ON 10^{12}: A CHECK ON EARTH CARRYING CAPACITY FOR MAN

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Foreword

This paper is obviously not meant as a proposal for tomorrow's action. However, it is helpful to go through such an intellectual exercise in order to straighten out our perception of reality.

Man has undergone many, often painful transitions. The change from a hunting to an agricultural society was such a transition; those who did not accept the challenge did not survive. Agriculture meant an irreversible commitment to a certain lifestyle, and at the same time a very significant increase in the carrying capacity of the earth. In more recent days, the invention of the steam engine and the consequent fundamental change in living conditions further increased the carrying capacity of the earth. It is highly probable if not certain that more such steps are possible. So considered, evolution as a whole is probably openended.

As there is much debate today on whether the carrying capacity of the earth is 4.8 or 20 billion people, it is a drastic undertaking of the author to ask for a carrying capacity of 1000 billion people. True, the author concentrates on the engineering and physical sciences aspects of the problem, which is all right as long as the other aspects are kept in mind. And they are. It is deplorable if a society's unwillingness to undergo transition is excused by technological shortcomings it perceives that in reality do not exist.

It is a radically different matter to ask whether such transitions are desirable. Should they be considered necessary, it would be important to assess not only the technological conditions for a larger carrying capacity but also the implications for institutions, society, and the individual.

But let us separate the issues. In the present context the author deals with only one: the natural science and technological side of the problem. It is in those terms that the paper should be understood.

Wolf Häfele

Preface

The basic design of human settlement patterns can be traced to the early cultures. These patterns were fundamentally influenced by man's physical capabilities to work and move material goods, himself, and information. Technology has brought about many devices that extend human capabilities. And indeed, nationwide and even worldwide systems have developed, such as agriculture, industry, and with it conurbations, that modify and shape substantial portions of the globe.

Still, we do not consider the planet Earth as one inhabited area to be designed for settlement, in the spirit in which our ancestors developed towns or other patterns of localized activities. Also, the number of concerned voices multiply, pointing to our limited natural resources that must be used to support an ever growing population.

In order to stimulate more precise and, as they appear to us, less biased investigations into this critical issue, some effort within the IIASA Energy Program is devoted to extreme cases. This paper radically diverges from the usual practice of modeling and forecasting in that it does not extrapolate from present habits and traditional technological choices into the future. It attempts to assess the receptivity of our planet by a different route: a very large number of people is assumed, and a technological scenario is designed for a *stationary* system to hold them, if possible happy and in good shape. The number of people finally chosen, 10^{12}, is intentionally unrealistic, simply to stress the problems to the utmost.

The result the author has obtained, at least at the level of this simple analysis, is that extrapolations of technologies that are well within present knowledge may show that it is possible to sustain this number of people without exhausting any basic resource, including environment. This is admittedly perplexing, and while it should by no means be interpreted as an invitation to multiply, it does cast some doubt on the reliability of resource investigations within too narrow assumptions about the adaptability of man to changing conditions.

Summary

Much has been said about the carrying capacity of the plant Earth, and with most contradictory results, as the arguments have too often been used in the service of prejudices.

In this essay we have made a static cross-section of a world very heavily populated by present standards; examined with a system view the level of basic necessities plus luxuries for this population; and indicated the technology to satisfy them. Where problems of a global level appeared, a geo-engineering solution has been sketched.

The result of this analysis is that from a technological point of view a trillion people can live beautifully on the Earth, for an unlimited time, without exhausting any primary resource and without overloading the environment. The global view of the problems and of their solutions makes the difference, and shows that most of the physical limits to growth stem from an inappropriate frame of reference.

Basic Map of the 10^{12} System

Number of Persons	10^{12} (this figure would be reached in about 300 years at the present rate of growth).
Dislocation	2/3 on the sea (floating towns, design as indicated by Craven*); 1/3 on land--essentially an ecumenopolis with 2000 men/km^2 (about five times the present density of Holland).
Energy Consumption	Maximum allowable in terms of albedo control (order of magnitude 10 kW(th)/man).
Staple Food	Essentially obtained from microbiological transformation of cellulose, paraffins, or hydrogen; from the point of view of procurement, has to be considered as part of energy consumption.
Housing	"Single roof" tridimensional towns, whose temperature is controlled by a properly variable conductive and radiation coupling with the environment; the materials can be a sophisticated version of the present ones (e.g. foamed glass), or abundant metals (Mg, Al).
Structural Materials	Metals: basically aluminum, magnesium, iron; non-metals: basically compounds of carbon, silicon, calcium, oxygen, hydrogen.
Water	Essentially through recycling; make-up via rain or desalination, or as by-product of hydrogen combustion when necessary.
Transportation	Essentially via magnetically suspended vehicles, in vacuum "tubes" for long distance and high speed; conventional technologies for local movement.
Communication	Essentially through cables of increasing capacity according to hierarchy--from wire couple to light-stimulated optical fibers

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*John P. Craven, University of Hawaii.

Number of Persons

The figure 10^{12} is based on a somewhat arbitrary maximum density, that of a "garden city" at the level of the globe. In practice the natural trends of a megalopolis will push toward zones of much greater densities, leaving the possibility of creating very low density patches or "sanctuaries" where everybody might go when he wished.

High densities such as those found in towns are under heavy criticism nowadays as vastly inferior to the great open spaces of the country (which in the citizen's ideology should be salvaged but with a good infrastructure). This point appears to have escaped the country inhabitants who, since the invention of the city, managed to swarm into it whenever possible. Is that due only to plain ignorance on their part, or is man naturally a city dweller?

The great drawback of modern cities is that they are never built to the measure of man; they tend to be a patchwork of "machines to live in" where only a limited number of functions are considered essential.

Medieval cities may hold the secret of the "human city" where a man will wish to spend all his life; *intricate personal links and beauty* may be the most important components.

Soleri's* and Craven's teams have produced very interesting projects respectively for land- and sea-based cities conceived as tridimensional single units. These structures may have positive feedback to the global system; the control of temperature and ventilation via proper control of the radiation coupling with the environment may also serve to control the albedo, which finally limits the amount of usable energy.

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*P. Soleri, Cosanti Foundation, Scottsdale, Arizona.

Dislocation

From the point of view of coverage of the Earth surface, the Craven project of cities on floating platforms makes the ocean equivalent to the land. The Craven city should not be more expensive than its equivalent on land, the platform and the supporting "bottles" being gigantic but essentially simple structures with multiple functions.

We feel confident that structurally and functionally a "human city" can be devised. The great size of these agglomerates appears as a major obstacle to the attainment of such a goal, but the hierarchization of the system into units of growing size with strong intra-unit couplings, and weak(er) inter-unit couplings, may solve the problem as it has done in the past.

These cities, like the Amazonian forest, will be essentially closed systems where most of the materials, including water, will be recycled, the only physical input being free energy and the only output heat. If the input is in the form of negentropy, there will be no output at all. So the only factors that have to be taken into account from the point of view of material balance are the "dowry", i.e. the materials locked into the system, and the losses in the recycling process.

If we assume for the dowry 100 tons of materials/man, of which 30 tons are "high energy" materials such as metals and organics and 70 tons "low energy" materials such as concrete, this may correspond to about 2×10^6 kWh(th)/man for their production, or 40 years of "manufacturing" energy on the basis of our minimum hypothesis for energy available at equilibrium (see next section). As the buildup of the system may well take 200 years, the ratio appears very reasonable.

Energy Consumption

The amount of energy available is calculated backward from the assumption that the thermal balance of the Earth is not modified for reasonable large areas (e.g. 10,000 km^2) and long times (e.g. one month). As the local (and global) thermal balance is controlled essentially by the albedo with respect to solar radiation, i.e. by the percentage of solar radiation immediately diffused back, and by the emissivity in the longwave IR spectrum, any sizable energy input of nonsolar origin should be balanced by a modification of these two factors.

The albedo of the sea is around 10%, that of cultivated land about 25%; the average input of the sun on the Earth surface is about 200 W/m^2. This means that by changing the albedo by ten points, a very easy operation with a sizable fraction of the built-up Earth surface, we can afford to dissipate 20 W/m^2 or 10 kW(th)/man of nuclear or fossil origin. Clearly, if part of the incoming solar radiation that would normally be absorbed is transformed into other forms of energy, e.g. electricity or hydrogen, this does not affect the thermal balance.

These 20 kW(th) correspond to the present per capita energy consumption in the USA, where, however, second law efficiency in its use is about 5%. Taking into account the natural evolution toward more efficient processes, we have assumed it to be 50% throughout: i.e., our man gets the equivalent of 100 kW with present technologies.

How can these ten "extended" kW(th) be spent? We consider four main blocks, giving them a somewhat arbitrary weight:

- Manufacturing	6 kW(th)/man
- Transportation	2 " "
- Communication	1 " "
- Space conditioning	1 " "

The figures for the last three blocks may seem unbalanced. But long-range transportation is assumed to be by vehicles suspended magnetically in vacuum tunnels and so requiring marginal amounts of energy to be operated; and communication and information processing will be at levels many orders of magnitude above the present ones. This power of 1 kW(th) corresponds to a processing capacity of something of the order of 10^{20} bits/second, at room temperature; space conditioning may be done in the good old way, using essentially the sun and ingenuity to drive the system. Lighting is included in this block, but clever ways can be devised to store solar light, e.g., in liquids "pumped" by solar radiation and discharged by electric stimulation.

As our system is imagined as stationary, manufacturing will be essentially geared to maintenance and substitution. The 6 kW(th)/man may correspond to 1 ton/year of aluminum or magnesium. The production of food may require 0.5 kW(th), 5% of the total energy budget or 10% of the budget for manufacturing, a non-negligible but not a major fraction.

From the point of view of procurement there seem to be no problems: e.g., uranium in the sea amounts to about 4.5×10^9 tons, corresponding for roughly 10^{20} kWh(th). This corresponds to 10^3 years for our 10^{12} men at 10^5 kWh(th)/year. As the cooling water of a nuclear power plant located on the sea carries about ten times the amount of uranium fissioned in the plant, this source already appears accessible with breeder reactors.

But this just scratches energy reserves. In fact the minimum energy per nucleon in an atomic nucleus corresponds to the elements in the center of the periodic table. The fact that we have just started nibbling at the edges is due to the relative ease of the corresponding nuclear transformations. But most of the elements can be used as nuclear fuels, conceptually, and the means will certainly be available in time. The capacity of profitably transmuting any element may also indicate the final solution for radioactive waste disposal.

Our system being almost homogeneously distributed over the surface of the Earth, no particular problems of waste heat disposal may occur once the above condition of radiative energy balance is respected.

It must be remembered that our starting hypothesis--that the albedo is changed by ten points only (out of the 70 available), and that solar energy is not really included in the budget--is on the conservative side, so perhaps a budget of up to 50 kW(th)/man may be feasible.

Staple Food

While talking about arable lands and irrigation schemes is the staple job of many respectable people, a simple analysis shows that this game cannot go very far. However, simple analysis from a slightly wider angle shows that the master clutch between the sun and the biosphere operates the trivial process of breaking water up into hydrogen and oxygen, hydrogen being the energy vector to the biosphere.

The answer to the question whether hydrogen produced in other ways can perform a similar task is affirmative. The implications are clearly of revolutionary importance.

The simplest way of doing the trick is through micro-organisms capable of using hydrogen as a reductant. These micro-organisms are in fact very common and are under intensive study (e.g. at the Institute of Microbiology of the University of Göttingen), because they permit the production of proteins, fats, and other chemicals using a completely inorganic substrate (CO_2, ammonia, phosphorus, iron, salts, etc.).

The mean energy input of a man is about 100 watts. The efficiency of the micro-organisms can be between 50% and 70%, and between 50% and 90% for transforming nuclear heat (or electricity) into hydrogen. So we transformed these 100 watts into the 500 indicated in the energy budget for manufacturing, to take account of all the inefficiencies. Half a kW(th) is then the amount of primary energy we earmark for the production of biosynthetic food.

The techniques that made it possible to produce such a splendid variety of wines and cheeses out of two insipid fluids can be deployed to reproduce the miracle.

The indoor growing of fancy foods such as capers or blackberries that is starting now may develop into a frenzy. A "wallpaper" of strawberries may give the owner great aesthetic rewards --and the thrill of searching for food in the wilderness--the year round.

Conventional agriculture can be kept up for the aesthetics of flowers and wines.

Housing

The conceptual structure of the city has not essentially changed from Babylonian times: a two-dimensional grid of communication (information) plus transportation lines (the streets), linking a set of living, working, and social places. The fact that energy is carried by electric cables or carts of logs is immaterial from the point of view of the conceptual structure of the system. The same is true when we use skyscrapers: the two essential functions, communication and transportation, are still operated on a two-dimensional grid.

The potential solutions offered by modern technology for construction, ventilation, lighting, transportation, and communication make feasible huge truly three-dimensional structures, *cathedral cities*, capable of containing millions of people. The Arcologies of Soleri and the floating version of Craven give a hint of the future. The necessity of building towns on the sea in places where the hinterland of existing cities is already choked (e.g. Hong Kong, Tokyo) may provide the proper ecological niche for realizing the ideas of Craven and Soleri and for their evolution into vital (and reproducing) systems.

The medieval city solved the problem of human interaction in a dense system, and the problem of separation from nature, by reconstructing nature sublimated in art. Modern technology may project the scale by two to three orders of magnitude by reducing the characteristic transit times in like measure.

The attainable densities fit the figures of our hypothesis reasonably well--we visualize 10% of the globe built-up, all the rest being left wild--as do the materials and energy necessary to build and run these structures.

As the studies of the Craven team show, there is no essential difference between land and sea for siting one of Soleri's Arcologies.

Structural Materials

All projections put great stress on this point, easily demonstrating that present reserves of copper, nickel, chromium, etc., will run out in the year 2021. But the rational way to set the problem is to stress the functions and then go back to the materials able to perform these functions.

To stay on the safe side we suggest using as "staple materials" elements whose availability on the Earth crust (surface) or from sea water can be considered as practically infinite; e.g., clay, an exceedingly common material, can contain 30% Al_2O_3, 65% SiO_2, 5% Fe_2O_3 (expressed in equivalent form); and Mg contained in the sea amounts to 10^{15} tons or 10^3 tons/man in our 10^{12} hypothesis.

The reason why these large resources are not used at present is that the economics of their exploitation are marginally inferior to those of high-grade ores. But development is going on and could be fostered in view of long-range objectives--e.g. to develop processes consuming an amount of energy double the theoretical minimum, with a certain disregard for the level of capital investment. After all, a 10^{12} population with an income of the order of (1977) $\$10^5$ per capita, in a static system, energy limited, may have some problems in placing their savings.

A great potential lies in old but upgradable materials, e.g. stones. Foamed glass can be an emblematic case. The amount of material to make up the "dowry" of the system (10^{14} tons, or about 10^6 km^3 of original material, or a cube with sides of 100 km) is really a negligible amount on the geological scale. It may be considered almost a byproduct of landscaping. On the other hand, carbon compounds may constitute the backbone of sophisticated materials (biological systems give a striking spectrum of the potential). The source of carbon can be atmospheric CO_2; the sea buffer; byproduct CO_2 in the production of metals from carbonates (e.g. $MgCO_3$); and coal and oil deposits. After all, humanity now extracts about 5×10^9 tons of carbon (coal and oil) per year, and reserves of carbonaceous materials may well be in the 10^{12} ton range, or one ton/man in the 10^{12} hypothesis. One can visualize the "dowry" in organics in the range of 5 tons/man, out of the 30 tons earmarked as metals and organics. Silicon can play a parallel role.

A non-negligible amount of carbon will circulate via the metabolism of this human population, about 200 g/man/day or $0.2 \times 10^3 \times 10^{12} = 200$ million ton/day, more or less what we burn now during one month. To this corresponds a metabolic power of 100 TW, somewhat striking if referred to humanity, but in the same ball park as the present metabolism of plants.

Water

Water is the fluid of life and much poetry has been poured over it. A free-living cell may require 1000 times its volume in water as its "Lebensraum"; a cell in our body is satisfied with 1/10 its volume in water: the magic word "recycling" makes the difference. This image parallels those of savage man drinking at the brook (and fighting for it), and of town dwellers whose water comes back in tighter and tighter circles.

The water for our megalopolis or ecumenopolis may come essentially from recycling, perhaps with some hierarchy to satisfy aesthetics. But as we assume a density of one man/500 m^2, rain, at the present level, may provide a fresh input of about one ton of water/man/day: an excellent value even at the level of present consumption.

With our assumption of 50% thermodynamic efficiency for all processes, "compressing out" impurities to recycle water requires very small amounts of energy. Dialytic membranes pave the way to such very efficient purification systems. So in the absence of agriculture, large-scale desalination does not appear to be a global necessity, and we do not give it a place in our energy budget. As hydrogen will probably be, with electricity, the main energy carrier, its combustion may provide another important source of water, let us say 200 liters/man/day.

Transportation

People and materials are now transported by vehicles that move within a fluid, dissipating most of the energy used to propel them. The necessary breakthrough to reduce this energy is to run the vehicles into evacuated tubes or tunnels. The evacuated space being expensive, it will be advantageous for this and other reasons to run the vehicles at high speed. Above 500 k/h, wheels are not very suitable, and the various systems of magnetic suspension under development may provide the final, i.e. nondissipative, solution. This may arrive through very strong permanent magnets or high-temperature superconductors, or perhaps in other ways. Such a system (a prototype is under very active development in Japan) has little limitation in speed and can have an enormous productivity (ton × km/hr).

However, it is very difficult to forecast the transportation needs of a system coagulated in clusters of 10^7 to 10^8 men, where materials are recycled, energy is produced locally, and high-level information transport and processing will make, in most cases, people travel a luxury and materials transportation marginal. Intracity movements, on the contrary, will probably be very intensive, and this will account for most of the energy budget we have dedicated to transportation. The three-dimensional city, e.g. as conceived by Soleri, through an appropriate space-function hierarchization, leaves much room for sheer walking as the main form of personal and light goods transportation.

Movement of fluids is essentially included under conditioning.

Communication

Information processing and transport are *the* core of our civilization, much more than the steam engine (or energy) as many people still think at the back of their mind. After all, the energy available per productive worker is today just an order of magnitude larger than for a medieval worker.

Information will be almost all in a 10^{12} world, because:

- The different levels of the hierarchy of organization will require internal processing for running the hardware and the software of the system;

- The amount of information available as software of the civilization will have reached enormous levels (it doubles every ten years for science alone, and no saturation is in sight);

- Each person will require a multipurpose high-level link (supervideophone) to every other person, to any place in the system defined as public, and to the hierarchical information stores, even if only a small fraction of the information carried is actually used. (After all, the eye is a narrow-angle, high-resolution, random scanner picking only the plum of what is available.)

Clearly the system will be essentially wired, a solution that has evolved in all higher organisms.