ICT Within Limits Is Bound To Be Old-Fashioned By Design

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Abstract

Crossing multiple planetary boundaries places us in a zone of uncertainty that is characterized by considerable fluctuations in climatic events. The situation is exacerbated by the relentless use of resources and energy required to develop digital infrastructures that have become pervasive and ubiquitous. We are bound to these infrastructures, dead technologies and negative commons, just as much as they bind us. Although their growth threatens the necessary reduction of our impact, we have a responsibility to maintain them until we can do without them.

In university setting, as well as in any public organization, urban mines *per se*, we propose an IT architecture based on the exclusive use of unreliable *waste from electrical and electronic equipment* (WEEE) as a frugal alternative to the incessant replacement of devices. Powered by renewable energy, autonomous, robust, adaptable, and built on battle-tested open-source software, we envision this solution for a situation where use is bound to decline eventually, to close this harmful technological chapter. Digital technology, the idol of modern times, is to meet its twilight if we do not want to irrevocably alter the critical zone.

Keywords

Planetary Boundaries, Negative Commons, Zombie Technology, Adaptability, Unreliable Hardware, WEEE, Low-Tech, Inverse Legacy, Urban Mine, Subtractive Innovation.

1 A Major Environmental Crisis

Following IPCC's statement [46], "climate change is widespread, rapid and intensifying". We are facing a significant increase in number and intensity of climatic events like extreme temperatures, drought conditions, heatwaves, fires, flooding, glacier and permafrost melting... Relative to the pre-industrial era, we face an average global temperature increase of +1.15°C, with local values highly dependent on the regions of the world considerd; for example, France faces a higher value with an increase of +1.7°C due to its geographical characteristics. As is the case on a regular basis, each passing month brings record-breaking temperatures.[1] 2024 was the first calendar year with a global average temperature exceeding 1.5°C above pre-industrial level [22].

Unfortunately, as we know, climate change isn't the whole story. The planetary boundaries' framework [72], which

> *delineates the biophysical and biochemical systems and processes known to regulate the state of the planet [...] to maintain Earth system stability and life-support systems conducive to the human welfare [...]*

reminds us that life on earth relies on additional properties. Interactions between the geosphere and the biosphere have controlled environmental conditions for over 3 billions years, with the Holocene that started about 11,700 years ago being rather stable.

Climate change is one of the 9 planetary boundaries[2] which includes Greenhouse Gases (GHG) expressed in terms of CO_2eq concentration and radiative forcing. If we consider CO_2, the current value is around 422.5 ppm [2] and [32][Page 7], way above the 350 ppm boundary and the 278 ppm value of the pre-industrial era.

In 2021, IPCC modelization in its sixth assessment report [18][page 20-21], states that (bold typeface from the authors)

> *For every 1,000 GtCO_2 emitted by human activity, global surface temperature rises by 0.45°C [...] remaining carbon budgets from the beginning of 2020 are 500 GtCO_2 [...]* ***The stronger the reductions in non-CO_2 emissions****, the lower the resulting temperatures are for a given remaining carbon budget [...]*

Four years later, in 2025, June the 19th, at the time of writing, the remaining CO_2 budget for a 50% likelihood to limit global warming to 1.5°C above the 1850-1900 level (Paris' agreement and SSP1-1.9) has been reduced to 130 Gt [29][Table 8 page 2663]. This budget would be exhausted in 3 years if global CO_2 emissions remain at 2024 levels (about 42 GtCO_2 yr^{-1}).

Multiple crossed planetary boundaries and among them, low CO_2 bduget, places us in a *zone of uncertainty* that is characterized by *considerable fluctuations* in climatic events. Moreover, IPCC projections commit us to *reducing our net GHG emissions*, or at least do the best we can to *avoid making the situation worse*.

2 ICT, an Unmaterial Limitless Technology

2.1 Exponential Laws with No Counterparts

Various *laws* in ICT, namely

- Moore's law [59] on the growth of the density of transistors integration into CPUs together with
- Dennard's scaling law [27] on the power density of a circuit - with transistors scaling down - remaining constant (at constant surface area)[3],
- Kryder's law [95] on disk storage capacity,
- Metcalfe's law on the network effect [56],
- Nielsen's law on the state of the art of available bandwidth [62],

[1] For example, in 2024, April that was the 11th consecutive warmest month globally [21].

[2] Six of which have already been crossed, with a 7th, ocean acidification, being currently crossed.

[3] The authors would like to thank G. Roussilhe for bringing this point to their attention, see [75].

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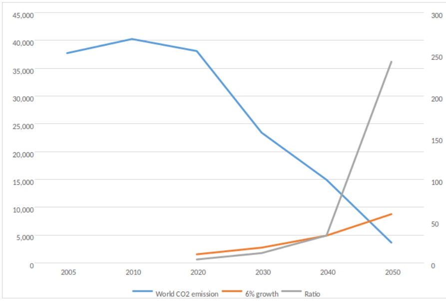

Figure 1: IPCC scenario SSP1-1.9 and *lower bound of ICT growth* (6%). Left ordinate are MT of CO_2 emission per year; right ordinate are percentages for the grey curve.

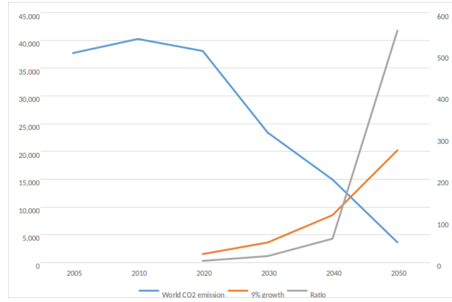

Figure 2: IPCC scenario SSP1-1.9 and *upper bound of ICT growth* (9%). Left ordinate are MT of CO_2 emission per year; right ordinate are percentages for the grey curve.

combined with software engineering principles based on extensibility [54], have built a disciplinary field structured on the exponential availability of resources with no physical counterpart. An economist's dream in action! This very state of mind is reflected in the name coined for the generalization of grid computing, *cloud computing*[4] where resources are supposedly in an ether, unlimited on-demand (hyperscale), without any constraint.

2.2 The Unavoidable Reality Principle

But the phantasm of the absence of materiality eventually collides with the materiality of the infrastructure and devices that enable the use of digital (non-convivial)[5] tools: the most conservative estimates [89] put the number for ICT devices to 34 billions with 4.1 billions users requiring about 5.5% of the world's electricity. All those devices communicate using, among others, submarine cables for a total of about (as of 2025) 1.48 million km with length ranging from 131 km (from Ireland to UK) to 20,000 km (from Asia to America) [88]; smartphones require more than 50% of periodic table of the elements [85] with rare-earth elements production having substantial geopolitical and environmental impact [34, 97].

2.3 Recycling Won't Help

Many growth scenarios for ICT are based on a significant ability to recycle essential elements found in devices. Recycling takes place at the final step of a product's life-cycle (which consists in the 5 following phases: raw material extraction, manufacturing and processing, transportation, usage and retail, waste disposal). Unfortunately, 100% recycling is impossible [86][page 4] as "[...] the life cycle of metal is most often a succession of material and energy losses, subject to physical and thermodynamic limits." (translated by the authors). As far as rare-earth elements used in ICT devices are considered, many have very low *end-of-life recycling rates*[6] for rare-earth elements that are crucial for ICT devices, high *loss rate*[7] and short *service life of metal*[8] (see figure 3 and 5 of [19]) the authors remind us of the "crucial role of *lengthening the lifespans of products* to improve the conservation of metals in the economy" [86].

One might wonder what would happen if, for a given metal, both EOL-RR (say 80%) and service life (say 10 years) where high and a reasonable (yet exponential) constant annual consumption growth rate of 4% would drive the use of that metal? The net effect of recycling would only *shift* the consumption of that metal by a mere 20 years.[9] In a *growing economy*, recycling is not the appropriate response to the issues raised by reduced availability of rare-earth elements used in ICT devices.

2.4 Incompatibility of ICT Growth of GHG Emissions with The Paris Agreement

Based on [31, 69], ICT is accountable for 5-6% of world primary energy consumption and between 2.1% and 3.9% of GHG emissions, *with 30% coming from embodied emissions*. Based on data for 2015-2019, the annual growth of these figures are between 6% (lower bound) and 9% (upper bound), that is, before the availability of generative IA.

Following the analysis suggested by D. Trystram, Y. Malot and G. Raffin at Université Grenoble Alpes[10], figure 1 (resp. 2 and 3) simulates CO_2 world and ICT levels in IPCC's scenario SSP1-1.9 with a minimal (resp. maximal and constant) ICT growth of 6% (resp. 9% and 0%) per year. The blue curve is the world CO_2 emission in Mt/year as it should be to comply with the Paris agreement; the red curve is ICT's share of CO_2 emissions; the grey curve is the ratio between the blue and the red curve in percentage (the blue curve includes the red curve in 2010, but they are independent for the rest of the simulation). It is clear that lower and upper bounds of ICT growth are absolutely not compatible with the Paris agreement. Even keeping ICT constant to its current share of GHG emissions does not enable compliance with the Paris agreement.

[4]Ironically enough, if you think about it for a moment, the name itself was a harbinger of ICT's major climate effects, as clouds are made of water droplets condensing from water vapor, which is the main (natural) GHG accounting for 15% of the Earth's GHG effect.

[5]This brief analysis of the (non)materiality of digital tools should be analyzed more thoroughly from the perspective of conviviality proposed by I. Illich [10] and from A. Gorz in "The Immaterial" [35].

[6]Abbreviated EOL-RR.

[7]The *loss rate* (in kg lost per kg of metal extracted per year) represents the rate at which extracted metal becomes unavailable for further use. It is calculated as the inverse function of the average service life. (translated by the authors from footnote 207 page 107).

[8]The *service life* of a metal (in years) represents the average duration it is used in the economy, from the time it is mined until it is completely lost to landfill or the environment, so that it becomes unavailable for further use. (translated by the authors from footnote 206 page 107).

[9]See [86][figure 77 page 164].

[10]Their app is available at https://edge-intelligence.imag.fr/trajectory_app.html.

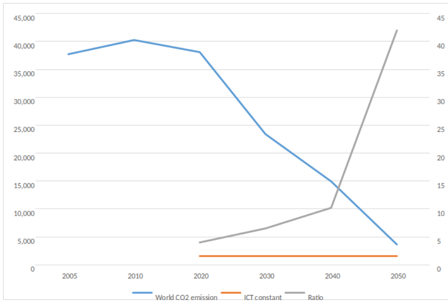

Figure 3: IPCC scenario SSP1-1.9 and *constant ICT*. Left ordinate are MT of CO_2 emission per year; right ordinate are percentages for the grey curve.

Clearly, the share of ICT in global GHG emissions must be reduced [65] in the same way as other sectors of activity[11]. If limits have to be set to the expansion of digital technology, and new fields of research explored (these two issues being discussed in the international workshop [61] and [1]), there is still a need to provide digital services, given their level of intricacy and pervasiveness in today's societies, but with the lowest possible environmental impact and without generating (direct or indirect) rebound effects. Considering digital technologies in its infantile stage of development, introducing limits leading to the gradual reduction of digital services, that is going past the peak ICT [90], if it is to be considered desirable, cannot be carried out abruptly; to paraphrase B. Latour, the landing on earth [49] should be gradual, collectively decided and fair.

3 Negative Commons, Zombie Technology and Attachments

As we have just seen, we are facing a bleak situation: climate change requires us to reduce GHG emissions, but it also increases the uncertainty and fluctuations of climatic events. At the same time, we have inherited a *large technical system* [28] - digital technologies - that permeates all levels of social organization. How can we understand this legacy, and what can we do with it? A few concepts help us to better grasp the particular situation in which we find ourselves, and how we can navigate through it: *negative commons*, *zombie technology*, *attachments* and *adaptability*.

3.1 Negative Commons

The *commons*[64] consist of a triptych (focused on monopolization): an incommon fraught with conflict - a resource that we wish to share; a resource managed by a community (which is neither the state nor a private firm); which sets up rules and governance for this purpose. This resource has a *utility*, it has *positive effects*. But what about the *negative effects* produced by certain things? Let's take the paradigmatic example of nuclear power plants: we *inherit* these infrastructures, they have a limited lifespan, they're impossible to dismantle[12]. We therefore need to extend their lifespan, but we can't do without them. We could simply say that a nuclear power plant is a waste product, but it's a special kind of waste, one that cannot be reintegrated into natural bio-geo-chemical cycles. It's not the economists' *negative externality*: it's not an unintended result, but on the contrary a *condition of possibility* for cheap energy that makes the construction of digital infrastructures possible. The extraction of precious metals by children, the war in the DRC, the former Agbogbloshie landfill in Ghana, the poor protection afforded to the workers who make smartphones, etc. are not side effects of their production: at this price on these markets, they are quasi-necessities, constitutive elements and not unfortunate consequences.

A. Monnin *et al.* propose the notion of *negative commons* [15, 57] to rethink the commons in the light of thoughts on the Anthropocene, and to move away from a solutionist vision in which the commons would save the world. Indeed, while the issue of the commons concerns the means of avoiding the appropriation of "common" realities, or of reappropriating what has been captured by enclosures, there remain the realities that nobody wants (organic and nuclear waste, technosphere waste, abandoned infrastructure, polluted soil, dried-up rivers, etc.). These are the ruins that fall into two categories: *ruined ruins* (called *ruina ruinata*), which escape any desire for appropriation (such as picturesque and romantic ruins) and *ruinous ruins* (called *ruina ruinans*) which are always in action.

The devices that dig them out, the economic models that make them profitable, the supply chains that export them to the four corners of the planet... these are the *negative commons we inherit*. These realities (technical, managerial, economic, logistical, etc.) are negative commons that we are inheriting, because an ever-growing proportion of the world's population is linked to them in the short term, even though their operation constitutes the greatest threat to the planet's habitability in the medium term. These ruins are not to be found in an imaginary world of decline or decadence, but in the gleaming, high-tech realities of the destructive regime of intensive innovation at every turn, and the incessant renewal it demands. It's the ruin that is still productive: productive of new ruins, ruinous or ruined. Some ruins are both ruined and ruinous, such as oil and its iconic wells, which are both ruined because they are the product of hundreds of millions of years of transformation of organic matter, and ruinous because they are a miracle product for industry (transforming the world) and a source of massive GHGs emissions.

3.2 Zombie Technologies

What characterizes ruins is their persistence over time. Certain technologies, involve finite resources (energy, metals, etc.) as opposed to the CHNOPS[13] chemical elements that make up living matter and are sustainable because they are renewable. These resources are drawn from available stocks, the most critical of which do not have a satisfactory recycling rate (see section 2.3). These technologies are doomed to survive in a degraded form for a very long time. This is why J. Halloy [38] refers to them as *zombie technologies* (or

[11] We won't go into the controversy over *decoupling*, which would enable growth while reducing environmental impact, but would not address the problems of raw material depletion mentioned in section 2.3; interested readers can refer to the work of T. Parrique [66].

[12] France's Brennilis plant, shut down in 1985, is a case in point. Its end is constantly being put off, and is scheduled for 2040, at an estimated cost of around 850 million €.

[13] Acronym for Carbon, Hydrogen, Nitrogen, Oxygen, Phosporus and Sulfur.

dead technologies, as opposed to *living technologies*) because they do not want to die or disappear. Activities can be zombified, such as agriculture, which is 14,000 years old and which, in less than a century, has been totally transformed (machinery, inputs, drones, etc.). In 2018, 9% of German farmers used drones (according to a study conducted by the DBV).

Zombie techniques give the impression of being alive, through their frenetic activity, but are undermined from within: a death in waiting. J. Halloy proposes three criteria that favor zombification [91][page 299]: the use of finite stocks that impose a time limit on the activity; the use of a power exceeding the capacities of the environment in which this technique is used; the generalization of these characteristics on a large scale (and we should add that they take part to the current ecocide, following [20]). It will be easy to recognize that all these characteristics are present in ICT. But these technologies pose an additional problem, that of our *attachments*.

3.3 Attachments, De-attachments and Re-attachments

We are *attached* [17, 40, 41] to the ruins, which requires us to question our values: *what we care about* and what we are *attached to*. This twofold movement is important for understanding the importance of ICT and the need to make it last over time. This attachment to our living conditions and our infrastructures is essential, even if they are negative and lead us to disaster in their current state (see section 2.4). Because we don't have the choice to make them work differently, we have the obligation to make do with them (as is the case with the digitization of a large number of essential public services, for example). This requires working on *de-attachment* and *re-attachment*, on a collective scale. The challenge is to make the non-political political in order to maintain habitable ecosystems. We face multiple problems:

- the scale (spatial/temporal/functional/organizational/etc.) of negative commons;
- the democratic challenge of determining the negative character of certain commons;
- not letting communities alone to manage negative commons, not rely on the resilience of populations or the administrative management of crises;
- technosphere/biosphere opposition: ask the question of their future, which threatens our future existence as much as it makes our current existence possible;
- the imperative need to maintain and take care of the ruins that are not yet ruined (roads, bridges, dams, ..., ICT)

While A. Monnin advocates an ecology of dismantling and closure [58], we believe that with regard to ICT, it is important, as we have said several times before, to keep these zombie infrastructures alive and in working order for a while longer (a very interesting initiative from [30], which is not contradictory to our point of view, is to consider smartphones as *commons*, implying a form of collective reappropriation, in a perspective that could enable the development of *rights* associated to *things* [26] – as opposed to the notion of *objects*) – to ensure a safe landing for societies that heavily rely upon them.

3.4 Technical Systems Focused on Efficiency Gains

In the development of *large technical systems*, modern societies focused, after the Renaissance and the Enlightment, on efficiency and growth. This technical choice has had significant consequences on the type of society that has evolved. Quoting O. Hamant [39] (translation and bold typeface from the authors)

> *[...] effectiveness and efficiency are the instruments of an optimization that locks us into a narrow path, and therefore inadequate* ***if everything is constantly subjected to change*** *[...]*

As we stated previously (see section 1), the Anthropocene is characterized by major uncertainties and considerable fluctuations in climatic events. Taking these fluctuations into account calls for the development of digital infrastructures that are frugal, robust and adaptable. In his very stimulating proposal, O. Hamant, being a biologist and using biology as a case study and as a metaphor reminds us that the robustness of living organisms is the result of a set of properties: *heterogeneity*, *randomness*, *slowness*, *delays*, *redundancies*, *inconsistencies*, *errors*, *incompleteness*, *sub-optimality*. Following on from these properties, it seems reasonable to us to add two important additional properties, namely *locality/interactions* and *emergence*, recognized by O. Hamant in [37] when dealing with complex systems.

These properties are highly desirable for the design of a computing infrastructure that should be resistant to significant climatic fluctuations.

4 LIFE Project: How Not To Worsen the Situation

To summarize our journey, so far:

- section 1 pointed out several factors: the low level of available CO2 if we are to comply with the Paris agreement and the planetary boundaries already crossed, resulting in significant fluctuations in climatic events;
- section 2 recalled several elements: the construction of the computer science disciplinary field as being limitless (even though reality massively contradicts this hypothesis), a constantly increasing use of resources incompatible with the climate emergency, and a recycling that will not address the depletion of natural resources;
- section 3 proposed studying zombie technologies from the perspective of negative commons, which we inherit, to which we are attached and which attach us and which must be taken into account to ensure a fair landing of societies; in order to accommodate significant fluctuations, this should favor *robustness* and *adaptability* (and not *adaptation* which is a static properties).

We could summarize all these points by the desire to dispose of a digital infrastructure that is compatible with the planetary boundaries and produces the least possible environmental damage, and thus enables (the least possible) low-carbon computing. This is the purpose of the LIFE[14] project.

4.1 Reintroducing Limits

As we have seen, the unlimited nature of digital technology has led to its very significant expansion. The reintroduction of limits is therefore necessary if we want to align the use of digital resources with planetary boundaries. It raises numerous questions:

- *time*: could data circulation be constrained by external resources (disposal of energy for example)?
- *space*: could communication and computation be constrained by local interactions (local mesh network, hierarchy of data access...)?
- *discontinuity*: could the operations only function on an intermittent basis?
- *computation*: should everything that can be computed be computed? Could computed data be pre-processed and stored to reduce further identical computations?
- *resource*: how to think in terms of (finite) stock and not (infinite) flux?
- *availability*: should a service be always available?
- *acceleration*: how to slow down exchanges?
- *exhaustivity*: how to un-digitize (willingly or by necessity)?
- *politics*: how to find the rhythm of the democratic deliberation necessary for the development of collective processes when digital tools progress at its own (fast) pace[15]?
- *side-effects*: and how can we ensure that no rebound effect (direct or indirect) occurs?

The questions of *discontinuity*, *computation*, *resource*, *availability* and *side-effects* will be specifically considered and taken into account in section 5 and following, while the others will be considered implicitly.

Reintroducing limits requires thinking in terms of non-extensible (but rather shrinkable [53, 54]) systems and considering the Cartesian product of

$$\{\text{intermittent, quotas, supply}\} \\ \times \\ \{\text{energy, communication, memory, computation}\}$$

These points should be taken into account in any project that aims to consider the operating of a digital system within the context of finite resources.

5 The Phases of the Project

Having all those previously discussed elements in mind and in order to take into account the constraints we discussed in the previous sections, we designed the LIFE project. It consists roughly of 5 steps:

(1) The first step will involve collecting the widest variety of WEEE within the university, enabling the construction of a small-scale data center (SSDC);
(2) The construction of a theoretical model to formalize the asynchronous functioning of heterogeneous constrained resources (in terms of computing power, communication capacity, available storage volume, operating systems and availability);
(3) This model will then be instantiated in the building of an effective small-scale data center that unifies heterogeneity and allows for the implementation of a variety of information systems;
(4) Once the data-center is made available, it will be extensively tested on concrete cases to validate the approach taken;
(5) During all these steps, it will be important to produce relevant indicators to measure the direct and indirect environmental gains achieved;

The five steps are detailed further in the following sections.

5.1 Waste from Electrical and Electronic Equipment as Basic Building Blocks

We aim at building a SSDC-type infrastructure using only equipment that is considered to have reached end-of-life (EOL). As the project is taking place within the context of the authors' university, this will be the source all computing devices used.

5.1.1 University as Urban Mine. An urban mine is "*all the activities and processes involved in recovering the components, energy and elements from the products, buildings and waste generated by human activity in the urban environment*" [8]. In our context, we restrict ourselves to WEEE. Its purpose is to extract valuable elements through complex and energy-intensive recycling processes. In our case, we do not consider the extraction of rare-earth elements from WEEEs, it would not make sense in our approach to minimizing environmental impact (including energy consumption). We are ahead of the circular economy. Besides, we are at a higher level of abstraction, that of the functionalities offered by products at the EOL but which are still fully functional[16]. Our university, but more generally administrations and firms in the technology sector that still have on-premise resources, are abundant *mines of high-level functionalities.*

5.1.2 Subtracting from the Technosphere. It would have been very tempting to take the classic approach of innovation by *adding* new computing infrastructures (and new software developments). This dynamic of additive innovation could be a classic bias in science and technology even though, quoting [4] (bold typeface from the authors)

> *Defaulting to searches for* ***additive changes*** *may be one reason that people struggle to mitigate overburdened schedules, institutional red tape and* ***damaging effects on the planet***

In the remaining paragraphs of this article, we propose to consider an additional constraint, which is to *innovate by subtraction* [36][17] at both functional and hardware level. As we have seen, ICTs are

[14]LIFE means in french "*Longévité Informatique et Frugalité Écologique*" which translates to "*ICT Longevity and Ecological Frugality*".
[15]see H. Rosa's book [73] for a theory of *social acceleration*, which embraces the acceleration of technology, social change and pace of life.
[16]One might wonder why these systems are being discarded. As far as our university is concerned, this is the case when maintenance contracts expire, the equipment is no longer under warranty and the continuity of service requires the IT Department to renew it. There is also a fad or a display effect which, in some places, wants to renew equipment so that it is always up to date.
[17]Consistently, this reference points us back to the concepts of *attachment* and *detachment*, previously discussed in section 3.3 above.

dead technologies whose end of life will add to the large volumes of zombie equipment. It appears crucial to maintain existing infrastructures (and thus subtracting the arrival of new hardware) in the technosphere for as long as possible in order to delay their arrival in the biosphere. This conservation will also have the potential benefit of not producing new infrastructures and thus reducing their environmental impact.

In addition to this first subtraction, we propose a second subtraction in the form of the operation of the infrastructure under conditions of severe resource constraints. This point will be addressed later in the section 5.3.3.

5.1.3 Collecting the Parts. The large quantity of equipment available (the upgrade to Windows 11 alone will result in the disposal[18] of at least 150 workstations - roughly 10% of the managed fleet[19]), whether in terms of active equipment (storage, switches, routers, WiFi access-points, backup robots, etc.) or computing devices (desktop, laptop, servers, all-in-one devices, smartphones, single-board computers, etc.) makes the university become an *urban mine*.

Ironically, the main problem raised by this approach is not the collection of WEEE but rather the difficulty in dealing with the phenomenal quantity of equipment available and its temporary storage waiting to be used in the project (as well as storage for spare parts and maintenance supplies). Both the volume of resources available and the windfall effect that the use, not the disposal, of WEEE represents for the IT Department could very easily cause the project to expand from a small-scale to a large-scale project, in a classic rebound effect. It should be noted that, even though this would deplete the mine at use, the rebound effect could be eventually avoided if the small-scale were to replace the university's official large-scale infrastructure. But we are still a long way from that scenario!

5.2 A Theoretical Model of Adaptable System

The aim is to build a system that can be adapted to a wide variety of situations resulting from constraints external and internal to the system, according to the discussion in section 1 and 3.4: it is a dynamical system characterized by a state, which itself is the aggregation of the states of its elements. The state evolves according to the perturbation caused by variations of the constraints, reaching a new stable state within its viability domain. Figure 4 describes a situation of perturbation and return to equilibrium of the dynamical system.

Internal constraints are:

- computation availability of *kind* (CPU, GPU) from an *element* (desktop, laptop, server, smartphone running Android or iOS) for a certain type of *operation* (communication, storage, computing... resources),

[18]One could argue that there is a very simple technical solution to switch the entire system to this new version of Windows: install Linux and an hypervisor, then install Windows in this environment. But for organizational reasons of the IT Department, this has not been considered.

[19]Given the size of the university's computer fleet (which has around 45,000 students), one might be surprised at the low number of workstation changes caused by the switch to the latest version of Windows. In fact, the 10% in question only concerns machines that are directly managed by the central IT Department, and the reason for the low percentage is that the policy for renewing the stock is such that it is extremely up to date, with machines that will accept Windows 11. If the management of the stock involved maintaining older machines, the disposal rate would be much higher.

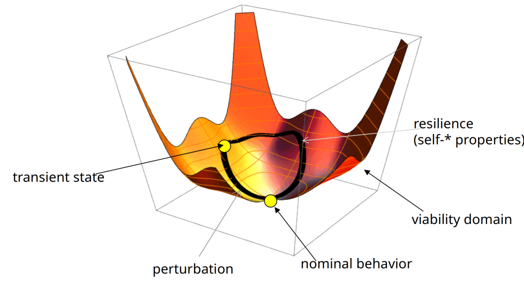

Figure 4: The small-scale data center seen as a self-adaptative dynamical system in 4 different states: its nominal behaviour when the system works as espected with all available resources; a perturbation coming from a change in the system, driven from an internal or an external constraint; the perturbation leads to a transient state and the self-adaption of the system to a new equilibirum within its viability domain.

- operational availability of hardware itself (elements may experiment failures, from the power supply to electronic elements on the motherboard, nic..., leading to the unavailability of the element for computing purposes).

while external constraints are:

- the energy available to enable the system to operate at various level (fully or partly),
- the addition (when a new element is avaible for the cluster) and removal (when a broken element has to be discarded from the cluster) of hardware elements to the data center.

To accomodate with our view of the data center as a dynamical system, we choose to follow the path lead out by IBM in 2001 with its *Autonomic Computing* manifesto [43, 47, 82] designed to address the software complexity crisis produced by applications that had become so large that it was no longer possible to control the systems on which they ran. IBM's proposal was to build systems that could manage themselves with given high-level objectives from administrators. A set of self-* properties were defined (self-optimization, self-configuration, self-diagnosis, self-healing, self-protecting...) ensuring the system's operational stability.

The design of these properties will be based on a formalism of MAPE-K loops where a feedback loop captures the state of the system and causes it to evolve according to rules. This loop consists of "[...] sub-components for Analysis of Monitored data, Planning response actions, Execution of these actions, all of them based on a Knowledge representation of the system under administration" [76]. These tasks are performed using informations gathered from *sensors* and produce a change in the system through *actuators*, see figure 5.

5.3 Putting the Pieces Together

The SSDC we want to build must fulfill several objectives, as described above: provide useful and robust services to the IT Department, operate on unreliable heterogeneous hardware, and continuously adapt to external and internal resource constraints. To achieve these objectives and in a consistent manner with our approach, we have chosen to use only free and open source software (FOSS), tools that are straightforward to deploy and have proven their reliability.

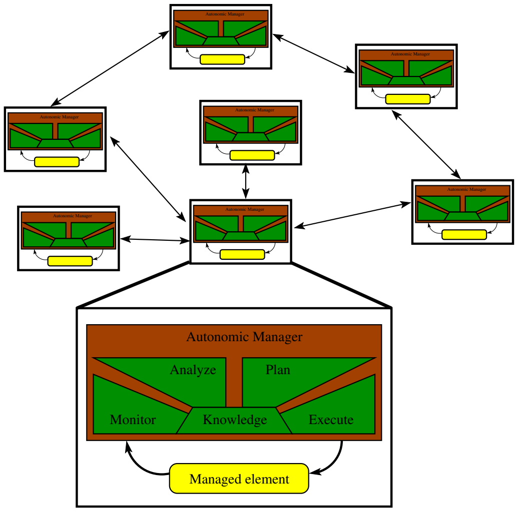

Figure 5: The structure of an autonomic element (below) where each element interact with other elements and with global guidelines via their autonomic managers (above). Each element has sensors and actuators allowing to make decisions based on its current state and the global state of the system. Picture redrawn from [47].

At the software level, the system should not require maintenance and operate as autonomously as possible, according to section 5.2.

For consistency, all computing elements – desktop, laptop, servers, smartphones, single-board... – will be referred to as *nodes*. If certain features are only available on certain devices (like a battery for smartphone), it will be specified each time.

5.3.1 Building an Adaptable Software Architecture. In order to test the adaptability and robustness of the architecture, we want to provide services of different types. To start with, we have identified usual services provided by the IT Deparment: a Mail Transfer Agent (MTA), a cross-platform file-hosting software system, a wiki farm, simple AI services[20] (some of the collected devices have GPUs[21] and the cluster will be used to conduct experiments in frugal machine learning as promoted at JRAF's conferences [92]) and high performance computing.

Smartphones. Smartphones are not a homogeneous class of computing devices. Within the Android-based smartphone category, there is a wide variety of architectures and ways to access the ROM: not all devices can be easily flashed with a new operating system. Here, heterogeneity is a source of significant problems for simply having a functional set of computing resources.

We envision three possibilities:

(1) smartphones on which a version of Linux like *postmarketOS* or *Ubuntu Touch* can be installed should be able to run the services as is[22];
(2) on those devices another option is by following [84] where micro-services are implemenented,
(3) and for devices where a Linux clone cannot be installed, a domain-specific framework similar to the *Berkeley Open Infrastructure for Network Computing* [14, 71] could be considered where tasks are sent to devices and results are aggregated in a backend.

These different systems will be able to provide facilities enabling the implementation of general services or specialized services such as data processing (as it was the case for the BOINC framework).

Smartphones have two other distinctive features: they have GPUs and batteries. The use of GPUs will enable testing of the suitability of simple AI projects, particularly in relation to energy efficiency since [48] showed that the power consumption of a mobile GPU is typically 2 orders of magnitude lower than its desktop version; battery management shall include control of charge and discharge cycles based on the energy available to the system. The presence of a battery will be a key factor to consider for the system's energy autonomy.

Regular Computing Devices. When it comes to nodes as regular computers (everything but smartphones), things are much simpler because there are many solutions available. We plan on using common tools:

(1) a Debian[23] distribution as Linux operating system;
(2) initial configuration using PXE[24] on the NIC together with DHCP and a TFTP server, SSH server and Ansible[25];
(3) virtualization using native Docker[26], ProxmoxVE[27], Kubernetes[28];
(4) backup using Proxmox Backup Server[29] and Restic[30] on RAID devices and a collected tape robot[31];
(5) monitoring with Prometheus[32] and Grafana[33].

Nothing fancy here, only battle-tested solutions.

Storage. A key element of any distributed computing project that requires a minimal level of robustness is data storage. To achieve this, we will rely on the infrastructure provided by Garage[34] [9] which provides all the desired features in an unreliable environment: "it's a lightweight geo-distributed data store that implements the Amazon S3 object storage protocol. It enables applications to store large blobs [...] in a redundant multi-node setting.". It is highly

[20]We do not wish to promote the development or even the use of AI, but we believe it is important to show that meaningful projects can be carried out in this field using older architectures and thereby show a path to cease the race for power in learning models. This sacrifice to current trends does not, of course, blind us to the environmental issues associated with this *large technical system*.
[21]Lonovo's ThinkStation S20 have Nvidia Quadro FX 580 cards, from 2009, with 512 MB of GPU memory. Its limited performance relative to current GPUs will provide an opportunity to test the limits of our approach.
[22]The Database of Digital Device lists a large number of smartphones and their alternative supported ROMs.
[23]https://www.debian.org/index.fr.html
[24]https://wiki.debian.org/PXEBootInstall
[25]https://docs.ansible.com/
[26]https://www.docker.com/
[27]https://www.proxmox.com/en/
[28]https://kubernetes.io/
[29]https://www.proxmox.com/en/products/proxmox-backup-server/overview
[30]https://restic.net/
[31]An Overland Storage NEO 2000e from 2013, see https://support.bull.com/ols/product/storage/lib/overland/lxn-neo-e/neoe2k4k.
[32]https://prometheus.io/
[33]https://grafana.com/grafana/
[34]A presentation is available at FOSDEM's 2025 edition.

resilient to network failures, network latency, disk failures, and sysadmin failures, all very likely events in our project.

Networking. To ensure maximum network robustness, redundancy will be implemented using a pair of refurbished 48 ports Avaya Nortel 4548GT-PWR switches[35]. The nodes will be connected differently depending on their type:

- Smartphones: they have two (actually three, but we do not consider cellular here) distinct means of communication, wireless and Ethernet connection via USB port. While wireless could be a fallback solution in case of network failure, a USB port connection is preferable as [60] have shown significant limits to the use of wireless.
- Non-smartphones: depending on the number of network cards on each node, they will be connected to one or both switches to ensure redundancy in the event of a malfunction (of the switch or node). Nodes with only one network card will be distributed across each switch. The failover from one subnet to another will be automatic.

A degraded operating scenario in which switches no longer function will take into account the construction of a point-to-point mesh network [45]. This infrastructure will enable the implementation of the *amorphous computing* model discussed below.

5.3.2 *Coupling Heterogeneous Systems for Robustness and Autonomic Computing.*

While the use of smartphones (mainly Android-based) or used computers for cluster computing is nothing new [16], their heterogeneity (all work seen so far only deal with one smartphone model, mainly Fairphones) and simultaneous use, taking into account adaptability and maximized autonomy, presents a number of challenges. The dynamic addition and removal of resources is one of the main constraints. Since the system must enforce self-* properties, it will be necessary to

(1) identify the capabilities (computing power, memory, bandwidth, etc.) available for each device;
(2) calculate an *efficiency* for each device in the form of a ratio *computing power* by *energy consumed* (in the form of mips and mflop per joule);
(3) map and schedule the tasks (ranging from high-level tools like an MTA to low-level data crunching in the form of micro-services) in order to maximize the use of computing resource with respect to available energy.

Implementing the autonomic manager described in figure 5 of section 5.2 requires local monitoring at the device level as well as globally. Initially, centralized monitoring (with redundancy) will be implemented to closely track the system's operation. Since the failure of a component may happen at anytime, devices will be continuously monitored by a watchdog mechanism, which will trigger, if required, a rebalancing of available resources. In a second phase, a decentralized task orchestration mechanism will be implemented to meet the autonomy and adaptability requirements. Moreover, a large amount of work has been done on self-repair strategies for autonomous systems based on FPGAs that could be of interest [77].

A direction we would like to explore is related to the *Amorphous Computing* (AC) project [3]. AC aimed at solving problems using a large set of simple and unreliable computing devices with very limited communication capabilities and only local interactions. These devices could break down at any moment, but this should not affect the current computation. While many low-level algorithms have been defined using the principles of AC we believe that the works in that field should help us design, at a higher level of abstraction, the behaviour of the SSDC in a severely degraded mode where the only possible communications are peer-to-peer and only low-level functions can be performed.

5.3.3 *Ensuring Optimal Functionality Under Energy Constraints.*

The energy required to operate the system (the boundary of the system is considered to be the connection to the network of the entity hosting the data center, here our university) will come from potentially multiple sources: the electrical grid, uninterruptible power supply, and renewable energy sources such as photovoltaic panels (we already have collected *uninterruptible power supply* (UPS) and only second-hand *photovoltaic panels* (PV) will be considered). When *variable renewable energy* is considered, two types of problems arise: how to manage variations in energy availability *at the node level* and *at the whole system* level.

Variable Renewable Energy at the Node Level. At the node level, the intermittent nature of energy availability has to be taken into account, as this is an external constraint on the system that will determine its availability. There is a significant literature on this topic, which is based primarily on two approaches: at the node level, a decomposition of the application into tasks, after which a backup of the system state is made, or the insertion of checkpoints into the application [11, 12, 93]. Both approaches will be considered depending on the nature of the services offered to the users.

Another approach being considered is the one developed as part of the SIRIUS[36] educational project: depending on resource constraints, an application is dynamically stripped of features to reduce its consumption. This approach requires questioning the purpose of each function served, its importance, and the possibility of making it temporarily (or permanently) unavailable. This is a concrete example of what was outlined in the questions on the reintroduction of limits in section 4.1, more precisely, an *ecology of functionality*.

Variable Renewable Energy at the Whole System Level. At the system level, fine-tuned management of energy availability will require predictive analysis based on weather forecasts in order to anticipate energy availability cycles. This anticipation, combined with the energy profiles of nodes and tasks, will make it possible to anticipate system availability (that is, which nodes are up) but will require selecting which functions will be unavailable (between the MTA and the AI application that analyzes data, which one should

[35]The university has a very large number of these switches, which are currently being replaced with newer versions following a change of the backbone network. All models are yet fully functional, the previous backbone was not congested with low latencies and only a low percentage of used bandwidth, but various local socio-technical constraints led to this choice.

[36]That translates into *Resilient, Useful, and Sober Information System*, a project developed in an engineering school to take into account the highly probable scarcity of resources in the near future and the control of the rebound effect, in a nutshell, "*computing within limits*".

be shut down?[37]). This could be done using classical multi-objective optimization.

Another way to address the problem is to keep only the most sober nodes – for this notion see section 5.5 on the impacts below – and move applications that are considered a priority to these nodes, if they are compatible. Indeed, some nodes like smartphones cannot handle all types of activity.

Variable Renewable Energy with Smartphones. As stated in section 5.3.1, smartphones having batteries means that they have both an additional source of energy available and that the available energy must be anticipated: in situations of energy shortage, we can imagine that the system would operate solely on the energy available to smartphones (at the risk of reduced performance [23]), but then only tasks eligible on these devices could be considered, conserving the scarce energy available for system administration (data collection, routing, orchestration...). Furthermore, smartphone batteries could also be used as a supplement to UPSs in a similar way to the *vehicle to grid* [87] technology, allowing bidirectional energy exchange between electric vehicles and the power grid. This would be a scaling-up of what is already possible using one smartphone as an induction charger for another device (many smartphones already have this possibility using the Qi standard). Here, the whole system would be powered by energy available in smartphone batteries (and we may even dare to dream that one day, institutions such as universities will have their own smart-grid, with PV panels and distributed management of energy production and consumption).

5.4 Robustness

The robustness of the SSDC will be a key element of the project to validate its ability to adapt to faulty nodes, intermittent power supply, while still providing meaningful services. As adaptability is more important than efficiency, particular care will be taken to ensure minimum operation, even in severely degraded conditions, as outlined in the previous sections. Whether through the use of uninterruptible power supplies and/or smartphones, or mesh network operation in AC mode, we shall be able to test the resilience of the system and the ability of the dynamical system to reach a stable state and return to a new stable state after a major system disruption.

Heat generated by the SSDC has to be taken into account. Smartphones are not a problem because they are designed not to heat up beyond a certain threshold, which, if exceeded, causes the smartphone to shut down. Furthermore, the heat generated is very low and a regular fan is sufficient to maintain an operating temperature [84, page 405] for over a hundred smartphones. The situation will be different for network equipment and servers. To this end, we are working with facilities management and ancillary services to study how to use the heat produced to heat buildings (in cold seasons) and how to make positive use of the heat produced in the hot seasons. Of course, excessive temperatures will have to be taken into account in order to shut down part (or all) of the SSDC if necessary.

[37]This seemingly mundane question will be at the heart of future debates when resources become scarce and choices must be made about what to keep and what to abandon or *close*, to use A. Monnin's terminology, see section 3 and [15].

The use of WEEE will probably lead to a large number of failures[38] that will need to be evaluated to establish the relevance and sustainability of the approach. However, these failures should be offset by the very large number of machines available, as long as the failure rate relative to available stock remains favorable. Robustness also refers to the system's ability to meet its commitments to reduce environmental impact, a point that is discussed in the following section.

It will also be necessary to continue discussions with the IT Department on the relevance of working with WEEE. Many French institutions (universities, hospitals, etc.) have been the target of hacking attacks that have shut down their IT systems. The SSDC could also be a solution to this type of situation, where minimum services need to be quickly restored while the information system is being repaired (which generally takes several months).

5.5 Assessing the Impacts

To determine whether our approach to a significant reduction in the impact of a SSDC, we need to assess both the impact of setting up and using the data center and the impact of what has been avoided by using it. We consider potential gains coming from three sources:

(1) equipment that was not purchased due to the extended use of existing equipment,
(2) increased efficiency through the additional use of specific devices (that is, smartphones) or the first life of the node,
(3) a reduction in the number and use of computing devices through a change in mindset that embraces digital frugality.

We review these gains which ultimately appear artificially distinct because they are so intertwined.

5.5.1 Unpurchased Equipment. We want to compare the following two situations: a subset of the IT Department's digital infrastructure that provides certain services and the SSDC that implements these very same services (for example those identified in section 5.3.1). First, a precise inventory of the IT Department's digital equipment must be carried out and the target services identified. Next, a life-cycle assessment[39] (LCA) must be carried out, for each service X, with functional unit "*provide service X for Y users over Z months*" on the IT Department's equipment and on the SSDC. We consider following the methodology of [79].

A quick analysis of the situation supports our belief that the SSDC should have a lower impact. While the increased efficiency of newly bought infrastructures to replace older devices is beyond doubt (see section 2.1), it appears, however, that according to [68], the environmental impact (in terms of energy, carbon footprint, and water) for integrated circuits was not significantly reduced in the 1980-2010 period[40]. In fact, for the SSDC, all phases prior to its use phase will be allocated to the IT Department (the equipment was purchased and used in the first phase of its life), and only the second use phase will be allocated to the SSDC (after an initial use phase

[38]This may well not be the case given the age of the machines collected, some of which date back to 2009 and are still in perfect working order. Maintenance of these machines will also be planned, as breakdowns are often due to a malfunctioning capacitor on the motherboard, which is easily replaceable.
[39]The reader not familiar with the concepts of LCA should consider reading [52] for a very good introduction to the matter, applied to digital devices.
[40]Meanwhile, the total silicon area produced grew by 3.6% per year, leading the authors to call for sobriety.

of approximately 5 to 7 years). Furthermore, given the electrical mix in France where the project takes place is very low-carbon intensive[41] the GHG impact should be minimal.

5.5.2 Increased Efficiency. For the smartphone part of the SSDC, the authors of [84] define *Computational Carbon Intensity* (CCI) as a ratio of GHG production (manufacturing phase + use phase) and computation. While this measure highly depends on the electricity mix used to power the devices and their lifespan, a smartphone-based system is 9.8 to 18.9 times more CCI efficient, after 3 years of use, depending on the nature of the application. Due to the first life of the node, this measure will also be very favorable for conventional computers.

CCI is a very good metric for the project, and we propose to extend it to take into account all the impacts revealed by a life cycle analysis – the 17 ReCiPe 2016 Midpoint (H) categories – and to adapt its calculation to take into account the first life phase of the node used in the SSDC.

5.5.3 Digital Frugality. An important side effect of increasing the lifespan of equipment is that it free up financial resources that can be reallocated to other areas, such as social programs, improving student life, building accomodations, insulating buildings... and possibly closing (or re-shaping) courses considered to be negative commons. One could even imagine a positive feedback loop that would lead university teaching and services to use fewer IT resources, thereby reducing the use of the SSDC itself, paving the way toward frugality.

6 Related Work and Concerns

6.1 Related Work

6.1.1 On a Technical Side. There is a large number of works, some of them old and others more recent, on related issues. Among these, the interested reader may wish to look at the following works: when it comes to computing with the least possible energy [25]; grid computing on mobile devices [6, 14, 44, 94, 96]; intermittently available energy [51, 70]; using virtual machines to overcome closed architectures [14]; mobiles devices as computing devices and edge-computing [23, 42, 67, 81, 84] or using microservices to access resources [33]; AI on smartphones [50] using Kubernetes and TensorFlow, using OpenMPI [60].

Several recent studies are moving in a similar direction to ours, at a smaller scale. The work of [83] explores strategies for degrowth and energy autarky using solar panels and supercapacitors to store energy for computing devices. The work by [84], already mentioned several times focuses exclusively on identical smartphones of the same model-year. We included smartphones in our approach (because we aim at dealing with heterogeneity and there is a massive amount of home-stored but unused smartphones), but due to the specific nature of our urban mine, not only do we have a lot of diversity among the collected devices, but they are also not the main resource at our disposal. However, as part of the European Week for Waste Reduction, we organized a campaign to collect used smartphones.

[41] According to ElectricityMaps, at the time of writing, in 2025, April the 30th, about 28 CO2eq/kWh.

6.1.2 Broadening the Discussion. The approach proposed by [24, 78] is particularly interesting since it combines equipment whose lifespan have been extended and use photovoltaic panels as source of energy in an edge-computing model. There is an added twist: hosted virtual machines migrate according to the availability of solar energy, which itself circulates between data centers. This combined approach could be adapted to a university campus such as ours, which covers more than 80 km from north to south (at least in terms of VM traffic, as solar energy is local)[42].

In an academic setting, the approach of [7] aims, through the RECLUSTER project, to re-internalize their cloud services, regain control of the infrastructure, use FOSS, and reduce WEEE by reusing equipment that was left on shelves and no longer in use. This means that control over tools is regained, less resource-intensive software can be used, and big tech services can be set aside. Ultimately, self-hosting allows to return to a situation similar to what universities were like before the outsourcing movement. We did not include their concern about the desire to reinternalize the services that universities have outsourced because this is not where our project originates. It seemed to us that the reasons given in section 1 and more specifically in section 2.4 call for a drastic change in the way we view and use computing architectures and WEEE. However, we fully agree with the authors' proposal and endorse their approach.

6.2 Related Concerns

What sets the LIFE project apart from all these approaches is its origin, which stems from a deep frustration at being part of the problem (both in terms of the transmission of IT knowledge and the use of computing resources). Without looking the other way, we felt it was necessary to come up with a way of maintaining services with the lowest possible impact, which could eventually be reduced to zero, if needed. Technically, we propose using heterogeneous, unreliable hardware[43] (including smartphones, computers, and active equipment) and unreliable storage media, which allows us to provide services intermittently, potentially reducing functionality, while remaining adaptable and composed entirely of WEEE.

6.2.1 Computing Meets Low-Tech. The low-tech community considers that placing ICT and low-tech in the same sentence is an oxymoron [13, 55]. Without getting into the controversy over whether digital technologies can(not) be low-tech, it can be seen that the properties that we want in our system share common points with those of low-techs. Low-tech [5] advocate for (we only keep the properties what our project shares with low-techs):

- *sustainability* with a low environmental impact and a reduced consumption on resources;
- *autonomization* by reducing interdependencies;
- *locality* by reducing resource pressure;
- *accessibility* by favoring robustness, cost-efficient system with an increased longevity.

It is comforting to see that the project we are proposing is in line with the low-tech movement, which places frugality and sustainability at the heart of its approach.

[42] But in a way, it breaks down our wish to bring back limits in time/space and discontinuity in 4.1. This should be investigated.

[43] We clearly are in the category of *hardware sufficiency* as defined in [80].

6.2.2 *Inverse Legacy Problem.*

Among the equipment collected, we have a few *Lenovo ThinkStation S20 model 4157* servers[44]. These servers are from 2009 and have Intel Xeon X3503 Microprocessors CPUs with Nehalem architecture. This architecture predates the Sandy Bridge architecture [74] released in 2011, and does not have RAPL instructions for estimating CPU consumption [63]. Although fully functional, these computers will not be able to execute code involving this instruction set. The situation is similar for the operating system, where there is no guarantee that Linux (in our case) will continue to include drivers for (very) old machines.

This situation raises the opposite problem of *legacy systems* that need to run older software on newer architectures (including CPUs, operating systems, and libraries). Here, the goal is to ensure that *newer code can continue to run on older hardware*, it's an essential requirement of the project. To our knowledge, this issue has never been addressed before even though it will become increasingly crucial in the coming decades. We propose to call this situation the *inverse legacy problem*[45].

6.3 Conclusion

This work has been guided by the twofold concern of an increasingly dramatic environmental situation and, at the same time, the need to provide computing resources for a society strongly attached to digital technology. We established that digital technology's current contribution to aggravating environmental issues was not compatible with the Paris agreement, and that recycling could not address the constraints linked to the reduced availability of resources. To find a suitable path through this set of constraints, we called upon the concepts of *negative commons*, *zombie technology*, *attachments/de-attachments/re-attachments*, and advocated the emergence of *adaptable* and *limited digital technologies*.

We have sketched out a project that will *never become old-fashioned*, because it is already old-fashioned *by design*, based on building blocks made entirely of WEEE from our urban mine at hand. The small data-center under construction, modeled as an autonomous dynamic system, will be powered by renewable energy. A study of the reductions achieved in terms of the system's environmental impact should validate the approach.

We'd like to conclude with a plea for research on digital technologies that takes the notion of planetary boundaries very seriously, avoiding their aggravation; that explores neglected research trajectories; that prioritizes robustness and adaptability over performance; that changes our perspective on waste; that questions our imaginations; and that places digital technologies at the center of the political debate. Only then will we be able to begin the process of digital degrowth, which we believe to be necessary.

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[44] https://pcsupport.lenovo.com/ec/fr/products/workstations/thinkstation-s-series-workstations/thinkstation-s20

[45] This notion differs from *regular obsolescence* in that it is a forward looking movement of unsupported technology, whereas inverse legacy is a backward-facing movement of unsupported technology.

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