Modeling the digital sector's production system: a timely & interdisciplinary endeavour

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1 Introduction

Global investment in data centers has doubled since 2022 [1]: almost all sectors of human activity are undergoing a digital transition. At the same time, the digital sector—like many others—is going through an energy transition: its actors massively invest [2] in so-called carbon-free energy sources (*e. g.* wind and solar) to limit greenhouse gas (GHG) emissions and mitigate climate change [3]. While the ecological transition is inexorable for the long-term viability of human life, the digital transition mostly reflects our everlasting pursuit of performance and efficiency.

Still, the digital transition needs scrutiny, because digital technologies are material, being entirely made out of electronics and energy supply. The expansion of the digital sector imposes the continuous construction and renewal of material infrastructures—*e. g.* data centers, electricity generation, storage, and distribution systems—which, in turn, impose a daunting pressure on primary resources: water, energy sources, and a vast and diverse intake of mineral elements [4].

Numerous studies have examined the climate impacts of the digital sector [5], yet few have investigated its other negative externalities—such as water and soil pollution, biodiversity loss, or land artificialization—and even fewer have assessed these impacts holistically [6]. Positive externalities are often promised, such as productivity gains from Artificial Intelligence (AI), but such benefits are particularly difficult to anticipate. More broadly, most anthropogenic intervention projects—whether public policies, technological innovations, process reforms, or behavioral changes—lack robust methods for predicting their eco-social consequences at the design stage.

2 To grasp the digital production system

The energy and digital transitions are engaged in a vicious spiral or positive feedback loop: carbon-free energy increasingly resorts to digital steering to overcome the intermittence of offer & demand, the digital sector keeps adding energy-intensive datacenters to its infrastructures. Both transitions offer undeniable benefits——such as the decarbonation of transportation, or the efficiency gains of digitalisation——but there is no such thing as a free lunch [7]: these benefits come at significant environmental and material costs. It is particularly important to focus on the digital transition, and therefore on the digital sector, which is currently experiencing uncontrolled growth. Digital technologies are becoming pervasive and a requisite across nearly all domains of activity, with an especially short time between service inception and global market adoption—for instance, in the case of the Vinted clothing resale platform [8] or of AI [9]. However, uncontrolled growth inevitably leads to uncontrolled environmental impacts. Environmental assessments of digital technologies consistently warn about their rapidly expanding footprint [5, 10–12], despite the assessors' acknowledged over-optimism: the French ADEME [11] and Shift Project [12] have both admitted that they had underestimated the digital sector's environmental impacts and overestimated its efficiency gains.

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In 2027, 3.9 trillion dollars are expected to be invested globally in the digital transition, nearly twice the 2.5 trillion that were invested in 2024 [13]. These expenditures are accompanied by bold promises, but it is not an easy task to measure precisely the tangible benefits. Moreover, our dependency on the digital production system is increasing, while this system exhibits more and more worrying single points of failure [10]. For instance, ASML is the sole producer of angstrom-precision lithography machines, TSMC nearly the only manufacturer of AI-compatible chips, China concentrates the majority of the market of critical minerals that are needed by both the energy and digital sectors. This concentration is closely linked to the opacity of global supply chains. The level of secrecy is such that the precise composition of devices like smartphones can only be determined by physically dismantling and spectrographically analyzing them component by component [9, 14]. Such analyses reveal that in 2020, smartphones contained more than 50 chemical elements, including many critical minerals [14].

In fact, the entire digital transition (as well as the ecological transition) depends on the continued extraction of a wide range of minerals [4], whose declining availability raises the risk of resource depletion [6, 15]. If current trends persist—and even accounting for possible advances in recycling decommissioned equipment—by 2055 we will have to extract as many minerals as humanity has mined throughout its entire history [15]. Concentration processes, which are particularly intensive in electronics manufacturing [10], cause lasting pollution and threaten ecosystems, biodiversity, and local communities [16]. Traditional environmental assessments struggle to fully capture these mineral-related impacts. Life Cycle Assessment (LCA), for example, relies on a scalar metric—the so-called antimony equivalent (eqSb)—yet the diversity of extraction processes (both between different minerals and across concentration stages) leads to highly heterogeneous impacts [10]. Furthermore, the environmental impacts of more than half of the world's mines remain undocumented [17].

3 Towards a systemic approach

Life Cycle Assessment (LCA) is currently the prevalent benchmark accounting methodology for assessing environmental impacts [5, 18], but its reductionist, retrospective, and quantitative approach makes it unsuitable for prospective, multi-criteria, and qualitative analysis. It fails to capture all the interactions between the different sectors. Our current tools are too isolated to capture the whole problem. The systemic method makes it possible to model the future evolution of an intervention in a complex system, based on a limited number of assumptions and without exhaustive accounting. The Meadows report [19] is an emblematic example of economic growth modeling; its projections are praised for their accuracy despite the simplicity of its assumptions.

Systemic analysis as a prospective tool [20] is particularly useful for qualitatively describing the dynamics and predicting the impacts of interventions on the socioeconomic system. It could capture the interactions of the production system: the interaction between digital and ecological transitions, and their mineral dependencies [4]. Recent works show its applicability as a strategic decision aid, able to display rebound effects [21]. With such a tool, one could anticipate the ecosocial consequences of large investments in the digital production system, or critical resources supply disruption.

4 Conclusion

Understanding and designing the digital sector's production system is an exciting project, yet not an easy task. The stakes are multiple as we need to understand how primary resources are acquired, the fabrication process of the electronics components, the infrastructure organisations, the usages of the digital services & their social consequences, the behaviours of agents and their economic and geopolitical relationships... Hence, this work can only be done following an interdisciplinary approach, by combining economic, sociological, geopolitical and technical knowledge fields. Thus, we come with the following question for our audience: **How can we best model the role and interactions of the digital sector in order to visualize and predict its holistic environmental and social impacts?**

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