Computing Efficiency, Sufficiency, and Self-sufficiency: A Model for Sustainability?

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ABSTRACT

Computing is an activity that is based on natural resources like any other human activity. Technological progress has made it possible to perform more and more computations with less material and energy input. This paper looks at this development through the lens of the three concepts of efficiency, sufficiency, and self-sufficiency, asking the question of whether it could lead to a state of self-sufficiency. This vision, which seems attainable for the activity of computing, is then taken both as a model and as an enabling element for a transition towards a sustainable circular economy based on relative regional self-sufficiency.

1. INTRODUCTION

All human activity depends on limited ecosystem services provided by nature. This is also true for the activities of building and using computers. Computing requires electric energy that is usually generated from fossil fuels, nuclear power, wind power or solar radiation. It requires the production of digital computer hardware, the first technology that involves more than half of all chemical elements of the periodic table [1,2]. These elements are extracted from mineral ores that are mined. All industrial processes in the chain from mines to devices need energy and in many cases also clean air and water. Emissions into air, water and soil and the waste produced utilize the capacity of nature to absorb these residues [3,4].

The ecosystem services involved in computing are therefore: providing primary energy and minerals, providing clean water and air, and to absorb emissions and solid waste. These services are provided by nature for free, and we use them to build all types of computing devices, including smartphones, servers, embedded processors, etc. We rely on the same ecosystem services to a much greater extent for other essential activities, such as building, heating and cooling houses, producing food and drinks, and transporting people and goods. Computing currently accounts for 2-3% of the global pressure on ecosystems; however, the trend is increasing [5,6].

This paper describes the dynamics of the technological and economic development underlying computing using the three concepts of efficiency, sufficiency, and self-sufficiency, using this development as a model to discuss the possibility of similar developments in other fields of human activity. We assume the following definitions of the three terms:

- Efficiency: Any process that converts inputs into useful outputs (goods or services) has the property called "efficiency", namely the ratio "useful output per input". A computing process produces the service of computing as its output and uses hardware resources and electric energy as input. Depending on how inputs and outputs are defined and measured, different instances of the efficiency concept result.
- Sufficiency: A system consuming some inputs from its environment can either increase consumption whenever it has the opportunity to do so, or keep its consumption within certain limits. In the latter case, the system is said to be in a state of "sufficiency". Depending on which inputs are considered, different instances of the sufficiency concept result. A sufficient system can improve its outputs only by improving the efficiency of its internal processes. Mobile computing devices have reached a state of sufficiency with regard to electricity input.
- Self-sufficiency: If a system can reduce its consumption of some inputs to zero, it is said to be "self-sufficient" with regard the that input. A pocket calculator powered by a photovoltaic cell is self-sufficient with regard to electricity.

2. SEVENTY YEARS OF COMPUTING

Using this conceptual framework to look at computing as a human activity in the context of natural limits, the following observations can be made:

1. The energy needed to perform a computation has decreased dramatically since the first electronic computer (ENIAC) was built in 1945. Roughly, the number of basic computations that can be performed for 1 kWh of energy input increased from hundreds (10^2-10^3) to quadrillions (10^{15}-10^{16}). A similar efficiency increase has been taking place with regard to the material input per computation [7,8].

2. The energy and material resources spent for computation by society *in total* have nevertheless been increasing. This is an example of what economists call the "rebound effect" or the "Jevons paradox": Higher efficiency (useful output per input) does usually not lead to the expected savings on the input factor because the demand for output is stimulated by the increase in efficiency [9,10,11]. Mobile devices, however, have triggered a culture of energy sufficiency in hardware and software development because energy is limited by a combination of battery constraints (energy density of the battery, acceptable weight of the battery, required battery life). The performance of

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mobile devices has only increased within the limits of energy efficiency progress of computing (and to some extent energy density progress of batteries), not faster. The consequence is that the per-device energy consumption is more or less stable, which can be considered a form of sufficiency.

3. Some computing devices even achieved a state of self-sufficiency. At least two of them are in widespread use: the solar-powered pocket calculator and the solar- or wind-powered cellular mobile base station [12]. The calculator can be considered self-sufficient both in terms of energy and material. It harvests its energy from the environment through a small photovoltaic cell, and it can be used until the end of the technical life of the hardware (usually more than a decade) because it needs no software update that could render the hardware obsolete and urge the user to buy a new device. The reason for needing no update is that the tasks it performs are clearly defined (arithmetics) and the algorithms are proven and unhackable. (What a sustainable world!)

The solar- or wind-powered cellular mobile base station is particularly deployed by the network operators in places where a power grid is lacking and the fuel of a diesel generator would be stolen. It is self-sufficient in terms of energy, but not in terms of materials because protocols, algorithms and whole technological generations of cellular networks change from time to time, which makes the exchange of functioning hardware necessary. These innovation cycles have been shown to create relevant amounts of hardware scrap [13]. If this innovation slows down in future, there will be a chance for almost completely self-sufficient cellular networks.

3. GENERALIZING SELF-SUFFICIENCY IN COMPUTING

Let's see if this three-step development to self-sufficient devices can be generalized to other forms of computing. An increasing share of total computing power is provided by data centers. What would be needed to make a data center as self-sufficient as a pocket calculator?

If we imagine that a data center is fully powered by its own solar and wind stations, the main challenge will be the fluctuating supply by these sources. There will be energy supply peaks and supply gaps. Storing energy (e.g., in batteries) is not the only strategy to cope with this basic problem. Another, maybe more important strategy is flexibilization of demand in space or time.

- Spatial flexibilization of demand: A computation can be performed remotely at a place where there is an energy supply peak. So, migrating the computation to a different place ("follow the sun" or "follow the wind") can contribute the temporal flexibility in energy demand that is needed locally. It is assumed that the energy needed for transferring the task through the Internet is small compared to the energy needed by the task itself, which is not always the case, but very often, as many studies have shown [14]. In the long run, spatial flexibilization of demand must be a winning strategy because data is much easier to transport than energy and the energy efficiency of data transmission is still increasing.
- Temporal flexibilization of demand: This strategy represents probably the most underestimated contribution of computing to a sustainable energy system: storing symbolic structures (computation results) instead of storing energy for computing. Some computational tasks have the only purpose of making an investment in structure that pays off later in terms of saving computation. Such tasks include indexing, deduplication or any type of translation between different formats, any defragmentation or garbage collection techniques for storage media. Moreover, in any system doing optimization, the solution of the optimization problem can be computed when energy is abundant with the goal to save energy by making use of the solution when energy is scarce. Any process that increases or decreases specific types of redundancy with the goal of reducing the complexity of another process is in fact a way of moving forward energy demand. Whole new hardware and software architectures can be envisioned that would be systematically designed for "computing in advance".

In other words, the issue of load elasticity that is discussed in the "smart grid" context could make substantial progress if data centers would radically strive for "Variable Power" or even "Available Power" loads [15]. Together with the spatial flexibilization of demand, this would transform data centers gradually into distributed infrastructures powered by decentralized energy sources.

Combined with short-term energy storage (of limited capacity) and continued progress in energy efficiency, these infrastructures could become self-sufficient in the future. They will maybe no longer be called "data centers" because they might develop into crowds of self-sufficient standardized containers that can be spread all over the world.[1]

This idea of a computing infrastructure based on simple, commodified devices is related to the principle of building „self-sustaining systems" as formulated by Raghavan and Ma: „Current networks are composed of a complex array of hardware and software assembled around the world with materials, energy, skills, and designs also from a global resource base. We expect that today's approach to the design, creation, and deployment of networking technology is likely, in time, to become too costly or simply physically infeasible. Thus networking technology should follow the principles of Appropriate Technology [...]: be designed to be a) simple, b) locally reproducible, c) composed of local materials / resources, d) easily repairable, e) affordable, and f) easily recyclable." [16]

One of the major challenges in such a scenario will be to keep the precious materials in service as long as possible. The flow of resources from mines to waste (with a device's life cycle in between) can only be slowed down if the useful life of the devices is extended. Only in rare cases today, it is technical failure that renders a device obsolete. Software bloat [9] and similar effects are the main drivers of hardware obsolescence. If the few basic functionalities that are needed in all types of application software would be more strictly and more universally defined, the innovation cycles for an infrastructure-type data center would slow down, and with them the hardware flow through the data center. That means that we should do away with all the proprietary noise that adds unnecessary complexity to an already complex world and find a way back to axiomatic principles and mathematically provable – and therefore eternal – architectures and algorithms for a self-sufficient computing infrastructure.

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[1] Already today, there are companies operating distributed data centers by placing servers in people's homes as heaters. This is done for energy efficiency (not self-sufficiency) in this case: The energy is used in a cascade, first for computing and then for heating.

4. SELF-SUFFICIENCY IN COMPUTING AS A MODEL FOR LOCAL OR REGIONAL SUSTAINABILITY

Assuming that the three-step development to self-sufficiency in computing – as sketched above – would turn out to be a feasible way to further increase available computing power while bringing down the 2-3% of total environmental impact of computing to close to zero, could this be a model for our activities that are responsible for the remaining >97%? (For a more fundamental discussion of types of impacts of information and communication technology see [17]).

Let's look at a region and think of strategies for energy and materials self-sufficiency. A region that would supply its total energy demand (for heating, mobility, agriculture, manufacturing) from local renewable sources such as solar, wind and hydro-power would face the same problem as the self-sufficient data center discussed above, namely the high fluctuation of energy supply. Again, storing energy is one strategy to cope with this challenge. A complementary strategy is flexibilizing energy demand in space or time. Shifting tasks to regions in a different part of the world, which works for computing tasks, is less useful as soon as physical objects are involved that can only be moved slowly and with a relevant energy footprint. This is a point where the analogy with computing reaches its limits. However, one could still think of a division of labor between regions that considers the characteristics of their local renewable energy sources. Temporal flexibilization of energy demand, however, is always possible. It may require the change of social practices.

Contrary to the current "anytime culture", people living in a self-sufficient region would have to adapt their lifestyles to the pace of the renewable energy supply. Strategies for doing things in advance, namely during an energy supply peak, could stimulate socio-technical innovation. Recycling is an obvious candidate for this type of innovation because recycling means increasing the value of material by creating structure at the cost of energy. Since the value of material can easier be retained than the value of energy, recycling should best be done when energy is abundant. Both the regional transport and the sorting and recovery activities needed in a circular economy could be paced by the availability of renewable energy. Such innovations would most probably rely on a highly capable computing infrastructure that would, for example, act as an enabler of cleaning, sorting and recycling robots. The local availability of materials would be increased during energy supply peaks, which will then save energy during supply gaps because secondary materials will be in place when needed. Approaching the goal of a circular economy within the region will slow down the flow of materials crossing the region's boundaries, which contributes to material self-sufficiency.

As in computing, in a circular economy the creation of structure can be used as a strategy to cope with fluctuating energy supply. In a very abstract sense, a circular economy is an economy with a higher level of cognitive capacity, a metabolism in which energy flows, material flows and information flows are more dynamically interwoven than in our today's production and consumption systems.

5. CONCLUSION

Self-sufficient computing could be both a model for and a necessary component of self-sufficient regions. Self-sufficiency is the end state of a three-step development: First, efficiency is considered a solution to problems of energy and materials supply, a solution which usually fails due to rebound effects. Second, efficiency is combined with sufficiency by introducing constraints that respect given limits. Third, constantly increasing efficiency combined with demand flexibility enables to cope with further limitations, a process which leads to relative self-sufficiency.

A post-industrial world of relatively self-sufficient regions, enabled by a self-sufficient computing infrastructure, would probably look very different from our current world. It would certainly be closer to the vision of sustainable development.

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7. REFERENCES

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