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Team Control Number

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T2 _____
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T4 _____**2019046**F1 _____
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F4 _____**2019****The International Mathematical Modeling Challenge (IM2C) Summary Sheet**

It is a question that now, in these times of extreme population growth, is very relevant and needs to be analysed: What is the Earth's carrying capacity for human life? To answer this question, there are a lot of factors to think about, but using modelling, we can find the answer. In order to make a sustainable model, we identified the factors: food, shelter, oxygen, water, and other factors such as roads, hospitals and schools. For each individual factor, we calculated how much area they need out of the habitable area, based on real statistics. First off, we calculated how much ha is needed under current conditions. We found out that we need a lot of oxygen. Luckily, algae, located in the sea, produce the vast majority. Still, we need a lot of trees in order to supply a person for life. We have taken in mind that we calculate based on the current conditions, and that our model needs to be indefinitely sustainable. How we manage the earth currently, is not indefinitely sustainable. That is also the reason why our calculated forest area is far greater than it currently is. This tells us that our oxygen levels are decreasing, and that we need to find a solution eventually in the real world. Luckily, we have a very large backup of oxygen made by 3.2 billion years of production.

Our model consists of two parts: the area needed to supply people with the oxygen from algae, and the remaining area, that we divided by our factors in order to get the remaining amount of people. However, these factors are quite complicated to calculate, so we can optimize our factors greatly, which is the task given in question 3.

We looked at each of our factors, and determined what is realistically achievable for each factor, especially since it's a model for our future. We decreased the amount of oxygen in the air to survivable levels, we increased the algae who produce our main source of oxygen, we increased our habitable land area, by forestation of the desert and land reclamation. We decreased the amount of area people need to live, and got rid of schools and roads. We calculated the decrease of agriculture, given we all switch to a vegetarian diet. All of this increases our carrying capacity greatly.

However, it is not a desirable way to live. It is very cramped, and we humans value our space. Still, we calculated the potential carrying capacity, but did not factor in the happiness level of people.

Overall, we compiled a sustainable, working model factoring in every major factor that determines the human carrying capacity, given the current conditions, and our optimized conditions.



Earth's carrying capacity for human life

IM²C

2019



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1: Identify and analyze the major factors that you consider crucial to limiting the Earth's carrying capacity for human life under current conditions.

Assumptions:

- 1: We will assume a perfect social world, without conflict at all, to reach the full capacity of the earth. That is why we will not include police and the army as a service.
- 2: We will also assume that almost everyone works from home, with the exception of farmers and builders and such, who work on site and don't need extra space. This way, there will be no space wasted for work.
- 3: We can not predict natural disasters or global epidemics, so that is why we will assume a world without any of these.
- 4: Climate change will not progress further, the conditions concerning climate will stay like how they are at the moment, meaning that the earth will not be harmed or changed.
- 5: We only took the major foods into account, not the minor ones, because it is hard to calculate and barely impacts our diet.
- 6: Everyone that lives on Earth either lives in a house or in a flat, because it is very hard to take homeless people into account.
- 7: Most importantly, we will assume that everyone keeps using the same of every resource (food, water, oxygen, energy, services, etc.) as people do now on average, so that conditions stay the same. *This assumption is only applicable for question 2. We will tweak the personal demand in the future, in question 3.*

First off, this is a very broad subject. It is almost impossible to account to every factor that is limiting the Earth's carrying capacity. So we had to make choices. After a discussion and a quick brainstorming session, we identified the following major factors:

Food: One of the primary necessities of every human. Without food, you will die. So obviously, it is the first factor on our list. We also put it on top of our list because we predict it will be the most complicated problem to solve, as it requires both habitable space and freshwater that need to be sacrificed. It will most likely be the most complicated factor to solve.

Shelter: The second of the basic necessities. Humans need shelter, and for that, they need resources and a living area. Resources will not be that hard of an issue, but living area is. How much habitable area do we have on Earth? Should we build skyscrapers, to accommodate everyone? How do we sacrifice forest and agriculture, in order to fit more people on earth?

Water: The same goes for water as goes for food and shelter: you will not survive long without it. On top of that, there is only a limited supply of freshwater. The equation also has many factors: how much water do we need for food? How much water do we need for daily life? Where can we get away with less water? How can we optimise water usage?

Oxygen: Here we get a little more obscure, but nevertheless, it is a factor to consider. If we, in order to fit more people, want to cut down forest, what are the sacrifices in oxygen? What is the best number of forest and shrub to have, while still keeping the oxygen percentage in the atmosphere at a safe level? It is a factor definitely can not be passed.

Energy: Society as of today requires energy to live with our current standards. However, we now rely on fossil fuels for our energy. Since our problem should have an indefinite solution, and we will eventually run out of fossil fuels, we need to drastically rethink our energy needs. How can we supply enough energy for a growing population?

Other: There are of course other needs for society to function like we are used to right now. We need services like hospitals, police force and education. Without it, a lot of the population would not survive. It may be minor, but it is a factor to consider, especially since services like that require habitable living space, which needs to be sacrificed from the general population.

We will now go in depth on how we determined the current conditions, and also how we analyzed them.

Water

To determine how much fresh water there is, we used the estimate of Igor Shiklomanov in *Water in Crisis: A Guide to the World's Fresh Water Resources*¹. That is the following table (see Appendix A):

Adding up all the freshwater sources except ice caps, glaciers, & permanent snow, because we can not extract water from them, gives us a net total of 10,530,583.61 km³ of water, which is $1.05306 \cdot 10^{19}$ L water. However, the resources are finite, but thanks to the hydrological cycle, it is renewable. Population growth is not. So, our limit regarding freshwater, is $1.05306 \cdot 10^{19}$ L.

According to Angela Morelli, globally, 3,496 L in our food + 167 L in industrial products + 137 L domestic use accounts to 3,800 L per person per day². According to this source, the hydrological cycle can take a long time, but most likely, it will be either in the atmosphere, or it will be in groundwater, which takes 1 to 2 months. We will give a generous average of 40 days. This means water will renew every 40 days, so there is $3,800 \cdot 40 = 152,000$ L per 40 days.

Shelter

We use the land for numerous things, such as agriculture, forest, fabrics, services and houses. But there are deserts and mountains as well, which makes it very hard to create living space for humans. We can mostly use flat land, that is under normal conditions, to build houses on. To increase our living space, we could look for ways to increase the earth's surface, by reclaiming land like many polders from the Netherlands, or decreasing agricultural land, forests or limiting the amount of services in an area.

¹ <https://water.usgs.gov/edu/gallery/global-water-volume.html>

² <http://thewaterweeat.com/>

By using the average house size and the average numbers of residents in a household, we can calculate the average space a person has for himself on the earth's surface:

$$S_{\text{personal}} = S_{\text{house}} \div \text{Residents}$$

We could decrease our personal surface by building flats instead of houses. That way, the amount of residents increase severely, but the surface of a flat is not much bigger than that of a household, and since flats are almost always built from multiple stories, the space that a person has if he lives on the first floor or higher, does not use the earth's surface. In addition, most of the rooms in flats are smaller, so the personal space would already decrease.

To have a big carrying capacity, we could increase our living space and/or decrease our personal space.

If we use our sources who say that the surface of an average house is 90 m^2 per house and the average amount of residents that live in a house is 3, our result would be:

$$90 \div 3 = 30 \text{ m}^2 \text{ p.p., or } 0.003 \text{ ha p.p.}$$

Oxygen

In order to map how much forest we need in comparison to the population size we need to find out a couple things.

1. How much oxygen is there in the atmosphere?
2. How much oxygen is produced each year by water?
3. How much oxygen is produced each year by land?
4. How much oxygen do we inhale?

For how much oxygen there is in the air, according to the article *Global oceanic and atmospheric oxygen stability considered in relation to the carbon cycle and to different time scales*³, there is $3.75 \cdot 10^{19}$ mol oxygen in the air, multiplying by 31.9988 and 24.5 gives us $2.94 \cdot 10^{22}$ L oxygen in the air.

This source⁴ states that algae produce around $300 \cdot 10^{15}$ g ($= 8.085 \cdot 10^{18}$ L) of oxygen each year, and that it accounts to 70%-80% of all oxygen production. That means that there is from $2.02 \cdot 10^{18}$ L to $3.47 \cdot 10^{18}$ L of oxygen made by land.

According to this source⁵, the oxygen produced by agriculture is negligible, so all that land-oxygen comes from forest and shrub. According to this source⁶, there is 39 million km^2 + 12 million km^2 = 51 million km^2 forest and shrub.

This means that $3.96 \cdot 10^{10}$ L to $6.79 \cdot 10^{10}$ L of oxygen is produced per year per km^2 forest and shrub.

³ <https://archimer.ifremer.fr/doc/00099/21024/18650.pdf>

⁴ <http://www.ecology.com/2011/09/12/important-organism/>

⁵ <https://www.quora.com/Do-farmers-crops-produce-oxygen-in-the-same-manner-as-other-plants-grass-and-trees>

⁶ <https://ourworldindata.org/land-use>

The current oxygen level is 20.946%^{3b}, and the carbon dioxide level is 405.0 ppm⁷, or 0.0405%. To sustain this ratio, we need to have $20.946 \div 0.0405 = 517$ times the amount of oxygen as carbon dioxide. We produce 4.97⁸ million grams of carbon dioxide, or 2.77 million L of carbon dioxide. This means we need $1.43 \cdot 10^9$ L of oxygen.

Dividing the oxygen produced by sea by 517 gives us the amount of people provided with oxygen by the sea, which is $5.65 \cdot 10^9$ people. For everything above that, we need 100 divided by: the amount of oxygen produced per km² divided by the oxygen needed per capita. Or simply put:

$$\text{From } \frac{100}{(6.79 \cdot 10^9 / 1.43 \cdot 10^9)} = 2.11 \text{ ha} \quad \text{to } \frac{100}{(3.96 \cdot 10^9 / 1.43 \cdot 10^9)} = 3.61 \text{ ha}$$

Food

To calculate the area needed for acquiring food we first needed to recognize that people from different parts of the world eat differently that is why we decided to split the world in 7 groups: the continents (including Antarctica even though nobody permanently lives there). There are two main ways to state how much you eat:

-kcal per capita per day (2013) (appendix b)

-kilograms per capita per year (2013) (appendix c)

To calculate the area needed only kg/capita/year was useful, because knowing the amount of food is necessary to get the area.

However not all food is the same: we do after all require a varied diet. In appendix d is the pie chart for the yearly consumption in the world (2013).

This shows what is eaten, but not its basic products. There aren't meat trees or ponds of beer. These products have been manufactured from animals and grapes respectively. According to the FAO⁹ around 65 billion animals had been slaughtered in 2013 the highest given here:

Chickens	60,670,000,000
Pigs	1,450,000,000
Turkeys	648,320,000
Sheep	532,330,000

Goat	432,190,000
Cattle	301,000,000
Other	870,140,000
Total	64,904,000,000

These animals also have to eat. A lot. According to our calculations 1258 kg of cereal.

Alcohol isn't one drink and is created using different ingredients. The three types of alcohol are: beer, from wheat; wine, from grapes; and distilled¹⁰.

There are two main types of sugar: beets and sugar cane. Of all sugar 45.5% is from beets and 54.5% from sugar cane

For milk, eggs and vegetable oils we already counted their producers and fish live in the sea, so that doesn't take up habitable area. Now we know the actual kg/capita/year (appendix e).

For fruits, vegetables, sugar(beet and cane) and cereal the FAO has the total area harvested. For meat¹¹ we had to take our own calculations. Divide the total area by amount of people and out comes the final result in hectare per person (appendix f):

Europe	0.184 ha/person
Africa	0.125 ha/person
Asia	0.0995 ha/person
North-America	0.229 ha/person
South-America	0.149 ha/person
Oceania	0.510 ha/person
World	0.123 ha/person

Energy

In 2016, the world consumed about 9.55 million ktoe of energy, or about 111 million MWh.¹² We also know the population in 2016¹³, which gives us an average energy usage per person

¹⁰ <https://www.trimbos.nl/kennis/cijfers/cijfers-alcohol>

¹¹ https://extension.unh.edu/resources/files/Resource000471_Rep493.pdf?v

¹² <https://www.iea.org/>

¹³ <https://www.populationpyramid.net/nl/wereld-aarde/2016/>