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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 km^3 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 day[2]. 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.

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[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:
$S_{personal} = S_{house} \div Residents$
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:
$90 \div 3 = 30\ m^2 p.p.,\ or\ 0.003\ ha\ p.p.$

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*[3a], 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 source[4] 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 source[5], the oxygen produced by agriculture is negligible, so all that land-oxygen comes from forest and shrub. According to this source[6], 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.

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[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 ppm[7], 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 4.97[8] 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 km^2 divided by the oxygen needed per capita. Or simply put:

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

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 FAO[9] 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

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[7] https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

[8] https://data.worldbank.org/indicator/EN.ATM.CO2E.PC

[9] http://www.fao.org/faostat/en/#home

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 distilled[10].

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 meat[11] 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 2016[13], which gives us an average energy usage per person

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[10] https://www.trimbos.nl/kennis/cijfers/cijfers-alcohol

[11] https://extension.unh.edu/resources/files/Resource000471_Rep493.pdfbv

[12] https://www.iea.org/

[13] https://www.populationpyramid.net/nl/wereld-aarde/2016/

worldwide: 14.4 MWh. Since we are working with the current conditions, we expect people to keep having the same living standards and use the same amount of energy.

The energy consumption worldwide is organised according to appendix G.

We also know that the energy has to be indefinitely sustainable, so we have to work with sustainable energy. The main three are: Hydro, Wind and Solar energy, divided according to the pie chart in appendix H.

Hydropower:
This means that we need to produce 76.4% of 14.4 MWh of energy per person, or $0.764 \cdot 14.4 = 11.0$ MWh per person per year.
The biggest hydro power plant produces 103.09 TWh per year[14]. 103.09 million MWh $\div$ 11.0 MWh = 9.37 million people. So one of these power plants is enough to cover the hydro powered energy of 9.37 million people. This plant takes up about 790,000 square meters of dam surface area, so $(1 \div 9{,}370{,}000) \cdot 790{,}000 = 0.084$ square meter of dam surface area per person. There is an enormous amount of dam area in the world, but since this area is not counted as habitable area, this area will not be included in the model.

Wind:
Wind needs to produce $0.176 \cdot 14.4 = 2.53$ MWh of energy per person per year. An average windmill produces about 6500 MWh[15] of energy per year, so one windmill produces enough wind energy for $6500 \div 2.53 = 2{,}570$ people. An average windmill in a seapark take up about 32,400 square meters of sea area[16], about $1 \div 2{,}570 \cdot 32{,}400 = 12.6$ square meters of sea area per person. We have more than enough sea area in the world, which is not used for any of the other factors in our model. The sea area is also not habitable surface area, so we will also not include this in our model.

Solar:
Solar power needs to produce $0.060 \cdot 14.4 = 0.864$ MWh per person. An average solar panel produces about 225 kWh per year[17], or about 0.225 MWh. That means we need about 4 solar panels per person. One average solar panel takes up around 1.65 square meters of surface area on the ground or on a roof[18]. This means that we need $4 \cdot 1.65 = 6.6$ square meters of surface area on the ground or on a roof per person. Every person has about 30 square meters of surface area for housing, plus surface area for other things like hospitals, schools etc. This total surface area per person is mostly suitable to place solar panels, for example on the roofs of the houses, hospitals and schools and on the side of the roads.

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[14] https://en.wikipedia.org/wiki/List_of_largest_power_stations#Top_20_largest_power_producing_facilities
https://en.wikipedia.org/wiki/Itaipu_Dam

[15] https://www.maritime-executive.com/blog/650-foot-wind-turbines-for-the-north-sea

[16] https://www.maritime-executive.com/blog/650-foot-wind-turbines-for-the-north-sea

[17] https://www.energieleveranciers.nl/zonnepanelen/opbrengst-zonnepanelen

[18] https://www.energieleveranciers.nl/zonnepanelen/opbrengst-zonnepanelen

In the end, we do need a lot of area to create sustainable energy, but this area is either non habitable area, or on top of used area, so that is why we will not include surface area for energy in our model.

Other

We want to keep the services as simple as possible, so we will only calculate the areas of the biggest services, such as schools, hospitals, et cetera. We will also count roads as services in the formula of shelter, so we can keep the formula small.

Services

Hospitals

Whenever you are ill or injured, you can go to the hospital. There is a global average of around 500 people per hospital bed. An average hospital holding 500 beds has a surface area of about 100,000 square meter[19]. This means, that we need to have $100{,}000 \div 500 \div 500 = 0.4$ m^2 of surface area per person for hospitals.

Schools

According to the United Nations, about 24.8% of the world population is in the age range 5-18[20]. We will use this as an estimate for how much of the world population needs education.
School guidelines around the world require a minimum of around 5 square metres of surface area per student[21]. Only 24.8% of the population are in school at a time, so this means we need $0.248 \cdot 5 = 1.24$ square meters of surface area per person of school.

Roads

If you are an adult, your primary transport vehicle is probably a car. Humans use it to get almost anywhere, for example going on a holiday, visiting someone, going to a supermarket, et cetera. To use these cars, all countries have set up a road network with both paved and unpaved roads to drive cars on. There are so many cars thanks to the increasing wealth of the world, that these road network have become big. To determine the area of these roads, we use the simple $length \cdot width$ formula.

According to Wikipedia, the length of all the roads in the world combined is $64.3 \cdot 10^6$ km = $64.3 \cdot 10^9$ meter[22]. And since lanes have an average width of 3 metres, we can easily

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[19] https://nl.wikipedia.org/wiki/Lijst_van_Nederlandse_ziekenhuizen

[20] https://www.populationpyramid.net/nl/wereld-aarde/2016/

[21] https://masht.rks-gov.net/uploads/2015/06/masht-vol1-eng-print-5mm-bleed-0mm-inside-final.pdf
https://wetten.overheid.nl/BWBR0008562/2014-01-01

[22] https://en.wikipedia.org/wiki/List_of_countries_by_road_network_size

calculate the area of the roads in the world: $3 \cdot 2$(roads mostly consist of 2 lanes)$\cdot$($64.3 \cdot 10^9$) = $353.8 \cdot 10^9$ square meters of surface area for roads. We will divide this by the population to get a global average: $353.8 \cdot 10^9 \div 7.7 \cdot 10^9$ = 46 square meters of road per person.

2: Use mathematical modeling to determine the current carrying capacity of the Earth for human life under today's conditions and technology

Now that we have determined how much surface a person needs to survive with all the major factors, we can make a mathematical model to determine the carrying capacity. We will divide the people in two classes, based on what produces the oxygen they breathe. This can be done by algae or trees. Then we can determine how much surface is available for the groups, and then calculate how many humans we can fit in that surface. These are the variables we will use in our model:

$x = \textit{ people that can breathe oxygen produced by algae}$
$O_x = \textit{ ha earth that x people need}$
$y = \textit{ people that can breathe oxygen produced by trees}$
$O_y = \textit{ ha earth that y people need}$
$C = \textit{ Carrying capacity}$

To find out what these variables are, we have made a model. In the model we use certain values. These are all the values that we know:

$\textit{ha food p.p. (per person)} = 0.12256$
$\textit{ha shelter p.p.} = 0.0030$
$\textit{ha roads p.p.} = 0.0046$
$\textit{ha schools p.p.} = 0.000124$
$\textit{ha hospitals p.p.} = 4 \cdot 10^{-5}$
$x = 5.65 \cdot 10^9$
$\textit{Habitable Earth surface} = 1.04 \cdot 10^{10} \textit{ha}$
$\textit{maximal ha forests p.p.} = 3.61$
$\textit{minimal ha forest p.p.} = 2.11$

$$(\textit{ha food p.p.} + \textit{ ha shelter p.p.} + \textit{ ha roads p.p.} + \textit{ ha schools p.p.} + \textit{ ha hospitals p.p.})x = O_x$$
$$(0.12256 + 0.0030 + 0.0046 + 0.000124 + 4 \cdot 10^{-5}) \cdot 5.65 \cdot 10^9 = 736,330,600 \textit{ ha}$$
$$\textit{Habitable Earth surface} - O_x = O_y$$
$$1.04 \cdot 10^{10} - 736,330,600 = 9,663,669,400 \textit{ ha}$$
$$y = O_y \div (\textit{ha food p.p.} + \textit{ ha shelter p.p.} + \textit{ ha roads p.p.} + \textit{ ha schools p.p.} + \textit{ ha hospitals p.p.} + \textit{ ha forests p.p.})$$

$9,663,669,400 \div (0.12256 + 0.0030 + 0.0046 + 0.000124 + 4 \cdot 10^{-5} + 3.61) = 2,583,645,000$ or
$9,663,669,400 \div (0.12256 + 0.0030 + 0.0046 + 0.000124 + 4 \cdot 10^{-5} + 2.11) = 4,313,514,206$
$C = x + y$
$5,65 \cdot 10^9 + 2,583,645,000 = 8,233,645,000,\ \textit{or around}\ 8.23 \cdot 10^9 \textit{people}$ or
$5,65 \cdot 10^9 + 4,313,514,206 = 9,963,514,206,\ \textit{or around}\ 9.96 \cdot 10^9 \textit{people}$

But how is it with water? We know that there is a fixed quantity of $1.05306 \cdot 10^{19}$ L, and we use 152,000 L per cycle. This means we have water for $6.93 \cdot 10^{13}$ people. This is way more than our current limit, so we do not have anything to worry about in that aspect.

3: What can mankind realistically do to raise the carrying capacity of the Earth for human life in perceived or anticipated future conditions? What would those conditions be?

The future has always been unpredictable. As seen in the Back to the future trilogy, they predicted all sorts of new inventions, that we would have invented by now, such as flying cars, but nowadays, we haven't even found a way to stop the climate change yet.

To raise the carrying capacity of the Earth, we need to change the factors, which decide the carrying capacity. We will go over every variable of our model and our ideas to change them, to raise the carrying capacity of the Earth.

Food

According to our calculations, most of our food production goes to the animals. So to drastically decrease the area per person we need to stop eating meat. This would decrease the area by 80.8%. However then you would also have to account for the loss of kilocalories. That would make it 67.4%. After that we decided to optimize our kilocalorie intake to 2500 which brings the ha per person down to 0.0422, that is 34.4% of what it was before. If we put this through our model, the population adds up to be 9.8 - 12.8 billion people. This drastically increases the Earth's carrying capacity.
However it might be possible to have a building with multiple levels for agriculture. It would be reasonable to assume we could get 5 stories on such a building. Cutting our area needed in 5 to 0.00844, which is only 6.9% of current conditions.
There are currently attempts to decrease or even eradicate food waste, this would decrease the area needed further by 50% to 0.00281 (2.3%) . All missing vitamins and minerals due to eating less meat can be added through supplements.

Shelter

As we already said in the first exercise, we can significantly decrease the amount of earth's surface a person needs by building flats. In the future, we want to build flats that have a surface area of $400\ m^2$, or $0.04\ ha$. In those flats live 1,000 families, consisting of 3 members, so our number of residents of 3,000.

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

$0.04 \div 3000 = 1.33 \cdot 10^{-5} ha\ p.p.$

Water

As we calculated in part two, there is more than enough water for 69.3 trillion people, so we do not have to change anything about that.

Oxygen

Currently, we work with a ratio of 20.946% oxygen. Humans can live with 19.5%[23]. This means that if we put this in our model, we will see that it changes from 8.23 - 9.96 billion people to 8.82 - 10.7 billion people. A small, but significant increase.

A major factor in our model, is the amount of people who use the oxygen from algae. If all our oxygen would come from trees, forests would take up over 90% of total surface area per person, while algae don't take up any habitable land at all. Instead, they only use the otherwise unused bottom of the ocean. That is why want as much oxygen as possible created by algae, so we can get rid of forests.
To reach this goal, we need to plant as much algae as we possibly can, everywhere we can. We need to be careful, not to produce an abundance of oxygen, since this could be toxic for animals and humans. If we have enough algae, however, we can remove forests, which would free up a lot of space for other factors.

If, for example, we manage to plant 1.5 times as much algae as there are now, that would mean algae would produce 1.5 times as much oxygen. Since we will decrease the sea mass to make land mass, the algae would decrease by 10%, but we will assume that we can compensate for this, so that the end result will be 150% as much algae as we have right now.This would mean the variable X would become 1.5 times as much: oxygen op $5.65 \cdot 10^9 \cdot 1.5 = 8.475 \cdot 10^9$ people would be sustained by algae. This alone, would raise the minimal carrying capacity from $10.96 \cdot 10^9$ to $12.64 \cdot 10^9$ people! But because of the lower oxygen ratio in the air, the algs can also support more people, since they need less oxygen. This means an increase of another 7.4% ($8.475*10^9$→ $9.10*10^9$).

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[23] https://sciencing.com/minimum-oxygen-concentration-human-breathing-15546.html

Energy

There is more than enough room for energy producing things such as windmills, solar panels and hydro power plants to power everyone in our current situation. However, when we go to live in flats, instead of houses, and when we turn sea into land, than it might become a problem to find the space these energy sources need. We expect that there will soon be a new, sustainable source of energy, which can replace every other source and make enough energy for everyone, while using very little surface area. We think, that it is very likely, that this will be fusion energy. Such fusion plants would take up a pretty substantial space, but there would only be a few needed to power the entire world, making it the most surface area efficient energy source to date. These changes in energy will not directly impact the variables in our model, but they will allow the carrying capacity to grow more, while still being sustained energy wise. We will also find a solution for the space issue with these reactors later on (see land reclamation).

Other

School

In the future, school will just be a collection of complete online courses, which teach you everything you need to know and more from the screen or in VR (skills like giving presentations in front of other people). This way, schools won’t take up any surface area at all, because these traditional schools will not exist. This will fully eliminate one of the variables of our model, and will free up space for the other variables.

Roads

If a new way of transportation is invented, we can get rid of all the roads in the world, which take up a lot of surface area. If we have flying cars for example, we could just have them fly from flat to flat, never touching the ground and never taking up any space at all. This will also fully eliminate one of the variables of our model, and will free up space for the other variables.

If we would remove both schools and roads from our model, the carrying capacity would increase from between $8.23 \cdot 10^9 \& 9.96 \cdot 10^9$ to between $8.24 \cdot 10^9 \& 9.98 \cdot 10^9$ people.

Land reclamation

We can turn all the deserts into forests or farmland, or we can use them to generate energy or even to live on. This is not only probable in the future, but we are actually already turning desert into forest in the sahara and the gobi desert. On earth, about a third of land mass is actually made up of desert, so if we can turn all of this into habitable land, we would end up with 1.5 times as much habitable land! This would increase the carrying capacity up to between $9.6 \cdot 10^9$& $12.3 \cdot 10^9$ people.

We can also turn sea into land. This has been done successfully already, like in Dubai. We expect that this technology will develop further and that we can efficiently turn much more sea in to habitable land. We must, however, not turn everything into land, because we also need water and places for algae, which give us oxygen. We also have to filter the saltwater accordingly, because if the water becomes to salty, the saltwater fish will die. If we would be to able to turn 10% of watermasses into landmasses, the carrying capacity would increase from between $8.23 \cdot 10^9$& $9.96 \cdot 10^9$ to between $9.20 \cdot 10^9$& $11.60 \cdot 10^9$ people.
All of the other uninhabitable land should be able to be used for our nuclear fusion reactors and to store energy. We can place smaller reactors and batteries on mountains and we can place a lot of large reactors and battery stations on massive landmasses, like Antarctica. This should both solve our energy problem and uninhabitable land problem. This would indirectly provide enough energy and thus increase the carrying capacity, but it would not directly free up space in our model.

Future potential

Lastly, we will try to answer the question:"What is the maximum potential for the carrying capacity on Earth in the future?".

To answer this, we will adjust the variables in our model, according to the realistic predictions we have made in this last part.
These are the adjustments:
1: If we would stop eating meat and start using multiple level agriculture, the variable “ha food p.p.” would increase from 0.12256 → 0.00281
2: Living in flats would decrease the variable “ha shelter p.p.” from 0.0030 → $1.33 \cdot 10^{-5}$
3: Decreasing the oxygen level from 20.946% → 19.5%, would decrease the Oxygen needed per Capita, which would decrease the ha forest pp and increase the variable “x”
4: A 150% increase of Algae would lead to the variable “x” increasing by 150% ($5.95 \cdot 10^9 \rightarrow 8.475 \cdot 10^9$). The lower oxygen ratio leads to another 7.4% increase ($8.475 * 10^9 \rightarrow 9.10 * 10^9$)
4: Since roads won’t be needed anymore, the variable “ha roads p.p.” will be removed.
5: Since schools won’t be needed anymore, the variable “ha schools p.p.” will be removed.
6: Land reclamation would lead to the variable ‘’habitable Earth surface” multiplying by 1.5 and than increasing by 10% of landmass ($0.36 \cdot 10^{10}$ ha)
7: The decrease in oxygen ratio means that people will need less trees to sustain their oxygen demand, so the “ha forest p.p.” variable will decrease from 3.61→ 2.24(maximal) and 2.11 → 1.31(minimal)

The model will become:

$x =$ *people that can breathe oxygen produced by algae*
$O_x =$ *ha earth that x people need*

$y = \text{ people that can breathe oxygen produced by trees}$
$O_y = \text{ ha earth that } y \text{ people need}$
$C = \text{ Carrying capacity}$

$ha\ food\ p.p.\ (per\ person) = 0.00844$
$ha\ shelter\ p.p. = 1.33 \cdot 10^{-5}$
$ha\ hospitals\ p.p. = 4 \cdot 10^{-5}$
$x = 9.10 \cdot 10^{9}$
$Habitable\ Earth\ surface = 1.92 \cdot 10^{10} ha$
$maximal\ ha\ forests\ p.p. = 2.24$
$minimal\ ha\ forest\ p.p. = 1.31$

$(ha\ food\ p.p. + ha\ shelter\ p.p. + ha\ hospitals\ p.p.)x = O_x$
$(8.44 \cdot 10^{-3} + 1.33 \cdot 10^{-5} + 4 \cdot 10^{-5}) \cdot 9.1 \cdot 10^{9} = 7.7 \cdot 10^{7}\ ha$
$Habitable\ Earth\ surface - O_x = O_y$
$1.92 \cdot 10^{10} - 7.7 \cdot 10^{7} = 1.9123 \cdot 10^{10}\ ha$
$y = O_y \div (ha\ food\ p.p. + ha\ shelter\ p.p. + ha\ hospitals\ p.p. + ha\ forests\ p.p.)$
$1.9123 \cdot 10^{10} \div (8.44 \cdot 10^{-3} + 1.33 \cdot 10^{-5} + 4 \cdot 10^{-5} + 2.24) = 8.5 \cdot 10^{10}$ or
$1.9123 \cdot 10^{10} \div (8.44 \cdot 10^{-3} + 1.33 \cdot 10^{-5} + 4 \cdot 10^{-5} + 1.31) = 14.5 \cdot 10^{10}$
$C = x + y$
$9.1 \cdot 10^{9} + 8.5 \cdot 10^{9} = around\ 17.6 \cdot 10^{9} people$ or
$9.1 \cdot 10^{9} + 14.5 \cdot 10^{9} = or\ around\ 23.6 \cdot 10^{9} people$

Conclusion

In the end, making all of these adjustments and fully optimizing the carrying capacity, would lead to an increase of, anywhere from $9.37*10^9$ to $13.64*10^9$ people! Or an increase of around 114% - 137%! Now that all the mathematical questions have been answered, one question still remains; do we really want this to happen?

Development

When we got the assignment, we immediately started brainstorming what factors we would include in the carrying capacity. After deciding what factor we would determine, we divided these factors between our group and started collecting information that we needed and wrote it down in excel.
In the second part, we had to make a mathematical model to determine the carrying capacity. We shared our information with each other, and created our model. Initially, we created a wrong model, because we used wrong statistics to calculate our oxygen levels, and had to change up our model, to factor in both ways to create oxygen. After we corrected our model, we filled in our variables to get the current carrying capacity.
Last but not least, we had to look for realistic ways to increase the current carrying capacity. Just like in the first part, we started brainstorming again for ways to optimize our factors. We

used excel again, so we could easily change up our variables, instead of having to recalculate every little change. Finally, we used the new variables in our model to see by how many people our carrying capacity would increase with the change we made.

Analysis

First of all, we want to say that it is very unlikely that our calculations are 100% true. We only included the major factors in our model, because if we wanted to include everything in our model, we would have to travel around the globe to collect data. We can only do so much in five days, so we had to choose what we would include and what not. We also had to make assumptions for this reason, mostly for the third part. If we choose not to factor some things into our model, we have to give a reason for that. For example, we decided to assume that in the world, there would be no more police departments needed, because it was very hard to find informations about how many departments there were in the world at this moment, and of course we can't predict any big changes to the world, like a sudden ice age that would make half of the Earth surface unsurvivable, so we chose to assume that those things would not happen. The internet can be very reliable, but there is a possibility that our data is outdated or not true, for example the average area of a house that we used could be too big or too small.

This was a bit of a problem during the first part. Some information that we needed was almost unfindable or if it was findable, every source had a different number for it. There isn't much we can do about this, except decide which source is the most logical one to use.

In the second part, we determined that our capacity was between 8 and 10 billion people. When we had just started this assignment, we were looking on the internet for estimates of the carrying capacity under current conditions. Almost all the sites also said that the carrying capacity was around 10 billion, so we think that we came pretty close to the actual carrying capacity.

The third part is hard to analyze. We again have to decide what will happen in the future, and this time, we can't really use the internet, because everyone's opinion about the future is different, and the future itself is quite unpredictable. We have no way to check if the assumptions we made for the future are true, so we tried to keep it as realistic as possible, so for example finding an infinite oxygen source or an alien invasion was out of the question. We think we made a close estimation for the future carrying capacity, but as we said earlier, there is not way to know for sure.

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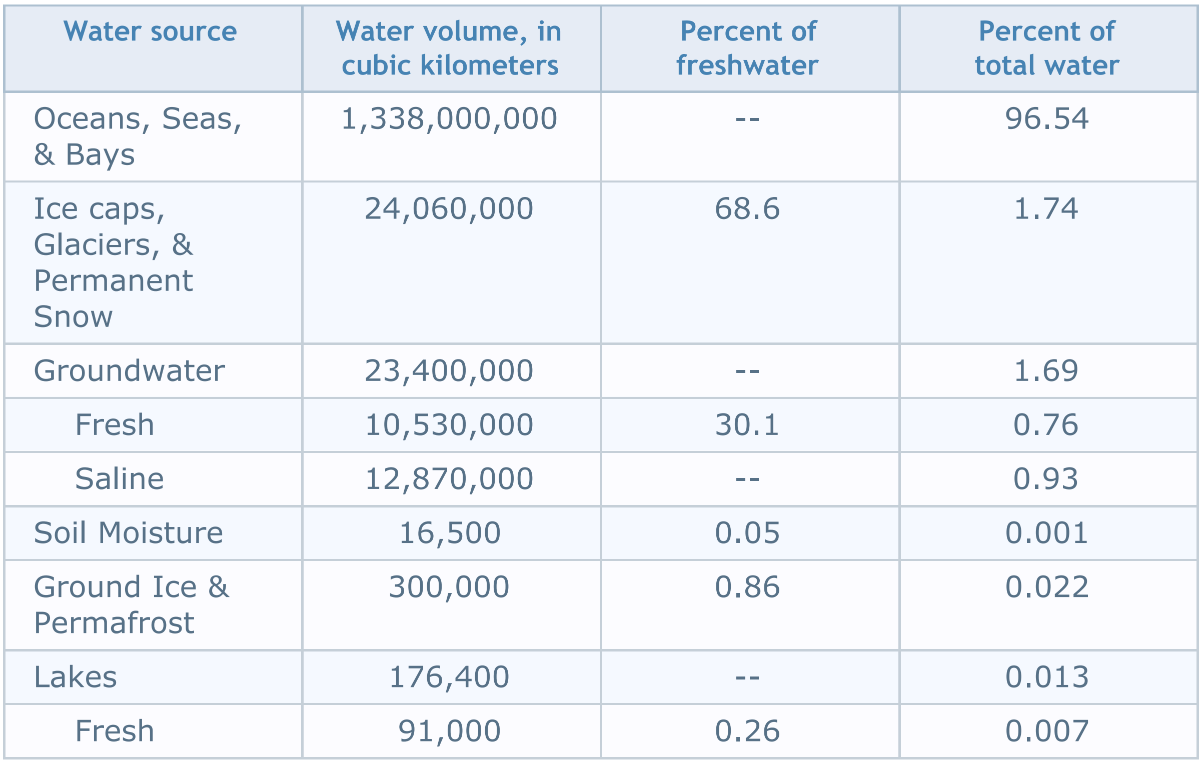
Appendices

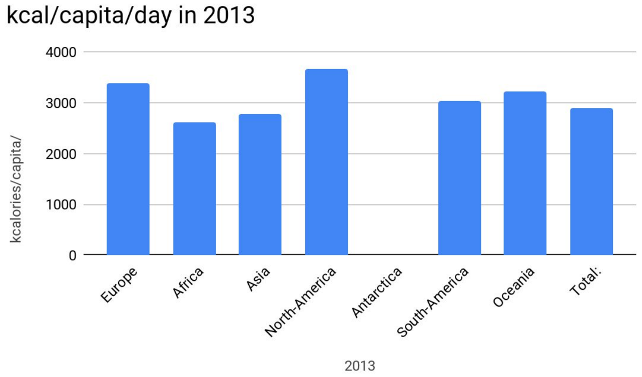
Appendix A: Water sources on Earth.



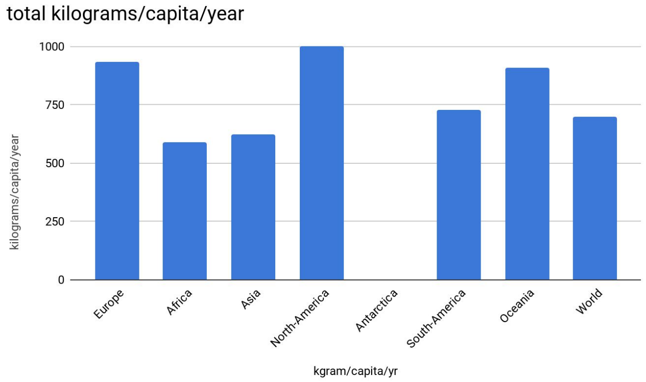
Water source	Water volume, in cubic kilometers	Percent of freshwater	Percent of total water
Oceans, Seas, & Bays	1,338,000,000	--	96.54
Ice caps, Glaciers, & Permanent Snow	24,060,000	68.6	1.74
Groundwater	23,400,000	--	1.69
Fresh	10,530,000	30.1	0.76
Saline	12,870,000	--	0.93
Soil Moisture	16,500	0.05	0.001
Ground Ice & Permafrost	300,000	0.86	0.022
Lakes	176,400	--	0.013
Fresh	91,000	0.26	0.007

Saline	85,400	--	0.007
Atmosphere	12,900	0.04	0.001
Swamp Water	11,470	0.03	0.0008
Rivers	2,120	0.006	0.0002
Biological Water	1,120	0.003	0.0001

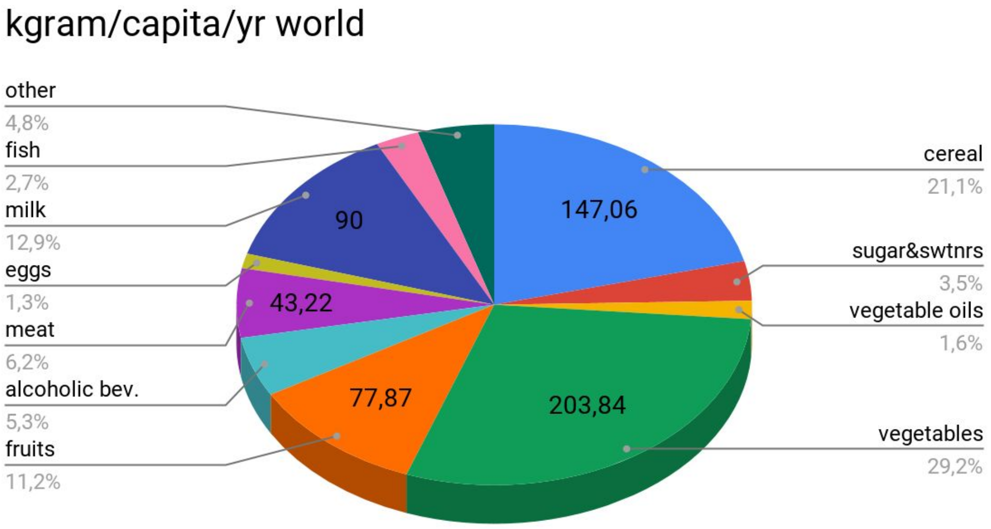
Appendix B:



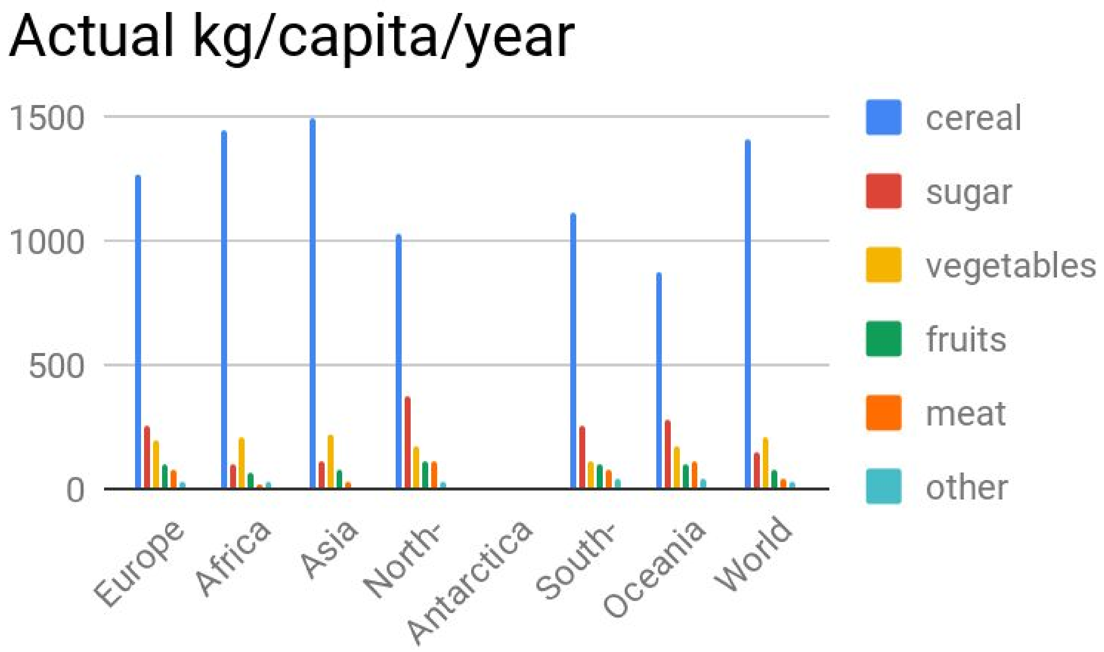
Appendix C:



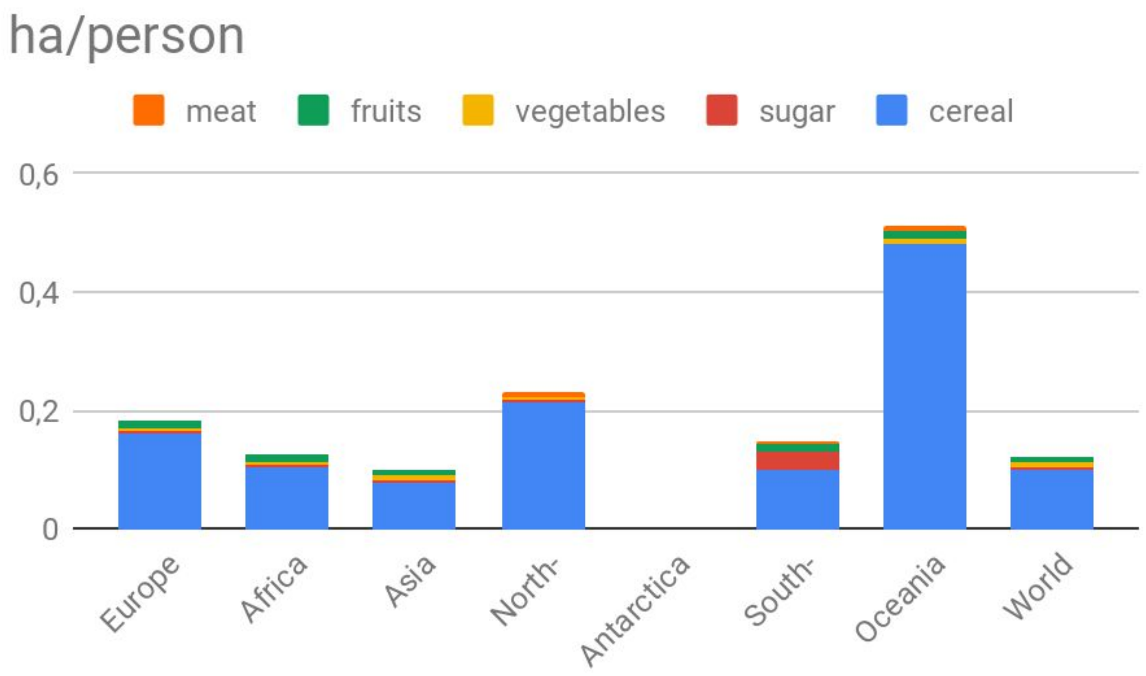
Appendix D:



Appendix E:



Appendix F:



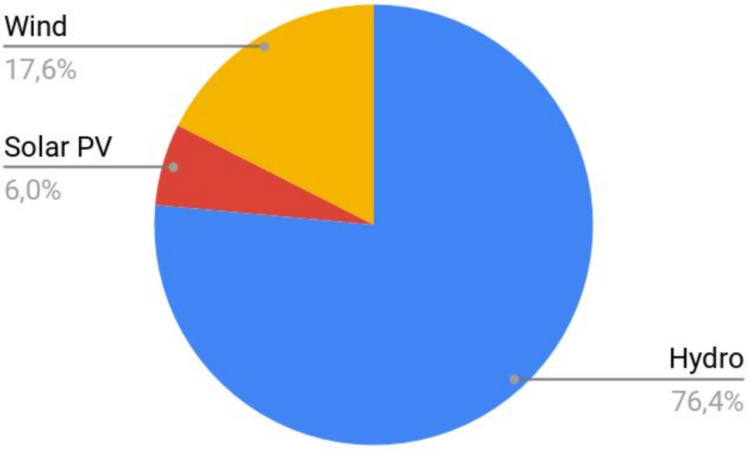
Appendix G:

Energy consumption			
Coal:	1,035,501 ktoe	12,042,876.63 MWh	10.84%
Natural gas:	1,440,262 ktoe	16,750,247.06 MWh	15.07%
Oil products:	3,893,250 ktoe	45,278,497.5 MWh	40.74%
Crude oil:	14,683 ktoe	170,763.29 MWh	0.15%
Geothermal, solar, etc.:	43,629 ktoe	507,405.27 MWh	0.46%
Biofuels and waste:	1,050,877 ktoe	12,221,699.51 MWh	11.00%
electricity:	1,793,937 ktoe	20,863,487.31 MWh	18.77%

heat:	283,185 ktoe	3,293,441.55 MWh	2.96%
total:	9,555,324 ktoe	111,128,418.1 MWh	100.00%

source: https://www.iea.org/

Appendix H



source: https://www.iea.org/