calculate interdependent factors in respect to population. We set thresholds that our key factors cannot transgress with so as to they fit in the SJS. Consequently, using Python, for every country, we calculated for what population the factors do not overpass the thresholds. We then summed the optimal population for each country and got **7.6 billion** as a result. This amount is incredibly close to the one that scientist have most oftenly predicted - 8 billion.

By expanding the Dynamic Model by Q-learning algorithm we created President Model that enabled us to predict future conditions and consequently calculate future Earth's carrying capacity. President model is a simulation in which a World President controlling the Planet makes decisions with aim to increase the carrying capacity of Earth. Using Q-learning the President achieved optimistic results of increasing Earth's carrying capacity up to 13 billion people.

Dynamic Decisions

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Introduction

Human population has lately surpassed 7.6 billion people and is rapidly growing. This growth is especially concerning and over the course of past years environmentalists tried to bring attention to the problem at hand. It is projected that there may be as many as 9.8 billion people in 2050, and 11.2 billion in 2100[1].

Every person consumes Earth’s resources whether it is food that we eat, water which we drink or oil that we need to run our cars etc. As human population rises, the total consumption increases as well. An increase in the standard of life, together with the spread of a consumptionist culture over the last 50 years has caused a further stress on the environment. The Earth doesn’t have endless resources however. At some point there will be just too many people and the Earth will no longer be able to provide for them.

Determining the number of people the Earth can hold and what it is impacted by is critical to the establishing of well-thought policies and sustainable development. We have to find a balance between the well-being of our species and the state of our environment here on Earth.

Problem restatement

Many scientist mistakenly took carrying capacity as population equilibrium - a point at which population stabilizes and does not change over the years[2]. Said stabilisation may be caused not by reaching Earth’s carrying capacity but by halting fertility with the use of contraceptives etc.

In our understanding carrying capacity is the population of humans which can live indefinitely on Earth. When the human population exceeds the carrying capacity, then the overconsumption leads to depletion of Earth's resources; and/or the waste and pollution produced by people destroys the environment and poisons humans[3]. At carrying capacity, Earth can support people persistently.

Using this definition of carrying capacity we divide our problem into 3 main parts:

- Finding key factors that limit the Earth's carrying capacity.
- Calculating Earth’s current carrying capacity.
- Predicting how Earth’s carrying capacity is going to change in the future and finding ways to increase it.

General Assumptions

1. **Trade of resources**
   We do not take into account the trade of resources as their production in the world remains the same regardless of their location of use and consequently does not influence the Earth's carrying capacity.
2. **Time spread of our data is negligible**
   In our model we used data from various sources and since some were lacking information from recent years (2008-2017), we were forced to make do with what we found. However, this time inconsistency is low enough to be considered irrelevant.

Key factors

To fully understand the carrying capacity, we must first identify what influences it and how does it happen. Choosing the most impactful factors is especially important since they will be a pivot point of our models.

Safe and Just Space

It is a framework proposed by Kate Raworth that contradicts the current idea of constant growth and further economic developments and instead concentrates on a fair division of the world's supplies. The SJS[4] focuses on sustainable environmental development while maintaining decent and just life for people. Thus, a doughnut-shaped space bounded by planetary and social boundaries is introduced (Fig. 1). It is a "safe operating space" for people to thrive in, while not damaging the environment and providing basic need for humans. Our model strongly focuses on calculating the carrying capacity by calculating the maximum population that can live within the Safe and Just Space.

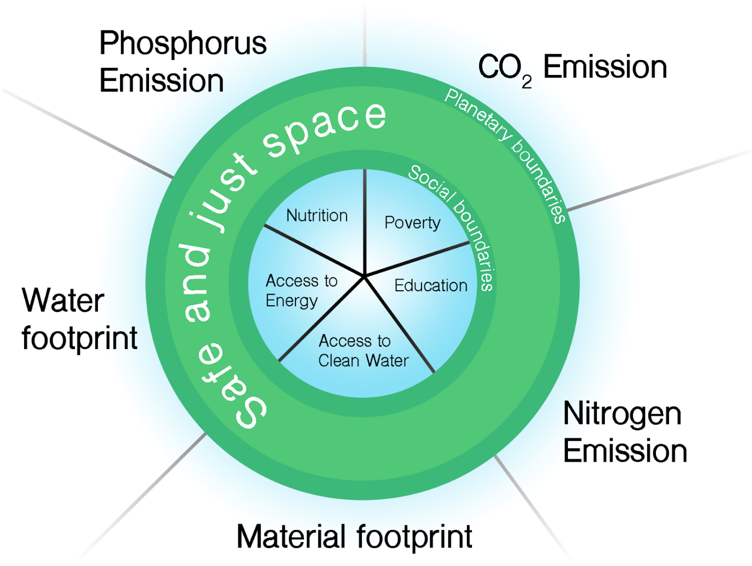


Fig. 1 - Visualization of Safe and Just Space

Factor selection

In accordance with the SJS framework we selected 10 factors that will help us determine the carrying capacity of our planet. We divided them into two groups: biophysical factors and social factors. The first group consists of biophysical factors that impact the environmental well-being, whereas the other group contains social factors, which influence the quality of life of Earth's inhabitants.[5]

Biophysical factors

- CO_2 emission

  The excessive amount of carbon dioxide in Earth's atmosphere is one of the main reasons why global warming is happening. The raise of global temperatures is dangerous, it causes a rise in sea levels as well as a decrease in crop yields, which may cause forced population displacement and food shortage. Though some may not see the consequences of high density of CO2 now, its future impact will be irreversible.[6]

- Nitrogen emission

  Nitrogen is released when petrol combusts in car engines in the presence of air, and because of the production of artificial fertilisers. Nowadays such fertilisers play a significant role in increasing crop yield. This comes with a cost however. Extensive nitrogen use devastates the soil, may cause acid rains and pollutes water. It can also cause breathing diseases such as asthma[7].

- Phosphorus emissions

  It is mostly a by-product of burning fossil-fuels and biomass, but also a result of the production of fertilisers. It may influence the carbon cycle[8] in unpredictable ways and cause the eutrophication of lakes. Their overuse can cause a decrease in water resources.

- Material footprint

  Material footprint shows the amount of raw materials (minerals, fossil fuels, and biomass) associated with the final demand for goods and services, no matter where it is extracted It is important as we are slowly running out of mined resources. According to some predictions we have already reached peak oil - the time half of the oil in the world has been extracted. Oil is used to generate electricity, but is also used in many products such as plastics. It is therefore crucial that we find alternatives, as oil is a very useful resource and we might not have it soon. Lately the reserves of rare metals as chromium have also been running low. They are used in many everyday objects, which are essential to our lives. The low availability may cause a rise in prices and thus prevent poorer people from accessing new technologies[9].

- Water footprint

  Water footprint shows the amount of water used by a country in a year. Water is called the staple of life as humans consist of up to 60% water. It is necessary in the production of food, in many industrial processes and is also used domestically, for drinking and sanitation[11]. It is therefore essential that our usage of water does not exceed the renewable reserves as people in many places in the world are already experiencing water scarcity or are subjected to water stress. The situation is not predicted to get better as the proportion of people affected by water stress is likely to increase, partly due to climate change[10].

Social factors

- Nutrition

  Receiving enough calories is a basic human need and a crucial aspect of living. Without it our organism cannot maintain it's immunity. In developing countries even one in every 3 children is malnourished. This results in stunting (insufficient height for a given age) and wasting (insufficient weight for a given height.).

- Percent of population living in poverty

  According to World Bank definitions extreme poverty is an income below $1.90/day. Without enough money, people cannot buy most needed things and thus fulfil their basic needs. This why it is such an important factor[12].

- Education

  Teaching young people about the environment is a first step to make a change. People need to be educated, especially in poor–countries, about family planning and ecology. It also allows for the creation of highly skilled workers who are crucial to running a modern economy.

- Access to electricity

  It's one of the basic human needs in order to live a decent life. These days almost everything depends on electricity - our smartphones, TVs or electric kettles. It frees us from the dependence on sunlight and allows us to work after sunset. Though such technology is not crucial for survival, it significantly impacts overall happiness of people and gives them more time to spend on education, work, and recreation[13].

- Access to clean water

  No person can live without water. In many places due to the lack of safe drinking water sources people suffer from diarrhea, which causes many death especially among the youngest. Only in 2015, 1.8 million people died due to polluted water.[14]

Our Models

Historical results

Many attempts to calculate Earth's carrying capacity were carried out in the past. The first known attempt has been carried out by Antonie van Leeuwenhoek, where he estimated the population density of the Netherlands, and then extrapolated it over the habitable area of the Earth. He arrived at a result of 13 billion. Other models were based on finding a resource which could limit the human population such as food or water consumption and then find the maximum number of humans that could be sustained by that resource indefinitely. At the start we tried both these methods[15]

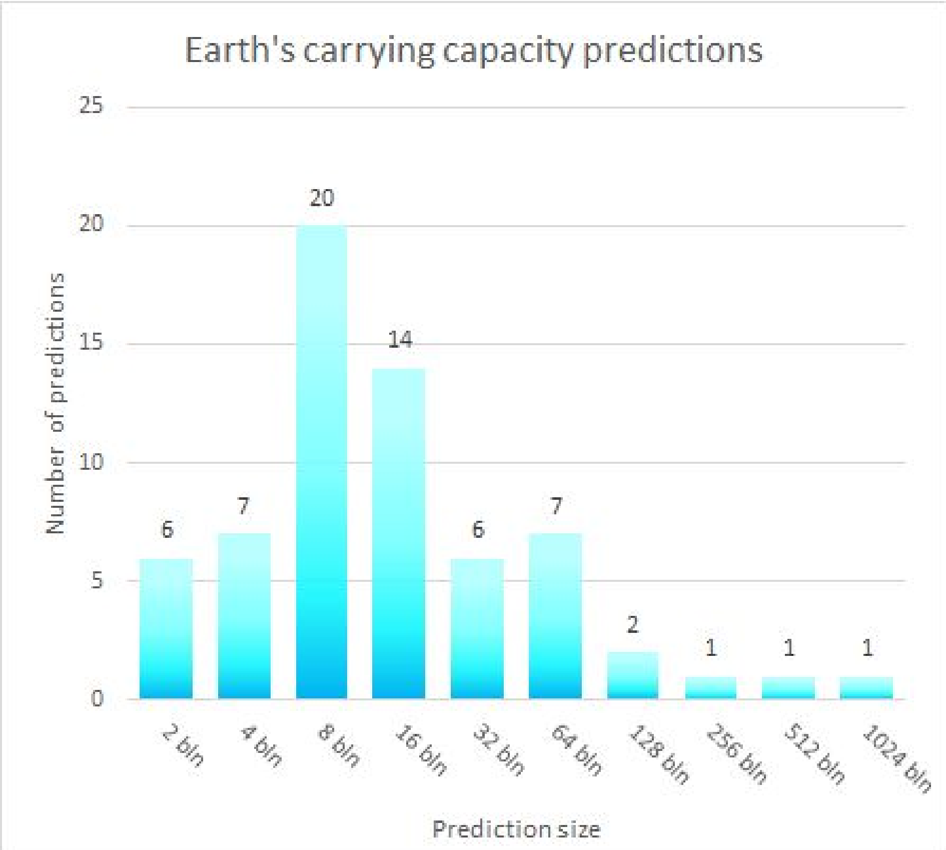


Fig. 2 - Chart of most commonly predicted Earth's carrying capacities.

Basic Model

Description

In our basic model we calculate the Earth's carrying capacity by measuring how many people can be indefinitely sustained by a one given resource. Similarly to past researches the resources we chose are: water, nutrition, and area as those are one of the most basic human needs.

Model assumptions

1. People have to eat at least 2000 kcal daily and we can obtain 8,278,200 kcal/year from a hectare of field[16].
2. We also assumed that the density of population in the countries of European Union (117.3 people/km^2) is an optimal one.

Calculations

The model calculates carrying capacity using the following formula.

$$carrying\ capacity = \frac{total\ amount\ of\ the\ resource}{need\ per\ capita}$$

These are our results:

	Need per capita per year	Available earth resources per year	Result
Water[17]	1385 m^3	42 809 * 10^9 m^3	**~ 31 billions**
Nutrition[18]	730 000 kcal	9.46 * 10^{15} kcal	**~ 13 billions**
Area[19]	8 525 m^2	104 * 10^6 km^2	**~ 12 billions**

The carrying capacity of this model is the lowest of the calculated amounts, which is **12 billions**.

Dynamic Model

Use of Safe and Just Space

In this model we make use of the Safe and Just Space Framework[20]. The Earth's carrying capacity is then the maximum population that fits in the Safe and Just Space. We set the planetary and social boundaries as thresholds our Key Factors must not transgress. We make sure that for each country the population at carrying capacity is both environmentally sustainable and socially just, as suggested by Kate Raworth.

Thresholds

The thresholds are values the factors cannot overpass. They are based on guidelines for sustainable environmental and social development from various sources.

	Threshold	Data source
Nutrition	2000 kcal / day per capita	World Bank
Population living in poverty	5%	World Bank
Access to education	75%	World Bank
Access to electricity	87%	World Bank
Access to clean water	95%	The Guardian datablog

	Threshold	Data Source
CO_2 emission	4 Tons / year per capita	World Bank
Water footprint	713 m^3/year per capita	Hoekstra, A.Y. & Mekonnen, M.M. (2012) 'The water footprint of humanity', *Proceedings of the National Academy of Sciences*
Material footprint	7.2 t / year per capita	Eora MRIO Database
Phosphorus emission	0.89 kg / year per capita	Eora MRIO Database
Nitrogen emission	8.9 kg / year per capita	Eora MRIO Database

System Dynamics

Our goal is to calculate for what maximal population do our Key Factors do not transgress the thresholds. Yet, with a change in population comes a change in every Key Factor and Key Factors are also dependent on other Key Factors. Therefore we have a system of interdependent Key Factors. Calculation of such in respect to population is extremely complex. Fortunately System Dynamics approach makes it simpler.

The notion of using System Dynamics in order to model population was first introduced in 1971 by J.W.Forrester in his book *World Dynamics*[21]. The World2 model developed by Forrester is a "simple" 5th-order differential equation that uses self-feedback loops in order to model population in respect to pollution, natural resources and other. A year later Dennis Meadows et. al. published *Limits to Growth*[22] in which he presented a more sophisticated and complex model than World2 called World3. We based our model on World3 with use of Safe and Just Space.

Calculations

Our model strongly relies on Python code that we used to apply System Dynamic to our model. BPTK_PY library equipped us with proper tool to do so. Yet, data needs to be prepared beforehand.

Firstly, after collecting data concerning Key Factors for every country, we calculate the correlations between population and all Key Factors (using linear and logarithmic fit) as well as between Biophysical factors and Social factors. This will enable us to see which factors correlate and where the change will be induced on others.

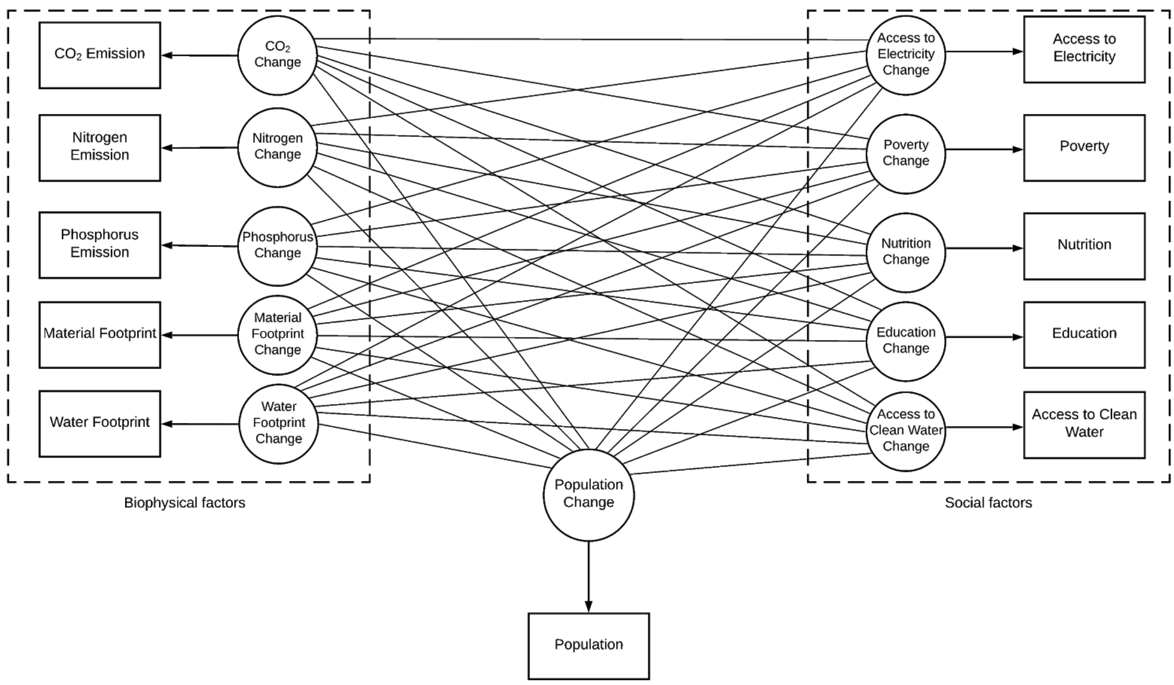


Fig 3. A simplified scheme of system dynamics approach.

Next, correlation coefficient must be calculated. We will achieve this by using the best fit (R^2) from linear of logarithmic correlation. From those calculations we will be able to see how much change does each factor induces on other factors.

Fig. 3 shows a simplified scheme of our use of System Dynamics. Boxes represent total value of a Key Factor which will change according to the change of a Key Factor shown as a circle. The Key Factor changes are interdependent. Population change induces change on the Key Factors' change while remaining unchanged by them.

Now, for each country, using the Python code, we can calculate how change in population of a country changes the state of its Key Factors.

Finally, our code calculates what is the country's maximum population for which none of the given country's Key Factors transgresses set thresholds. This maximum population is the Carrying capacity of said country. Summing results for each and every country will give us the Earth's carrying capacity for human population.

Models results and comparison

According to Dynamic Model we are currently at Earth's carrying capacity - 7.6 Billion. It is a significantly lower number than the one Base Model estimates - 12 Billion. However, the result is a close match with the most often predicted number, which is 8 Billion[23].

Strengths and weaknesses

Strengths

- System Dynamics takes interdependence of Key Factors into consideration
- Social Factors are included in the model
- Ecc is calculated for every country separately
- The model allows for analysis of how each Factor contributes to Carrying Capacity and thus it enables us to find ways to increase it

Weaknesses

- Lack of insight control of model calculations because of the fact that we work on Python library
- Economic processes are not taken into account

Raising Earth's Carrying Capacity

Introduction

Our environment is constantly changing. This is an undeniable fact. Moreover with the change of our environment a resulting increase in awareness about the problem must follow. With a massive influx of natural disasters, warming and cooling periods, different types of weather patterns, drastical emission of CO2 and much more, people need to be aware of what types of environmental problems our planet is facing.

Our planet is poised at the brink of a severe environmental crisis. Current environmental problems make us vulnerable to disasters and tragedies, now and in the future. We are in a state of planetary emergency, with environmental problems piling up high around us. Unless we address the various issues prudently and seriously we are surely doomed for disaster. Current environmental problems require urgent attention.

Possible solutions

Saving the environment is no longer just a problem for environmentalists and policymakers. Our very own existence may soon be put into question. Individuals, NGO's, corporations, and governments must come together and join hands to protect what is left of our planet so that the future is not wiped out before it's time for a curtain call.

In order to raise Earth's carrying capacity we researched many solutions in different branches that have a great impact on reducing for example CO2 emission. This possible solutions will be used in President Model in which every solution will have its own *impact table*.

New resources of energy:

- Nuclear fusion[24] and cold fusion[25]
- Nuclear power[24]

Global environmental improvements:

- Reforestation[26]

Environment focused politics:

- Electrical cars policy

Change in population diet and food production:

- Grow only corps for human[16]

Resource efficiency:

- Liquid coal or ultra supercritical effectiveness of burning [27]

Reduction of greenhouse gases:

- NO with carbon monoxide on copper-cobalt oxide[28]
- Capturing carbon dioxide[29]

Renewable energy:

- Space solar[30]
- Tidal [31]
- Geothermal[32]

Trash management:

- Plastic decomposing bacteria[33]

President Model

Model overview and justification

President Model is based on combination of creating probability decision tree and agent based algorithm Q-learning. In this model we want to check what is the best combinations of decisions to raise carrying capacity. Our model could be a great tool in creating import decisions starting from CEO's to country presidents.

In President Model creating an environment for agent is vital, therefore we tried many different possible scenarios. Q-learning used in the model perfectly fits to this problem because of its simplicity in application, fast learning time and ability to adapt to environment with given set of rules.

Model Assumptions

1. Possible solutions proposed by us can have measurable impact on factors limiting Earth's carrying capacity.
2. We assume that with time chance of more advanced decision showing in decision tree will rise (eg. current technology is not able to create cold fusion but with time this technology might be more accessible).

Model

In our model we will use Q-learning reinforcement algorithm because of its adequacy and simplicity. The goal of Q-learning is to learn a policy, which tells the president (agent) what action to take under what circumstances. It does not require a model of the environment, and it can handle problems with stochastic transitions and rewards, without requiring adaptations.

For any finite decision process, Q-learning finds a policy that is optimal in the sense that it maximizes the expected value of the total reward in our case Earth's carrying capacity over any and all successive steps, starting from the current state (7.6 billion). Q-learning can identify an optimal action-selection policy given infinite exploration time and a partly-random policy. "Q" names the function that returns the reward used to provide the reinforcement and can be said to stand for the "quality" of an action taken in a given state.

$$Q(s,a) \leftarrow Q(s,a) + \alpha(R + \gamma Q(s',a') - Q(s,a))$$

This update rule to estimate the value of Q is applied at every time step of the president's interaction with the environment. The terms used are explained below:

s – *current Earth's carrying capacity*

a – *current decision chosen by the president* (*eg. Nuclear Power*)

s' – *future Earth's carrying capacity*

a' – *best future decision that will maximize Earth's carrying capacity*

R – *current change in population* (*reward*)

γ – *reward discounting factor* (*the higher the president will prefer long – term solutions*)

α – *years taken to update estimation of* $Q(s,a)$

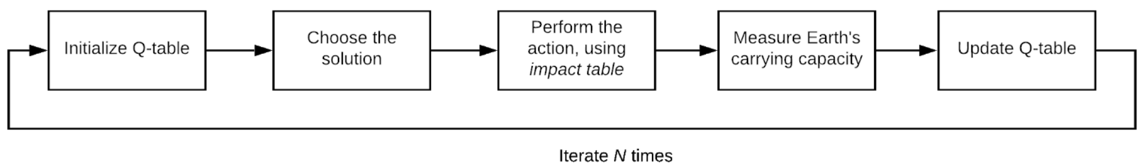


Fig. 4 - Q-learning algorithm flow chart

For our model we created an environment which is representation of decision making processes where each decision impacts Earth's carrying capacity. Each decision has its own *impact table*. *Impact table* is a prognosed impact on key factors that we proposed before. Eg.

$$Cold\,fusion \;=\; \{"CO_2\ emission" :\ \ -0.34\% \ldots etc\}$$

Then after each decision we calculate Earth's carrying capacity using System Dynamics model. This leaves us with graph (environment) in which Q-learning model will try to find the best combination of decisions that raise Earth's carrying capacity.

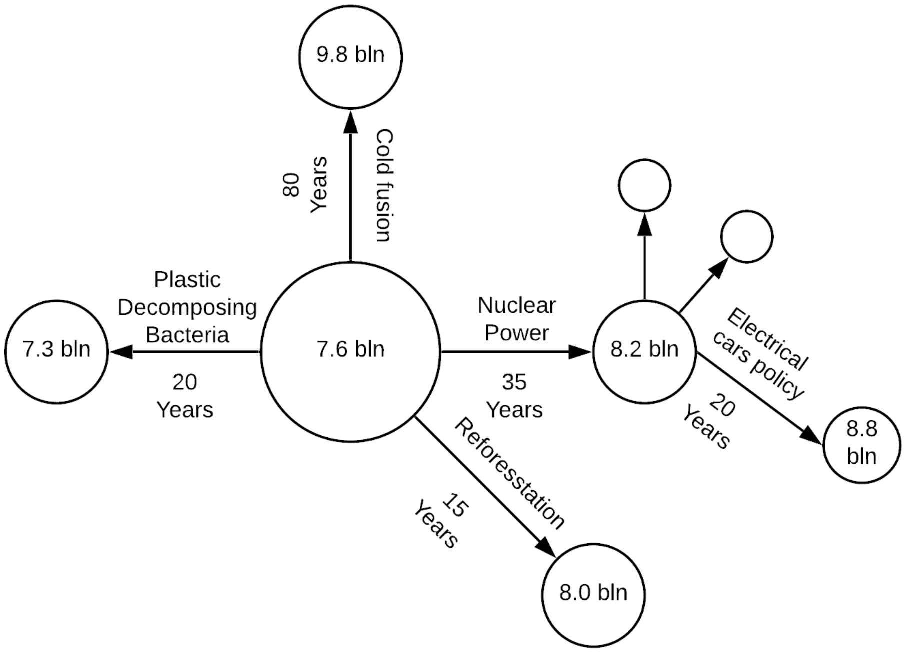
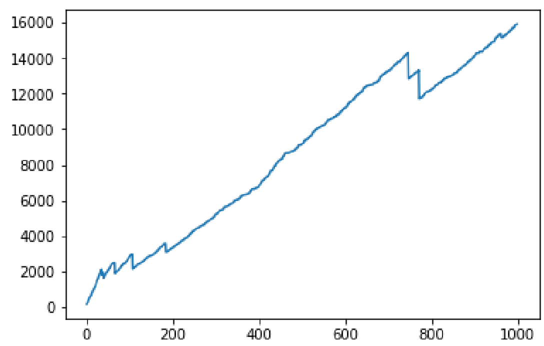


Fig. 5 - Example of environment where edges represent decisions over time and nodes the resulting increase or decrease in Earth's carrying capacity

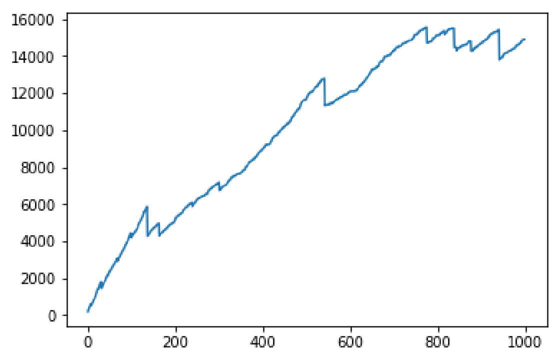
Having created the environment, we can run our model on 4 gamma parameters.



$\gamma = 0.6$

Results: +0.63

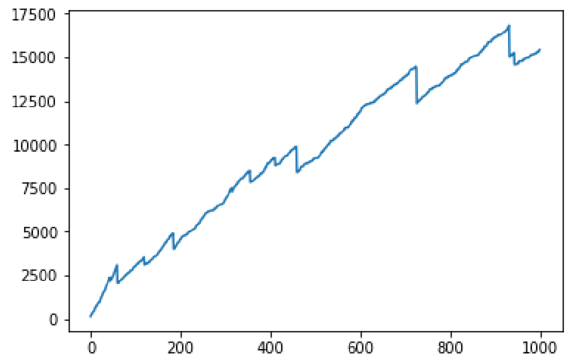
Earth's carrying capacity: 12.3 bln



$\gamma = 0.9$

Results: +0.73

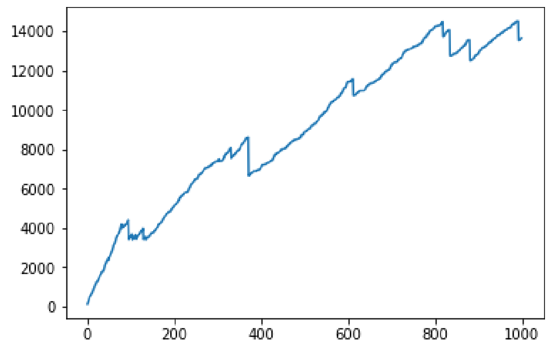
Earth's carrying capacity: 13.14 bln



γ = 0.85

Results: +0.68%

Earth's carrying capacity: 12.76 bln



γ = 0.95

Results: +0.78

Earth's carrying capacity: 13.54 bln

Fig. 6 - Q-learning reaching best results over number of simulations

This results will leave us with average **70%** raise in future Earth's carrying capacity which gives us **13 billion** people that our Earth's can hold.

Strengths and Weaknesses

Strengths

- Our agent (president) based model can be used in various environments with ability to adapt to it.

Weaknesses

- We base impact of each solution based on our research but in reality the impact might be bigger or smaller.
- Complex world decision can't be shown in a simple graph form because they don't include internal correlation between each node.

Future work

The environmental crisis is complex, requiring many solutions. However, it is our responsibility to protect and improve the environment. In future we would like to improve our results by providing the model with bigger amount of data. We would also considered more factors to precisely define how many happy and eco-friendly habitants can the Earth support. With more data acquired we could make variants of basic model by changing the values of thresholds.

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