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**2019**

**The International Mathematical Modeling Challenge (IM<sup>2</sup>C) 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.

## 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<sup>[1]</sup>.

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<sup>[2]</sup>. 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<sup>[3]</sup>. 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<sup>40</sup> 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.

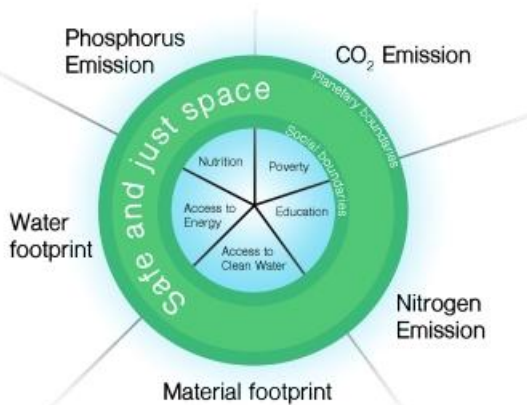


Fig. 1 - Visualization of Safe and Just Space

## 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.<sup>[6]</sup>

### Biophysical factors

- CO<sub>2</sub> 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 CO<sub>2</sub> now, its future impact will be irreversible.<sup>[6]</sup>

- 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<sup>[7]</sup>.

- 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<sup>[8]</sup> 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<sup>[9]</sup>.

- 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<sup>[11]</sup>. 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<sup>[10]</sup>.

## Social factors

- Nutrition

Receiving enough calories is a basic human need and a crucial aspect of living. Without it our organism cannot maintain its 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<sup>[12]</sup>.

- 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<sup>[13]</sup>.

- 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.<sup>[14]</sup>

## 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<sup>[15]</sup>

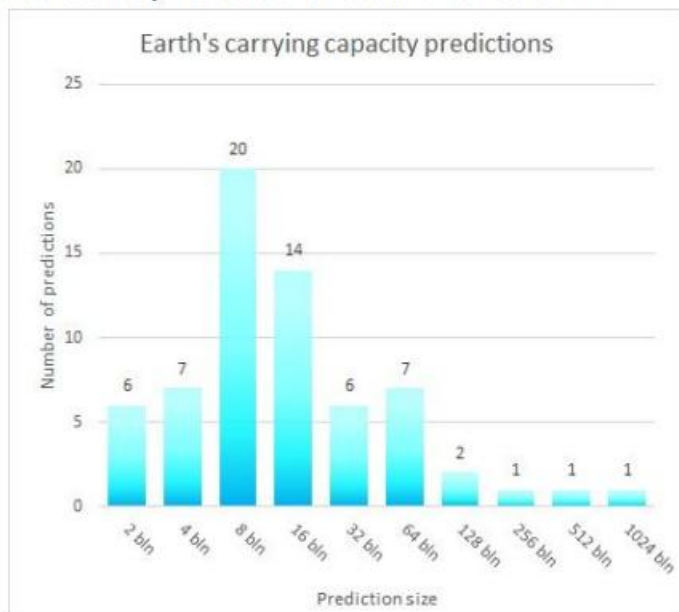


Fig. 2 - Chart of most commonly predicted Earth's carrying capacities.

### 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.