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Donati, F.; Dente, S.M.R.; Li, C.; Vilaysouk, X.; Froemelt, A.; Nishant, R.; ... ; Hashimoto, S.

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The future of artificial intelligence in the context of industrial ecology

Franco Donati^{1,2}  | Sébastien M. R. Dente³  | Chen Li¹  | Xaysackda Vilaysouk³ |
 Andreas Froemelt^{4,5}  | Rohit Nishant⁶  | Gang Liu⁷  | Arnold Tukker^{1,8}  |
 Seiji Hashimoto³

¹Institute of Environmental Sciences (CML),
 Department of Industrial Ecology, Leiden
 University, Leiden, The Netherlands

²Science for Democracy, Rue d'Arlon, Brussels,
 Belgium

³College of Science and Engineering,
 Ritsumeikan University, Shiga, Japan

⁴Swiss Federal Institute of Aquatic Science and
 Technology, Eawag, Dübendorf, Switzerland

⁵Chair of Ecological Systems Design, Institute
 of Environmental Engineering, ETH Zurich,
 Zurich, Switzerland

⁶Faculty of Business Administration,
 Université Laval, Quebec City, Canada

⁷DU Life Cycle Engineering, Department of
 Green Technology, University of Southern
 Denmark, Odense, Denmark

⁸Netherlands Organization for Applied
 Scientific Research TNO, DA Den Haag,
 Netherlands

Correspondence

Sébastien M. R. Dente, College of Science and
 Engineering, Ritsumeikan University, Shiga,
 Japan.
 Email: sdente@fc.ritsumei.ac.jp

Franco Donati, Institute of Environmental
 Sciences (CML), Department of Industrial
 Ecology, Leiden University, Leiden, The
 Netherlands.
 Email: f.donati@cml.leidenuniv.nl

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 Majeau-Bettez

Abstract

Artificial intelligence (AI) applications and digital technologies (DTs) are increasingly present in the daily lives of citizens, in cities and in industries. These developments generate large amounts of data and enhance analytical capabilities that could benefit the industrial ecology (IE) community and sustainability research in general. With this communication, we would like to address some of the opportunities, challenges, and next steps that could be undertaken by the industrial ecology community in this realm. This article is an adapted summary of the discussion held by experts in industrial ecology, AI, and sustainability during the 2021 Industrial Ecology Day conference session titled "The Future of Artificial Intelligence in the Context of Industrial Ecology." In brief, building on previous studies and communications, we advise the industrial ecology community to: (1) create internal committees and working groups to monitor and coordinate AI applications within and outside the community; (2) promote and ensure transdisciplinary efforts; (3) determine optimal infrastructure and governance of AI for IE to minimize undesired effects; and (4) act on effective representation and on reduction of digital divides.

KEYWORDS

artificial intelligence, data, digital technologies, industrial ecology, interdisciplinary research, sustainability

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1 | INTRODUCTION

The increasing diffusion of artificial intelligence (AI) applications, such as machine learning, expert systems, computer vision, along with the rapid expansion of digital technologies (DTs) for data collection, storage, and consumption, is providing society with an unprecedented capacity to generate insights into how to improve the quality of life and the environment (UNSGHL, 2019). These developments, often referred to as the fourth industrial revolution (Combes et al., 2018), provide opportunities to improve the sustainability of society's production and consumption system and its governance (Nishant et al., 2020).

While a commonly shared definition of AI remains in many cases evasive (Frolov et al., 2021), in this paper we define it as software employing methods and models aimed at emulating or exceeding humans' intelligence and ability to accomplish given tasks of different levels of complexity (Ertel, 2017; Frolov et al., 2021; Negnevitsky, 2011). Applications of AI span across the following fields (Russell & Norvig, 2010): Natural language processing; knowledge representation; automated reasoning; machine learning; computer vision; and robotics.

However effective AI methods may be, they rely on good-quality data to provide good-quality insights. As such, it is paramount to discuss the potential of AI in industrial ecology (IE) in combination with data processed to generate insights. Data can come from a variety of sources using traditional quantitative and qualitative data collection methods such as surveys, interviews, and so on; but also, from sensors spread across society and a variety of applications. In this article, we also refer to global digital infrastructure as the global network of interconnected DTs such as information and communication technologies (ICT) for the purpose of collecting, storing, and consuming data from a multitude of sources (e.g., statistical offices and organizations, remote sensing technologies such as satellite data, smart devices, and sensors for the Internet-of-Things, smart cities and industries, and many others).

Since its foundation, IE has provided tools and knowledge to support the sustainable management of resources and environmental impacts and investigate the unintended consequences of human activities (Ayres & Ayres, 2002). The increasing use of AI and the expansion of DTs present great opportunities, but also challenges for the IE community. The scientific and societal role of IE could be strengthened by increasing the timeliness, details, and insightfulness of policy recommendations designed to tackle the great environmental challenges of our time. For example, Luque et al. (2020) argued that industrial sensing technologies could be combined with life cycle assessment (LCA) and machine learning to provide real-time environmental monitoring and improvement of industrial operations. Rolnick et al. (2019) presented ways in which machine learning could be employed to tackle climate change for 13 domains from the electricity system to education and finance.

There are, however, challenges in the development of a global digital infrastructure and the use of AI for sustainability. For example, Xu et al. (2015) indicated that while big data obtained from DTs could offer new data and opportunities for analytical techniques enabling IE to develop more realistic complex system models based on the capture of the "temporal, spatial and demographic heterogeneity of industrial systems," we should be aware that "bigger data is not always better data." Similarly, bigger and more complex models resulting from the use of AI may not always be preferable or better than simpler ones. In fact, they may prove difficult to understand and explain or may require substantial resources (i.e., energy and materials) (Lottick et al., 2019). Additionally, they could perpetrate societal biases and unfair allocation of resources, or have economic barriers causing unequal access to information and enjoyment of its benefits through society. They could cause systemic cascading shocks due to failures of nested and decentralized AI systems, or the promotion of unsustainable practices that prioritize few objectives over the overall spectrum of sustainability (Galaz et al., 2021).

The recent (2022) special issue of *Data Innovation* in the *Journal of Industrial Ecology* addresses multiple of these questions with special attention to opportunities (Majeau-Bettez et al., 2022), and similar efforts are also addressed in other disciplines under the environmental science umbrella (Hsieh, 2022; McGovern et al., 2022; Rolnick et al., 2019). The present article builds on these efforts and summarizes the seminar discussion on "The Future of Artificial Intelligence (AI) in the Context of Industrial Ecology (IE)," which took place on June 21, 2021, during the Industrial Ecology Day (ISIE, 2021). Based on this knowledge, we propose a vision for the role of AI and DTs in the future of IE. This article contextualizes the opportunities and challenges and indicates the next steps to be taken by the IE community.

2 | ENVISIONING THE ROLE OF AI IN IE

The diffusion of AI can greatly benefit the IE field by strengthening its capacity of mapping flows and stocks of materials and energy across society and identifying solutions to reach society's sustainability goals. We divide the IE community work into descriptive and prescriptive, where the former concerns the analysis of current and past factors and trends of societies' economic and environmental flows and stocks, while the latter is the analysis of possible and alternative future scenarios based on this accounting and other factors.

In recent years, descriptive efforts have taken advantage of remote sensing and geographic information systems (GIS) to reach a higher level of spatio-temporal details of material flows and stock (Corea, 2019; Haberl et al., 2021; Peled & Fishman, 2021). Froemelt et al. (2020) used machine learning to combine remote sensing and GIS-data with household budget surveys and agent-based models to develop a spatially resolved large-scale bottom-up model that is able to derive highly detailed environmental profiles for individual households. Techniques of text mining, mode and image recognition (e.g., Google Street View), and analysis of nighttime lights from satellite images can allow a high-resolution capture of material types

and volumes in the built environment (Arbabi et al., 2022; Mesta et al., 2019). Additionally, the expansion of *Open & Agile Smart Cities* is providing additional information through sensing technologies (Degbelo et al., 2016; Open & Agile Smart Cities, n.d.). Some of these data are also available in data marketplaces such as *Fiware* (Cirillo et al., 2019) and European Union Data Portal ("Datasets—Data.Europa.Eu," n.d.) and others may also arise. These data sources could be used with AI methods such as computer vision techniques to infer additional information about the built environment, transport modality, emissions, and biodiversity in cities (Ibrahim et al., 2020).

Direct data collection could be strengthened by the expansion of DTs in industrial operations. Better data could then be used directly to assess and monitor the environmental performance of supply chains by connecting it to LCA (Luque et al., 2020). However, this is only possible if relationships between IE practitioners and industrial actors have been established. Where such privileged relationship is missing, industrial ecologists could rely on simulation tools and support the development of digital twins. Digital twins are "digital replications of living as well as nonliving entities" (El Saddik, 2018) such as in digital twins of the earth system (Bauer et al., 2021), of the built environment (Ketzler et al., 2020), and industrial activities.

While data collection through DTs is of great importance, the community cannot have the expectation of being able to collect all possible data. In fact, this may not even be desirable, practical, or even feasible given the material requirements of DTs and concerns of data protection. For this purpose, estimation through machine learning and data mining techniques could be useful. For example, there are opportunities to be investigated in the conversion of domain-specific data into data useful for life cycle inventories, as shown by Mittal et al. (2018) in the use of data mining to convert industrial process databases in data useful for LCI. Zhao et al. (2021) show how unit process data can also be estimated using machine learning. Such developments could not only benefit LCA but also input-output databases in mapping activities and products as well as their environmental extensions. Some authors have also started using these approaches to estimate missing data in impact categories for life cycle impact assessment starting from diverse national databases (Cashman et al., 2016). The use of these approaches should be encouraged and supported, as they reduce dependency on data requests from industrial actors.

Such approaches in data collection and estimation, as well as model creation, could then be instrumental for prescriptive efforts in the implementation of sustainability solutions. The prescriptive efforts of IE concern the prognostication of the impacts of future policies and technologies for sustainability. For example, AI can facilitate a better comprehension of households' consumption and environmental impacts by linking diverse data sources and submodels (physically based, agent-based, and data-driven approaches) (Froemelt et al., 2018, 2020, 2021), which can then be combined with top-down input-output models to investigate system-wide effects of demand-side sustainability solutions (Froemelt et al., 2021). It could also provide more effective energy load levelization by combining AI with energy models and shedding light on additional factors affecting new energy systems (Zahraee et al., 2016). It could also check the validity of recommendations and optimize them against multiple values (e.g., social and environmental performance). Furthermore, intelligent systems embedded in consumer products and services could help avoid undesired effects of novel technologies, rebound effects, or problem shifting, by supporting consumers toward the adoption of sustainable lifestyles or embedding sustainable management systems within a given technology.

More generally, AI can help society in designing targeted and more timely policies that take multiple values into consideration and optimize them to reduce unintended consequences. Such a holistic viewpoint has been at the core of methodologies developed by the IE community, for example, in LCA. To this end, multivariate assessment and optimization of current systems and future solutions could be instrumental to avoid political and technological interventions where mitigation of ecological issues in one part of the supply chain simply shifts problems toward other parts, negatively affecting other desired outcomes. While IE methods such as LCA, material flow analysis, and environmental input-output analysis have played core roles in detecting problem shifting, the combination of IE methods with AI and DTs could achieve unparalleled spatio-temporal granularity and make results more meaningful for scientists and policymakers at different levels.

The severity of many social and environmental impacts depends on time and place of emissions or resource extraction. For example, companies are rapidly expanding data collection along their supply chains thanks to embedded tracking technologies. As they assess their operations, environmental impacts and the well-being of workers could also be quantified. This data could then be used to support their decision support systems to reduce socio-economic and environmental risks (Alavi et al., 2021) and improve their operations. In this context, AI in combination with IE methodologies can help the business community create new sustainable business models answering the social-economic and environmental challenges of our times.

3 | CHALLENGES

In this study, we identified three main challenges:

- Resource requirements
- Data accessibility and governance
- Explainability, interpretability, and causality

3.1 | Resource requirements

Industrial ecologists have an active lead in assessing the energy and material flows and stocks embodied in products and infrastructures, and their environmental impacts. The tremendous insight generation of DTs and the use of AI require energy and materials that could exacerbate environmental pressures. For example, AI models have known issues of high energy consumption, which are also projected to grow beyond 2% of the world energy consumption (Lacoste et al., 2019; Lottick et al., 2019; Strubell et al., 2019). For this reason, tools have been developed to assess the carbon intensity of models (Schmidt et al., 2022),^{1,2} which should accompany other efficiency and typical metrics (e.g., accuracy and robustness) as a push toward yielding “novel results without increasing computational cost, and ideally reducing it” (i.e., Green AI) (Schwartz et al., 2019). Additionally, the resource consumption of DTs has also environmental impacts of its own, so it is important to mitigate burden shifting across environmental areas of concern (e.g., from resource depletion to climate change). In this regard, attention should be given to: (1) containing the need for large graphical process unit (GPU) clusters; (2) mitigating excessive dispersion of sensing technologies for monitoring; and (3) avoiding repetitive data-harvesting practices. Given the long history of industrial ecologists assessing unintended consequences of policies and technology implementation (Font Vivanco & van der Voet, 2014), the community has a responsibility to hold Green AI standards together with the study of minimal expansion of digital technologies.

3.2 | Data accessibility and governance

The issue of data governance is inherently political and concerns many aspects such as data ownership, data storage, data dissemination, and the question of unequal access to the digital economy. These problems often have clear reasons. For instance, detailed information from which we can derive material and energy efficiency of processes, production volumes, or product compositions are often at the core of the competitive advantage of firms. Additionally, managing and exploiting big data has become a highly profitable business model for a very limited number of internet companies. They hold and monetize vast amounts of data while they may provide limited access to the public and scientific community.

Gathering data and maintaining big databases are labor-intensive and costly activities. This creates an inherent problem in making data open access as database curators need to be concerned with financial sustainability of their operations and data confidentiality. As a result, many of the most-used datasets in the IE field, such as the life cycle inventory database *Ecoinvent* (Frischknecht & Rebitzer, 2005) or the IEA (e.g., the IEA Energy balances), are licensed and for the most part only accessible for a fee. With the expansion in data volumes, there is a risk that these business models become more common and that reliance on private services to handle and manipulate such data in the AI infrastructure increases.

This represents a barrier for an equal enjoyment of data (e.g., economic, industrial, and environmental data) and AI solutions regardless of the income level of data users, and it exacerbates global inequalities in data accessibility and deployment of DTs (i.e., digital divide). Data access, quality, and internet infrastructure notoriously differ across regions, which risk endangering sustainability (Mehrabi et al., 2020). The digital divide will continue growing unless there are policy interventions. The use of AI for sustainability should heighten awareness of these inequalities and address them whenever possible. In various cases, data accessibility and openness should be expanded, such as for geographic information and the built environment.

Industrial ecologists should investigate how public and private data may be governed to serve its objective of aiding decision-making for a sustainable society. They can investigate different policy frameworks and mechanisms to ensure compliance to these frameworks (Mahanti, 2021) such that quality data is available for effective use of AI. One such mechanism could be the creation of openly accessible benchmark models and datasets for common IE analytical tasks (e.g., data estimation for LCI and EEIO, or environmental impact assessment under different climate scenarios). In a variety of other AI fields, such benchmarks (e.g., MNIST and CIFAR) have been instrumental in providing quality input data to train models, promoting transparency, comparability of models, and focused progress (benchmarks.ai, 2022). The existence of such benchmarks would also be in line with the current efforts for open and shared data in the IE community (Hertwich et al., 2018).

Furthermore, in order to support data availability, the system of incentives for scientists may also need to be modified to promote timeliness, wide access, and interoperability of data and software of fundamental importance to sustainability objectives. Currently, scientists may not always want to publicly disseminate their work, for example, until they are able to submit a given number of publications or to ensure co-authorship in publications using their work. However understandable these practices may be, they remain undesirable behaviors, which may slow down the community's ability to provide timely and replicable analysis for sustainability.

At last, AI, DTs, and annexed services can be intrusive in the private life of citizens and have profound influence on their physical, mental, and financial well-being. At the same time, AI could also induce new behaviors and help reach sustainability objectives (Froemelt et al., 2018). However, currently there is a significant risk that AI could be used to support and exacerbate unsustainable levels of consumption and production. If there is no purposeful choice of direction toward sustainability from the governance perspective, the choice will be of those with the higher resources in the market to leverage AI and DTs developments. In this regard, AI and DTs should be closely scrutinized.

3.3 | Explainability, interpretability, and causality

The way AI models are able to explain the world (i.e., explainability) and their ability to be understood by humans (i.e., interpretability) are of great importance to ensure trust in sustainability insights and effectiveness of sustainability solutions. Real-world data carries over biases to intelligent systems thereby perpetuating misconceptions, discrimination, and enhancing the risks of other injustices. Improving explainability could prevent these issues by better representing the heterogeneity of complex socio-economic and ecological systems, highlighting where and how humans should intervene to correct AI models and reduce biases. Additionally, in the scope of IE, especially concerning scenarios analysis and dynamic systems, it is of fundamental importance to ensure clarity between cause and outcome. For example, in the use of multiobjective optimization of production and consumption system under different climate scenarios, we need to ensure that we can identify influential factors in such scenarios and explain the dynamics governing them. This is especially important in cases where AI is employed to enhance decision-making. Recent studies such as Sgaier et al. (2020) present strong argument in favor of causal AI as acting on outputs from AI models that do not explain the root causes leading to ineffective, biased, poor decisions.

4 | RECOMMENDATIONS

We have several recommendations for the IE community in moving forward in the use of artificial intelligence (AI) and digital technologies (DTs):

- Creation of internal committees and working groups for AI and DTs research. Such committees and working groups could:
 - Provide research directions and promote standards and protocols for governance of data, models, and software within and outside of IE;
 - Support knowledge transfer from and to fields that successfully embarked on interoperable data sharing and best practices in AI applications;
 - Establish and/or promote data and model benchmarks as well as good modeling practices;
 - Provide a platform for networking among researchers and establish relationships with other interest groups and institutions to promote governance of AI toward sustainability.
- Support transdisciplinary and cross-societal efforts to ensure successful implementation and use of sustainability knowledge and solutions. In particular:
 - Computer science, data science, and mathematics are at the core of the expansion of the DTs, and developments in AI and collaborations should be actively sought out to improve our methodological and technological approaches;
 - Anthropologists, social scientists, and law experts are also indispensable in understanding the consequences of AI on the social and economic organization of society. These experts carry with them different perspectives and approaches to the complex issues of sustainability;
 - Strengthen links between citizens, research, policy, industry, and communication.
- Privilege simplicity and fair trade-off between complexity, and explainability, interpretability, and causality. The community objective should not be to create models as complex as the world itself, but to provide systems that not only aid sustainability but embody it while improving insights, and quality and coherency in data and models; The community should also strive to avoid always prioritizing predictive models and also direct effort to building better causal models that help us develop a better understanding of our dynamic and complex world.
- Maintain awareness of inadvertent impacts of AI and DTs due to material and energy requirements. Determining the optimal amount of data and connectivity that are required to support decision-making and sustainable solutions. While IE should embrace AI developments enthusiastically, it is paramount that we are critical of the way AI is implemented and that we try to understand what such developments entail.
- Maintain awareness of the digital divide, biases, and issues of demographic diversity and representation in data and in AI-enabled decision-making. The IE community should employ methods of data collection to increase representativeness and create models that take these issues into account.

In conclusion, AI can be an important instrument to solve the greatest sustainability challenges that are currently faced by humanity. However, it should not be seen as a silver bullet but, rather, as a helpful instrument to be handled with scrutiny. The IE community has a promising and yet rapidly changing path ahead. AI and DTs are changing the way data is handled, services and products manufactured and consumed, and society and industries governed. IE can provide tools and insights to direct such changes toward sustainability. At the same time, these advancements also have a potential to greatly support the work performed by IE. These mutually beneficial opportunities should be nurtured and actively directed to ensure we reach our sustainability objectives.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

ORCID

Franco Donati  <https://orcid.org/0000-0002-8287-2413>

Sébastien M. R. Dente  <https://orcid.org/0000-0002-9545-0973>

Chen Li  <https://orcid.org/0000-0001-8506-2806>

Andreas Froemelt  <https://orcid.org/0000-0001-9388-7816>

Rohit Nishant  <https://orcid.org/0000-0001-7201-4901>

Gang Liu  <https://orcid.org/0000-0002-7613-1985>

Arnold Tukker  <https://orcid.org/0000-0002-8229-2929>

NOTES

¹ ML CO₂ Impacts tool: <https://mlco2.github.io/impact/>

² Python-based CodeCarbon: <https://codecarbon.io/>; <https://pypi.org/project/codecarbon/>

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