Technologically mediated practices in sustainability transitions: environmental monitoring and the ocean data buoy★★

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ABSTRACT

The discourses of sustainability are inextricably linked to the influence of technology in shaping the future. Information and Communication Technology (ICT) in particular is crucial for understanding the environment and human impacts, as well as for providing future solutions for mitigating climate change. Yet only by integrating technology development with social innovation is sustainability possible. Sustainability transitions research extends the well-established field of socio-technical systems analysis by requiring closer attention to environmental, economical-social-political and technical factors. Guidance towards future socio-technical pathways requires a deeper understanding of the relations between humanity and technology. To fulfil this requirement we apply the technological mediation concept and identify four ICT mediated practices in sustainability transitions: *information gathering*, *communicating*, *decision-making*, and *self-reflection*. These practices are described in the context of Sustainable Development Goal 14 *Life Below Water*, then elaborated through the specific example of the development and use of remote sensing ocean data buoys. In discussion we demonstrate the utility of technological mediation perspective to shed light on the interdependence of society, technology and the environment, and open critical discourses on sustainability transitions that can help shape equitable future alternatives.

1. Introduction

Sustainability thinking is futures thinking, in which we observe the consequences of past and present human activities and attempt to reduce the social, economic and environmental burdens that will be carried by coming generations. Technology occupies a prominent place in futures thinking [1], and exerts an outsized influence in sustainability discourses [2, 3]. Information and Communication Technology (ICT) in particular is our primary means of understanding the environment and human impacts, through data collection, its structuring and analysis as information, identification of trends, and extrapolation into future scenarios [4, 5, 6]. ICT also backgrounds social innovations and the challenges of equitable sustainable development and citizen participation so necessary to mitigating climate change. Paradoxically, the over-exploitation of planetary resources for financial gain that is today's status quo has been driven by technological development, and ICT is equally destructive as constructive, for instance by increasing industrial output, fostering exploitative mining practices, propagating e-waste, negatively impacting work-life balances, and enflaming capitalism with new modes of unsustainable production and consumption.

For these reasons the complex relations between society and technology in the context of sustainability [7] are influential in shaping our visions of the future. Apart from the sustainability discourses, *socio-technical systems* research [8] has thoroughly examined these relations, commonly explicating the development and use of technology via *Actor Network Theory* (ANT). This proposes that society and technology co-construct each other, forming networks in which societies and citizens enter into hybrid assemblages with technical and social artefacts [9]. As addressing climate change has become more urgent, research has shifted attention to the topic of *sustainability transitions* [10, 11] and the active exploration of strategies for transformation and change to balance social, technological and environmental futures [12, 13]. Sustainability transitions research attends more closely to social aspects such as policy guidance and behaviour change [10], places emphasis on the necessary social innovations [14] and seeks to avoid the historical over-emphasis on technological development associated with transitions [14]. While the acknowledgment that technology alone is unable to enact sustainability transitions is important [15], it must be accompanied by critical

★★ Abbreviations:

- AI: Artificial Intelligence
- ANT: Actor Network Theory
- EIA: Environmental Impact Assessment
- HCI: Human Computer Interaction
- IPCC: Intergovernmental Panel on Climate Change
- ICT: Information and Communication Technology
- MCES: Marine and Coastal Ecosystem Services
- MLP: multi-level perspective
- MPA: Marine Protected Areas
- MSFD: Marine Strategy Framework Directive
- SDG: Sustainable Development Goal
- SIDS: Small Island Developing State
- UN: United Nations

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theoretical examinations, for example on the role of capitalism in stifling change [16], and the potential of technology developments and social innovations to introduce new inequalities and dependencies [17] as well as unsustainable behaviors in the future.

In this article we address the role of technology, and in particular ICT, in sustainability transitions through the perspective of *technological mediation*, an approach that elucidates technology as mediator of human perception and experience, and explicates how humans and technology are related to and influence each-other [18, 19, 20, 21]. Technological mediation, or mediation theory, allows us to study human-technology relations beyond the classical interpretation of socio-technical systems by providing a postphenomenological account of humans as ontologically and experientially bound to technology. This approach draws focus to the emergence of socio-technical *practices* [21] which are central to sustainability transitions and future reconfigurations of the status quo [22, 23]. Through technological mediation we define four ICT mediated practices that are instrumental to sustainability transitions (i.e. *information gathering*, *communicating*, *decision-making*, and *self-reflection*) and serve as a framework to analyse specific socio-technical assemblages. These ICT mediated practices are then applied to and elaborated within the domain of ocean technology, using the specific example of remote sensing data buoys. These artefacts and their use in environmental monitoring are central to UN Sustainable Development Goal (SDG) 14 "Conserve and sustainably use the oceans, seas and marine resources for sustainable development", also known as *Life Below Water* [2, 3, 24]. Through this example the analytical utility of the ICT mediated practices is demonstrated beyond simple descriptions, as frames of reference for critical analysis of a variety of issues related to sustainability transitions and future human, technology and nature matrices.

The article is organised as follows, Section 2 summarises the state of the art on socio-technical systems and sustainability transitions research. Section 3 introduces to the approach of technological mediation and Section 4 describes the four ICT mediated practices. The application of the ICT mediated practices to the ocean data buoy is provided by Section 5 and Section 6 focuses on the critical analysis and reflections of the practices in terms of sustainability transitions. Finally, Section 7 concludes with an overview of the concepts and elaborations that have been presented.

2. Socio-technical systems and sustainability transitions

The complex relations between humans and technology have been widely examined through the lens of *socio-technical systems* [8]. This approach combines analyses of both social and technical elements [25] and outlines matrices of *technical artefacts*, *human agents*, and *social artefacts*, such as norms [26]. The concept of socio-technical systems is historically grounded in organisational research, examining the structures, roles, groups, works allocation, and relationships within organisations. [8, 27, 28, 29]. The overarching objectives of socio-technical approaches have been to harmoniously integrate technical requirements and the necessities of humans [28] and to avoid problematic mismatches with organisational goals [30]. Hence the design of socio-technical systems addresses human factors, including in the loop the people and artefact-technical systems that constitute organisations [30]. Socio-technical systems research has cross-pollinated many fields from ergonomics to computer science, and is prevalent in Information Systems (IS) and Human Computer Interaction (HCI).

Analyses of socio-technical systems often borrow from ANT [9] the assertion that technology has an influencing role, that a certain agency can be recognized in the forms and affordances of technology. ANT relates how systems and artefacts are inscribed with values [31], through scripts that take positions about how one should act in the world. These inscription capabilities can be leveraged for social and political persuasion [32], for changing attitudes and behaviors [33] or as agonistic confrontation to challenge the status quo [34]. While these are important insights, overall ANT focusses on the network, viewing humans, systems and artefacts on the same level and can tend to downplay the importance of human actors vis-a-vis technology [21, 35].

The discourses of climate change and sustainability have expanded the socio-technical approach to link technology, society, and the natural environment (in any order of relevance) into a broad range of inquiries known as *sustainability transitions* [10, 11]. This rapidly evolving field leverages rich understandings of socio-technical transformations and pathways by which societies and technologies co-evolve [23] but takes a specific focus on fostering more sustainable modes of production and consumption. Sustainability transitions are inextricably linked to socio-technical transitions, but differ somewhat in the importance placed on governance and guidance required to facilitate transformations [10]. They envision closer integration of society and technology in the future, and in calling for systematic change elaborate issues of justice, power, geography, ethics, policy and the political [11]. Thus socio-technical scholarship foregrounds sustainability transitions research and together they make clear that meaningful and effective solutions for environmental and development challenges depend on widespread, systemic and often radical change in both societal and technological systems.

Chief among several theories that have been developed to represent and analyse sustainability transitions [14] is the multi-level perspective (MLP) [23] which focuses on transition evolution through *niche-innovations*, *socio-technical regimes*, *socio-technical landscapes*. Socio-technical regimes represent the status quo, the current configurations of society and technology which are resistant to change. Niche-innovations attempt the subversion, or overthrow of the status quo through new ideas and designs. Socio-technical landscapes are social, political, technological and environmental contexts in which regimes and innovations exist and which influence both evaluations and affirmations of niche-innovations and regimes. While the MLP does help capture and evaluate transitions in general, the approach can suffer from an overly techno-centric emphasis at the expense of social factors, its focus on privileged classes of actors to drive transitions and its uneven consideration of specific contexts, scale and places, such as those of the Global South [14, 16]. These discourses tie into broader commentaries surrounding sustainability transition approaches, in particular concerning the perceived lack of attention to capitalism as the central economic and political actor that influences development, innovation and transition [16].

Transitions are by their very nature intangible, they represent pathways between present conditions and those of an unfolding future. They overlap in particular with futures studies which reinterpret human existence through its socio-technical characteristics [1] and observe human development as entangled with technological development [36]. Sustainability transitions, in identifying and attempting to overthrow the current status quo, map out improved forms and uses of technology, incorporating specific value judgements as to the preferred state of our future societies. As such, they engage critical theory which focuses on emancipation from all forms of oppression, overthrow of systems of power and control, and the establishment of norms for criticism [37]. These futures and critical perspectives become increasingly important as we examine both design and use of technology to incite socio-political and environmental transformations [38].

Technology is often idealized as a tool for our survival, perhaps even as the solution to the environmental crisis [7] and given that it shapes and facilitates the collection of data, its analysis as information and worldwide dissemination, ICT in particular factors in all environmental sciences and sustainability discourses. A plethora of sustainability-engaged fields have emerged in ICT scholarship since the early 1990's such as Computational Sustainability, Green ICT, Environmental Informatics and Sustainable HCI [39]. However, decades of scholarship combined with the exponential technological development have not created technologies powerful or widespread enough to effect any substantial mitigation to climate change trajectories [15]. Technologies acquire agency only as socio-technological assemblages, and it is the social factors such as norms and regulations, policies, practices, knowledge, behaviors, and collective experiences that define the impact of any particular technology or artefact. The overthrow of existing socio-technical regimes which vehemently resist sustainability transitions is not only a technological endeavour it is a social and political one [23] that requires cooperation and coordinated action among networks of innovators [40]. These human factors are inextricably linked to, and co-evolve with technology, and sustainability transitions that shape our future relationships with nature, also define the future shape of humanity, both of which will be strongly mediated by technology.

3. Technological mediation and postphenomenology

Technology is a tool that humans use to shape the world and to shape the future. Technology also affects how we experience the world, each-other and ourselves; increasingly technological artefacts become instruments that influence society and drive policy. Thus through their design and use contexts, technology and humanity co-evolve in recursion with their shaping of the world [41]. These concepts are captured and explained by the perspective of technological mediation, an approach based on postphenomenology, that focuses on how humans and the world shape each other through the *mediation* of technology [18, 19, 20, 21]. Thus only through the presence of the technology can certain human experiences occur, generating imaginaries, ontological and epistemological structures, and possibilities to act in a certain way [21].

Postphenomenology shares with ANT the concept of mediator, which modifies, distorts, translates and/or transforms what is carried between entities in a network ([9] p. 39), yet it offers richer explanations on the nature of that mediation. While ANT is concerned with the co-construction of entities within networks, postphenomonology examines individual elements, elucidates how they interact [35] and provides sharper distinctions between humans, non-humans and their related agency. This approach suggests that technology carries an intentionality that is expressed through mediation, engaged and realised in the interactions between humans and artefacts situated in different use-contexts [19, 20].

At the centre of postphenomenology are four specific kinds of technology-based mediating relations between humans and the world: (i) embodiment, (ii) hermeneutic, (iii) alterity and (iv) background [18, 42]. The first relations, *embodiment*, define the manner of experiencing the world with the senses through technology. For example eyeglasses mediate the human experience of seeing the world [18]. This kind of mediated experience is said to be "optimal" when the embodied relations are *transparent*: the technology is developed enough to ensure its technical function (e.g., the lens of the eyeglasses are ground to match the eye), the use of technology is learned (e.g., I quickly understand that the eyeglasses I can use for reading are not appropriate for driving the car), and the presence of the technology becomes imperceptible (e.g., the eyeglasses become the extension of my vision) [18, 19].

The second relations are *hermeneutic*, in which the technology symbolically represents aspects of the world, understanding of which requires our interpretation of the technology's signs, symbols and semantics. An example of hermeneutic relations is a nautical chart, which represents the reality or a portion of it, yet requires an interpretation of its symbols as well as a compass to be useful as a navigational tool.

The third relations, *alterity*, regard technology as an independent entity, a *quasi-other*, an athropomorphisation or animation of artefacts. These kinds of relations are made possible by personifying the technological object and then interacting with it [18, 19]. The paradigmatic example is Artificial Intelligence (AI), in which a set of techniques are applied towards autonomous learning and simulated intelligence [43]. AI has long been humanised by attributing to it quasi-human capabilities, even as it is distinctly non-human. The *otherness* represented in the alterity relations can be also interpreted in terms of relations among technologies (technology-technology relations) in which the human subject is not anymore included in the interplay, such as the relations of *machine embodiment* and *machine hermeneutic* [44].

The fourth and final category of relations are called *background* and occur where technology is extant and active, but often goes un-noticed [42]. An example of background mediations might be the energy optimisation capability a solar charge controller, operating automatically without that a person is constantly aware of its presence and activity, even as it directly effects the charging of batteries and availability of electricity.

These four relations are often taken as a basis to understand the human knowledge of the world, actions in the world, and ontology of the world though the mediation of technology and its material engagement. These kinds of analysis can be also adopted to support future scenarios to evaluate technology designs dependent on the use-context [21, 45].

3.1. On the notion of mediation

The concept of "mediator" has been widely described and discussed in ANT [9], in which a mediator is able to change or transform what is being mediated. Also in postphenomenology the (technological) mediator plays an *active* role within the relation among objects that are mediated [46]. Although postphenomenology assumes several positions that are similar to ANT, it stresses the importance of the relations and the co-shaping between subject and the world through technological mediation, whereas ANT is more focused on the outcomes that derive from the relation itself [35]. With the aim of clarifying the concept of mediation with regard to technology, in this section we provide a brief elucidation of the notion of mediation and the role of technology in such relations.

Human-technology relations involve three entities: (i) the *subject*, (ii) the *technology* and the (iii) technological mediated *world* experienced and perceived by the subject. The subject is typically a (human) agent that exhibits *intentional moments*, such as beliefs, desires and intentions [47], the technology is a physical or non-physical, agentive or non-agentive artefact bearing functions [48], e.g., a drone or software system, and the world can be defined as a specific state that is experienced / perceived by the subject at time *t*. From an ontological point of view, mediation is a kind of relation in which an object (i.e., the mediator) arbitrates a process which includes two or more participants [49]. Note that the mediation relation is indirect [49]; using a technology example, a sensor mediates the human perception of phenomena by measuring particular states of the world, however the sensor does not change the actual state of the world that has been recorded. Mediation is not to be confused with *facilitation* and *influence*, as these two involve more direct engagement to effect changes [49].

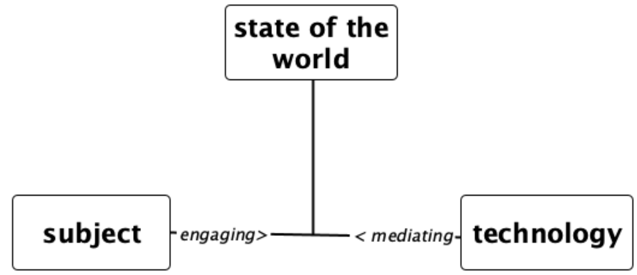

Figure 1: Conceptual model of technological mediation.

In postphenomenology technology mediates human experience and perception of the world as a reciprocal relation. This mediation is realised within a process or activity by which humans *engage* with technology. The embodiment relations require *adopting* a technology to extend some human potential in the world. The hermeneutic relations are manifested by *interpreting* the symbols of a technology. Alterity relations are realized by *interacting* with technology as a quasi-other. Background relations differ somewhat, in that the engagement is invisibly embedded in every-day lived experience. However even as this relation may seem automatic and unconscious, the presence of any technology "in the background" has always been initiated by another human and indeed, each of the technological mediating relations are bounded by human experiences, language and practices. Figure 1 conceptually represents the mediation relation of technology, inspired and re-adapted from [50], in which a relation between two objects exists only if a third entity mediates between these two. In Figure 1, *that* state of the world exists only through the *mediated engagement* between the subject and the technology. Focusing on the co-shaping relation between subject and technology, the former without the mediated engagement with the latter could not: (i) form certain intentional moments [47] nor (ii) execute specific actions and, at the same time, the technology could not exhibit certain functions and uses. Thus, subject and technology are co-dependent in the manifestation of particular properties they bear.

4. ICT mediated practices

The perspective of technological mediation offers an alternative analysis of the co-evolving relations between humanity and technology and stimulates a conceptual shift on the role of the technology in human life, from a mere instrument to achieve specific goals, to a fundamental element that shapes perception and experience of the world. As mentioned in Section 2, technology is central to sustainability transitions research, in particular ICT, as the entirety of sustainability sciences is dependent on long-term data collection and analysis of complex social, environmental and economic systems.

However it is important to recognize that although people and societies design and implement technology, they are reciprocally influenced by that technology. ICT is used in specific contexts and social values are carried through that use. This can inform the design and development of technological artefacts and systems to support citizens, scientists, and policy makers to enact meaningful change [51].

Sustainability transitions are dependent on reciprocal innovations with social, technological, and political dimensions to be successful [7], this means fostering change in human behaviors alongside design and development of technological solutions, radical policy interventions and again, social innovations in order to produce reconfigurations [17, 22]. In this section we describe ICT in terms of technologically *mediated practices* [21] that are related to the human experiences of the world through technology and can facilitate these reconfigurations. We do not make any specific commitment to one notion or another of practice and refer the readers to the discourse in [52] and [53], from which emerges a collective definition of practices as interconnected constellations of embodied knowledge, mental activities, artifacts and their uses.

4.1. Four ICT mediation practices for sustainability transitions

The first mediated practice we identify is called *information gathering* which concerns both the use of ICT's as well as their technical underpinnings. This mediated practice represents the ICT function of collecting data from the environment that serves as the basis of humans' understanding of a given domain in terms of information. *Information gathering* can be expressed as:

> access to information concerning the world w is only realised through the mediated engagement between the (human) subject s with the technology t.

This practice is grounded in embodiment relations: technology enhances our sensing abilities, it measures the state of the environment with a sensitivity, resolution and temporal range far beyond what is humanly possible, and thereby mediates our knowledge of the environment. ICT's also extend our physical reach, enabling access to areas of the planet not possible without technology, either through augmented human bodies or our robotic extensions. Information gathering technologies employ hermeneutic relations, as sensors translate aspects of the environment into numerical data and vectors which symbolically represent the world, and through which we can quantify and compare states of the environment as time series. Once we have collected this data ICT provides us with tools for managing it; databases, filters and transformations, graphs, animations and countless others allow us to translate vast amounts of data into information that we can then begin to interpret [18]. Within these tools are many background mediation relations, as ICT operates invisibly to most users in the performance of data processing and back-end computing functionality.

In *communicating* we recognize a second practice as ICT is ubiquitous in climate science and its discourses. This mediated practice of *communicating* involves (i) information transmission within and between artefacts and systems and (ii) information sharing between humans in the course of sustainability science and discourse. In the first case there exists technology-technology relations:

> technology t transmits data/information within the ICT system in which it is embedded.

In this case humans are not always aware of the underlying technological processes (i.e. backgound relations). t to t communicating also expresses machine hermeneutic relations as ICT systems function on their own languages, semantics and interpretations, formed of protocols and communication processes to exchange data between systems. For instance, a sensor gives a reading that is packaged, transmitted, received, unpacked and stored. In the second case of *communicating*:

> the exchange of information between two or more (human) subjects $s > 1$ concerning the world w is only realised through the mediated engagement between $s > 1$ with technology t.

This describes the situation in which ICT is the primary channel for sharing environmental information, in form of maps, graphs, spreadsheets, everything from simple word processors to elaborate collaboration platforms, all of which mediate our environmental research communications and their dissemination to the public.

The mediated practice of *information gathering* and *communicating* are prerequisites for individuals, institutions and policy makers in what we identify as a third ICT mediated practice, *decision-making* [19, 21]. The information made accessible by technology and its communication as shared understanding is fundamentally important in decision support. This can be expressed as:

> the development and enaction of decisions upon the world w is only realised through the mediated engagement between the (human) subject s with the technology t.

Data-driven maps and climate modelling are prime examples of hermeneutic mediation relations, tools for visualising spatial information and vast amounts of environmental data that play important roles in the shaping of climate policy. These types of visualisation tools have become requisite to decision-making for sustainable development, as have softwares dedicated to analysis and visualization of ecosystem services.

A fourth mediated practice of ICT in sustainability transistion is *self-reflection*, in which we revisit and renew our conceptualization of the human condition using understandings that are again, mediated by technology. In this practice:

Table 1
ICT mediated practices' definitions.

ICTmp	Definition
information gathering	The access of the information concerning the world w is only realised through the mediation engagement between the (human) subject s with the technology t.
communicating	(i) Technology t transmits data/information within the ICT system in which is embedded. (ii) The exchange of information between two or more (human) subjects $s > 1$ concerning the world w is only realised through the mediated engagement with the technology t.
decision-making	the development and enaction of decisions upon the world w is only realised through the mediated engagement between the (human) subject s with the technology t.
self-reflection	The reflection on the human existence, as part of the world w, is elaborated by the (human) subject s only trough the mediated engagement with the technology t.

> the reflection on the human existence, as part of the world w, is elaborated by the (human) subject s only through the mediated engagement with the technology t.

This practice is central to many technology studies that try to make sense of culture and society by examining technological artifacts, use-contexts and practices, especially those that probe human experiences through the design and deployment of new technologies. The alterity mediation relations are particularly evident in this *self-reflection*; for example the development of AI and machine learning have spurred deeper investigations into the very nature of consciousness, memory and learning, and computer scientists' attempts to automate artefacts and develop robotic systems constitute new reflections of the self. Developments in supercomputing allow for modelling of the earth's climate and weather patterns in different scenarios, wherein ICT's even take on the role of oracle, predicting the future of the earth and humankind, which then influences human behaviour and choices.

The practices of *information gathering*, *communicating*, *decision-making* and *self-reflection* are recursively linked. For example *information gathering* may seem a precursor to *communicating*, however the latter includes aspects such as dialog and discourse that are integral to the social construction and sharing of meanings [54] through which data is translated into information. *Self-reflection*, *information gathering*, and *communicating* should also be preconditions for *decision-making* in order to assess and execute appropriate contextual decisions. *Self-reflection* is also linked at its core to the other practices, as we shape our own understandings of ourselves as beings in a shared world through *information gathering*, *communicating*, and *decision-making* [55]. A summary of the four ICT mediated practices (labelled *ICTmp* for a reason of space) definitions is presented in Table 1.

5. An example of ICT mediated practices in sustainability transitions: the remote sensing ocean data buoy

In this section we demonstrate the application the ICT mediated practices descriptive framework to the context of sustainability transitions, specifically in the domain of marine and coastal environments and SDG 14. We take as an example one kind of technological artefact and its use, the remote sensing ocean data buoy which is fundamental to environmental monitoring, the evaluation of past and present states, identification of trends, and the measured anticipation of future impacts in marine and coastal environments [56, 57].

There are currently nearly 9000 data collection platforms installed in the open ocean and in coastal waters [58]; the magnitude of this technological investigation of the marine environment is visualized on a number of online maps, for instance the EMODnet physics map viewer [59], OceanOPS [60], the US National Data Buoy Center [61], the Lagranian Drifter program [62] and the EU platform JERICO-RI [63]. Data buoys contribute greatly to scientific understanding of the ocean, either moored to the seabed or drifting with the current, above and below sea level. Such buoys are equipped with a range of sensor typologies dependent on their monitoring targets, and are constantly logging and transmitting observations of meteorology, wave dynamics, currents, physical and chemical properties of seawater and more. These measurements are positioned in a long trajectory of technological development, initiated in the early history of seafaring as observations collected by ships' officers at sea. With the advent of telecommunications in WW2 the first weather monitoring buoys were developed for the arctic [64]. Drifter buoy deployments began in the 1970's and technical progress has been exponential ever since, with contemporary data buoys acting as wireless sensor networks which leverage satellite communications and the Internet of Things [65]. While more precise satellite telemetry is replacing some buoy functionalities, *in situ* data buoys are still required to calibrate those measurements from beyond the atmosphere [66]. Thus data buoy technology has become integral to scientific understanding of the oceans, defining necessary transitions and informing policy decisions to effect sustainable future exploitation while maintaining the (relative) future health of the oceans [67].

Understanding the functionality of a technology is important to refine knowledge and procedures and define new and future uses, however functional analysis alone is not enough. As we engage with buoy technology, our experience of the world and expectation of the future of humanity and planet earth is changed, thus a wider investigation of the social and cultural influences of the technology including the identification and the emergence of practices is also needed. We do not only use data buoys to know the environment, we design and develop the buoy technologies specifically to monitor human impacts on the oceans, and foretell possible consequences. As we develop new monitoring artefacts and systems, these too are scripted, embedded with the values of sustainability and development, and in turn they potentially foster new behaviours and uses. Thus data buoy technologies have a mediating influence on the future state of the world and embody our practices as agents in defining the future. In this way *information gathering*, *communicating*, *decision-making* and *self-reflection* are all manifested within remote sensing ocean data buoys.

Information gathering. As mentioned in the previous section the practice of *information gathering* is first grounded in the technical aspects of ICT's, and relate to the functionality of the technology systems. In the case of the data buoy, this begins in design and planning stages, identifying the environmental parameters to be sampled, which are rooted in specific research questions. For example GOOS defines a set of ocean variables to be observed, these range from physics (e.g., sea height, current, temperature), to biochemistry (e.g., oxygen, nutrients), biology and ecosystems (e.g., fish distribution) and human impact (e.g., debris, sound) [68]. Many of these ocean parameters are monitored using dedicated sensors that mediate human perception of the sea. In some cases sensors expand and refine human senses, such as in the measurement of water temperature, while in other cases sensors open new monitoring possibilities beyond human capabilities, such as the ability to quantify concentrations of oxygen present in seawater.

Hardware and software are subsequently developed to read and store data from the sensors, typically this includes some form of battery-powered micro-controller, and frequently solar panels to recharge over longer-term deployments. In addition to the data being collected, and depending on its intended use Global Navigation Satellite Systems (GNSS) are often added to the buoy to track the precise geospatial origin of individual data points. Data buoys also require some waterproof physical structure to protect the electronics and ensure their operation. Thus a data buoy's *information gathering* capability is made possible by specific kinds of dedicated technologies, intricate configurations of physical and electronic components, and complex engineering design processes.

Information gathering in the data buoy context is related with technology systems as well as data collection, however there is a strong social component at its core. The purpose of the data buoy is to retrieve reliable, meaningful data for analysis, and therefore data buoy development is a collaborative and interdisciplinary process requiring input from hardware and software developers, oceanographers, marine biologists, environmental management and conservation professionals, and increasingly data scientists and experts in machine learning, pattern recognition, and AI. This cooperation is laying the foundations for future environmental sciences upon which the technology mediated practice *information gathering* will have an even stronger influence.

Communicating. At the boundary between *information gathering* and our next technology mediated practice of *communicating* is where resides ICT and the core activity of a data buoy, which is monitoring the environment and recording representations thereof. This involves multiple layers of communication, as through the data buoy, environmental states are translated into digital information between sensors and circuits, data is packaged and passed to a micro-controller via Serial or Inter-Integrated Circuit (I2C) protocols with the micro-controller. Once digitized the information can be filtered or otherwise processed, and stored in a database. Data buoys being developed as sensor networks can transmit gathered information to the cloud, using Long Range Radio (LoRa), Global System for Mobile (GSM), Wi-fi or satellite communications (e.g. Iridium). In this way the data buoy's main function, *information gathering* is itself mediated by ICT practices of *communicating*.

Equally important, however, are the more social aspects of technology-mediated *communicating* such as data representation and information dissemination. Data buoy output is collected into databases and used to create models, graphs (e.g., Ocean Monitoring Indicators (OMIs) of Copernicus [69]) and maps that we have mentioned above. These digital media representations allow the sharing of knowledge and collective sense-making of ocean information. Many collaborative digital instruments are also employed, ranging from the simple text editor, to e-mail exchange among experts, shared folders and dedicated platforms for sharing ocean data, for example the EMODnet Data Ingestion portal [70]. At the core of climate sciences and sustainability is the communication of information extrapolated into future scenarios, visions of potential outcomes which, through the technology mediated practice of *communicating* relay the urgency of collective action, and impact of inaction on sustainability issues. Several documents and reports have been produced to address the ocean conditions, such as the UN SDG 14, the 2019 *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [56], the 2020 *Copernicus Marine Service Ocean State Report* [71], and the 2021 *Climate Change 2021: The Physical Science Basis* [57], which has a ocean dedicated section. These documents often propose different communication strategies, offering versions for specific audiences, and include graphics, tables and summaries to accommodate readers at various levels. Indeed *communicating* is the backbone of interdisciplinary discourse between scientist and citizen, institutions, public and politics that articulates the values and aspirations of sustainability transitions.

Decision-making. In sustainability transitions *information gathering* and *communicating* are supporting our third ICT mediated practice, *decision-making*. Each individual data buoy only provides a tiny sampling of the state of the world's oceans, yet each contributes to current and future *decision-making* as part of the ever-expanding picture of ocean health that is big ocean data [58, 72]. The information gathered from ocean data buoys is applied to a wide range of planning and *decision-making* activities for example in Environmental Impact Assessments (EIA) [73] where coastal habitats are monitored before and after infrastructure installations, valuation and assessment in management of Marine and Coastal Ecosystem Services (MCES) [74], providing weather and wave information for commercial and recreational sea traffic and many others [71]. In this way the buoy artefact becomes an essential part of our understanding of long-term change, linking past environmental states to current conditions and future consequences that ultimately factor into the design of infrastructures and policies.

The data buoy also influences *decision-making* in a more urgent way, as for example information from a tsunami warning system that consists of networked offshore wave buoys can influence local populations' plan of action in the immediate future. Such *decision-making* is relevant in the present moment for survival of individuals and their families, not in the bigger picture of humanity's continued existence on the planet. Looking at longer-term *decision-making*, the EU directives for water quality and sustainable use of marine resources [75, 76] exemplify how data supports planning and development initiatives. Due to the specific monitoring and reporting requirements of the directives, *information gathering* and *communicating* are also recursively promoted.

Self-reflection. Prior to scientific advancements the ocean was a place of mystery and mythology; humanity had very limited access to and understanding of marine environments. Much of our contemporary knowledge of the ocean is mediated by technology, including that embodied by the data buoys. Each of these artefacts is a small bit of plastic and electronics and batteries, an inconsequential object afloat on the ocean. Yet each one contributes to our knowledge of the ocean. This is in some way representative of individual human impacts on the ocean: each of us may personally do very little damage, but our cumulative negative effect is almost overwhelming. However as human awareness towards the ocean increases, supported by such technologies as data buoys and the mediated practices of *information gathering*, *communicating* and *decision-making*, so we increase the chances of shaping, and acting towards a collective vision of preferred futures that have transitioned to more sustainable exploitation and protection of the oceans.

The increased knowledge of and attention to the deteriorating health of the oceans has triggered serious and meaningful *self-reflection* for many, which in turn is shaping possibilities for our future selves. Recent years have witnessed the rise of membership and participation in ocean conservation organisations that are fostering sustainable values, taking action to protect marine ecosystems through marine activism, citizen awareness and public outreach. Evidence of this sort of active transition are the events organised around World Ocean Day [77] and citizen science training such as Project AWARE [78], the Reef Life Survey [79] and Ghost Diving [80], which not only monitors, but involves diver volunteers to revitalize marine environments by removing of abandoned fishing gear from the ocean (e.g., fishing nets) that can be hazardous for marine life. These aspects and activities are clear signs that citizens and organizations are engaged in *self-reflection*, questioning and changing the status quo of negative human impacts on the oceans.

6. Critical discussion of ICT mediated practices for sustainability transition

The ICT mediated practices we propose in this article can be applied to many different aspects of technological and societal development, and examining the integration of social and technological influences as practices we gain useful insights into the shaping of sustainability transitions. The demonstrative analysis of practices in sustainability transitions presented here focuses on marine and coastal environments, taking the opportunity to illuminate one of the biggest challenges of sustainability which is often the lowest priority for policymakers [81]. However the technology mediated practices represent a descriptive framework that can be adopted to analyse technological, social and environmental configurations in many other domains, to confront established paradigms that inhibit innovation [51].

Challenge and overthrow of the status quo are at the center of critical theory and analysis [37, 82], and in the following section we offer some critical reflections on the ocean data buoy and SDG 14 that surface through the analysis of ICT mediated practices.

6.1. Information gathering

Data supplied through *information gathering* is clearly fundamental to monitor environmental impacts and strengthen arguments for sustainability transitions. Yet information can be misrepresented to support political and economic positions that run contrary to sustainable development, or simply to more efficiently exploit ecosystem services. An example of the latter, aquaculture information systems integrate sensor technology with management software to make visible relevant biological and ocean chemistry parameters. This *information gathering* helps maintain the health of the system and data is used maximize the profit of the aquaculture business. Sea surface temperature readings are used to calculate maximal feed and caloric uptake, while dissolved oxygen is used monitor optimum fish growth, and signal impending algae blooms that require imminent harvesting of mussels for market before toxic bacterial levels are reached. The same information is used to monitor the health of the environment [75] and in places where EIA are required for aquaculture, *information gathering* presents a variety of conflicts. When data is provided by the aquaculture producer rather than environmental protection or fisheries authorities, there can be significant skepticism as to the integrity of reported information [83]. In addition, monitoring technology can be prohibitively expensive for poorly funded local municipalities, thus favoring large-scale aquaculture businesses [84].

Similarly the presence of *information gathering* artefacts does not necessarily result in a functioning data acquisition system. For example a tsunami warning system had been installed prior to the devastating 2004 Indian Ocean tsunami that claimed 240,000 lives. However few if any of the (donated) buoys were functioning, and furthermore, the initial earthquake destroyed many of the cell-phone towers that would have been used to send warning text-messages. A replacement system for the Indian Ocean was planned, partially installed, yet never completed due to inter-agency wrangling. Another problem which has plagued such buoy-based tsunami warning systems and indeed other data buoy platforms is vandalism. Data buoys are often fouled by fishing activities, moorings and data cables deliberately cut, and they are often stripped for parts, in particular solar panels, batteries and meteorology payloads [85]. This demonstrates again the need to integrate local education and community participation in tandem with deployments of technology [86].

6.2. Communicating

Again to reiterate this fundamental point, sustainability transitions do not only require technological solutions; the challenges that transitions pose to the status quo will ultimately be enacted through social innovation, that is driving change to attitudes and behaviors, to inform future policy and equitable governance and shift to sustainable patterns of production and consumption [10, 11]. This will be facilitated in part by *communicating*, and the technology mediation in dissemination and discussion of environmental data. Interoperability is key, as a wealth of data is being collected, but it is not always available to, or actively shared between programs [87]. In the development of data buoys, in particular those using low-cost technologies, there is considerable overlap between dozens of projects, with no clear standards for ordering and storage of data nor for the communication of results [65]. The most pressing challenges however are socio-economic and cultural which impact the availability of data. The deployment and access to ocean data platforms is concentrated in richer, more developed nations. Yet marine resources are shared resources [88] and less advantaged communities such as those in SIDS are disproportionately dependent on those resources [89]. In the Caribbean, for example, communication is paramount, and the development of collective value systems, acceptance of a variety of management approaches and local cultural differences, as well overcoming the diversity of languages spoken all impact access to and mutual benefit from environmental information [90].

Calling for open access to and equitable distribution of information is part of a broader discourse concerning access to technology, knowledge transfer and capacity building for regions, nations, organizations and citizens who need, but simply cannot afford monitoring technology [67]. For example, the aforementioned commercial aquaculture management systems are prohibitively expensive for many small businesses and entrepreneurs who inevitably will form the backbone of local sustainability transitions [91]. Yet the implementation of such monitoring systems can help guarantee the health of aquaculture products and viability of business practices, while *communicating* to the public about the use of these monitoring technologies can boost consumer confidence and reciprocally strengthen local aquaculture businesses' role in local food security [84]. Here again the technology development needs to mesh with social and economic innovations, to effect new capabilities on the part of producers, and support new behaviors on the part of consumers, all of which are facilitated by *communicating*.

6.3. Decision-making

There can be no denying that the importance of technology mediated *decision-making* for sustainability transitions extends far beyond marine and coastal environments. Monitoring the impact of human factors, identifying pressures and state changes are central to sustainability policy development across the board, and all rely heavily on technology mediating practices of *information gathering* and *communicating*. Yet defining and facilitating sustainability transitions for marine and coastal environments is exceedingly complex, and even when mechanisms exist to inform *decision-making*, the science is often poorly elaborated [92], monitoring is mismatched with policy and implementation, and the need for social innovation and stakeholder engagement in support of decision-making is inadequately addressed [93].

For example, the EU Marine Strategy Framework Directive (MSFD) explicitly calls for an ecosystem-based approach which acknowledges the close correlation between social and ecological systems [76]. The complimentary EU Water Framework Directive [75] in its annexes defines specific requirements and timetables for monitoring of environmental parameters to quantify human impacts. However precise indicators of ecosystem health, and therefore clear and measureable thresholds for sustainable exploitation of their resources simply have not been defined for complex socio-ecological systems [94] and even where they attempted, MCES assessments are rarely included in MSFD decision-making processes [92]. In the EU context, additional frameworks for Integrated Coastal Zone Management, Fisheries Policy and Maritime Spatial Planning add to the confused state of policy recommendations, it is no wonder the MSFD is haphazardly implemented [95].

Another important critical reflection on *decision-making* for sustainability transitions concerns values, value-systems and the challenges of quantifying MCES. Though the EU directives outline assessments and address the environmental, social and economic aspects, simply having well defined policy does not ensure that meaningful scientific information is available or even included in *decision-making* [93]. While scientific observation and time series data can clearly demonstrate the ecological importance of for example coral reefs to fish stocks, and mangroves to shoreline protection, it cannot fully capture the aesthetic, ethical, or social value of these ecosystems [96]. The remedy to many of these issues is for the practices to address power imbalances in the valuation process: local and indigenous knowledge needs to be included in *information gathering*, marginalized voices and perspectives must to be raised and meaningfully addressed in *communicating* about what has value and for whom. In this way the trade-offs between long-term benefits to society and short-term profits, for example those exclusively earned by established tourism and aquaculture operators, can be more equitably negotiated in *decision-making* for marine and coastal environments [97].

6.4. Self-reflection

Technology development has provided the time-series data and visualisation systems that make clear human impacts on the environment, and forecast dire consequences if current trajectories continue. This in turn has led to the design and development of new systems and artefacts that embody our changing values and the evolution in the relationship between ourselves, technology, the environment and the future. Technology can be considered to be discourse, a continually updating archive for *self-reflection* on the nature of humanity, and our values, past, present and future. That discourse is situated in human progress and development which are themselves contingent upon solving the climate crisis and ensuring a future for humanity on the planet. Taking modern fisheries as an example, we can see that this sector derives its value from fish, an ecosystem service so valued by humans that it has been extensively commercialized and exploited to the point of depletion of fish stocks and the near collapse of many fishery industries. The environmental, social and technical assemblage that is aquaculture emerges as a response to declining wild fish stocks, yet what began as a traditional industry covering food-security has now become saturated with unsustainable commercial fish and shrimp farming practices. Yet aquaculture also represents a socio-technical-environmental innovation that can potentially revive marine ecosystems that have been decimated by commercial fishing. For example, recovering biodiversity in mangrove forests depleted by shrimp farming may in fact be assisted when restoration efforts are integrated with aquaculture [96], management of which is of course, augmented with monitoring technology. Here again the complex relationships between the impacts of technology and the promise of innovation are exposed through a technology mediated *self-reflection*.

An even more important critical *self-reflection* addresses values in socioeconomic situation of technology use, its availablity and the need for attention to social practices which accompany new technologies. We have established why environmental monitoring is so important, and point to technologies that effect *information gathering*. Yet monitoring technologies are beyond reach in many SIDS, which results in a deficit of *information gathering* accompanied by a lack of information sharing, poor *communicating*, and inadequate stakeholder participation in *decision-making*. Especially when it concerns all-important MCES, communities in SIDS are greatly disadvantaged by their lack of access to environmental data, even as they already experience rising sea levels, more powerful hurricanes, storm surges and food-insecurity relating to the depletion of local marine resources. Research and environmental monitoring programs in SIDS are limited [89] while funding organizations and scientists in the Global North, fascinated by technology are busy developing data and applications, satellite imaging, remotely operated vehicles and supercomputers for climate change simulations. Yet in SIDS, it is not only inadequate science, the *information gathering* that leads to failure in sustainable management and exploitation of MCES, but also conflicts among users and ineffective governance, [90, 97]. These correspond to *communicating*, and *decision-making* and demonstrate the entangled roles that our technology mediated practices have in sustainability transitions. The challenge of technology development for sustainability is to address social concerns, and this is reflected in budget allocation of previous decades dedicated to climate change research, wherein the natural and technical sciences have received 770% more funding than social sciences [98]. This technology mediated *self-reflection* so proposes that investment in local education and community programs in the Global South and peripheral regions to promote Ecosystem Services approaches [97, 67] is equally important for sustainability transitions as technology development.

Table 2
Critical points of ICT mediated practices.

ICT mediated practice	Critical points
information gathering	(i) Source of information (ii) Information awareness and education
communicating	(i) Interoperability (ii) Information access
decision-making	(i) Unified policy (ii) Define thresholds (iii) Address power imbalance
self-reflection	(i) Values embodied in artefacts (ii) Social innovation

Table 2 lists the critical points originated from the ICT mediated practices applied to ocean data buoys.

7. Conclusion

The discourses on sustainability often devolve into two threads, one focused on the perceived influences of technology, and the other on the need for social innovation. In the former, technology can offer solutions to social, economic and environmental problems; in the latter the reconfiguration of social value systems, attitude and behavior changes can drive future sustainable development. In this article we examine these two perspectives as one and the same through the lens of technological mediation, which views society and technology as co-constructing each other and the future as unfolding through integrated technological and social transformations. We apply this approach to sustainability transitions research and identify four ICT mediated practices, *information gathering*, *communicating*, *decision-making* and *self-reflection* that epitomize the entanglements of humanity, technology and the natural world. These practices are examined within the domain of monitoring technologies for SDG 14 using the specific example of remote sensing ocean data buoys. In this way we demonstrate the utility of mediated practices approach to define and describe socio-technical aspects of the future and open critical theoretical discussions on the role of technology to mediate human experiences, knowledge of the environment, and discovery of pathways to sustainable futures.

The intended takeaways from this discussion are to draw attention to how technological artefacts embody values and how, by paying closer attention to social attributes and the insights of technological mediation, we can inform the design of artefacts and systems to overthrow the status quo of unsustainable social, economic and environmental exploitation. We elaborate the inscription capabilities of technology not to celebrate its influence, but to define it as a mechanism for design to encourage, incite, even enforce sustainability values on politicians, scientists and citizens who use technology. Technological mediation and the ICT mediated practices are presented here as a perspective to inform action, to provoke and challenge through critical reflections, and force publics and policy-makers to re-evaluate the impacts of contemporary choices on the environment.

CRediT authorship contribution statement

Greta Adamo: Conceptualization, Methodology, Writing - Original draft preparation. **Max Willis:** Conceptualization, Methodology, Writing - Original draft preparation.

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References

[1] N. Bostrom, The future of humanity, Springer, 2009, book section 10, pp. 186–215.

[2] U. Economic, S. C. ECOSOC, Special edition: progress towards the sustainable development goals, Tech. Rep. E/2019/68, United Nations New York, 2019 (2019).
URL https://sustainabledevelopment.un.org/content/documents/24978Report_of_the_SG_on_SDG_Progress_2019.pdf

[3] U. N. Un, Transforming our world: the 2030 agenda for sustainable development, Working papers, eSocialSciences (2015).
URL https://EconPapers.repec.org/RePEc:ess:wpaper:id:7559

[4] H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, et al., Ipcc special report on the ocean and cryosphere in a changing climate, IPCC Intergovernmental Panel on Climate Change: Geneva, Switzerland 1 (3) (2019).

[5] P. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H. Pörtner, D. Roberts, P. Zhai, R. Slade, S. Connors, R. Van Diemen, et al., Ipcc, 2019: Climate change and land: an ipcc special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, Tech. rep., Intergovernmental Panel on Climate Change (IPCC) (2019).

[6] W. M. O. (WMO), State of the global climate 2020, Tech. rep., World Meteorological Organization (WMO) (2021).
URL https://library.wmo.int/doc_num.php?explnum_id=10618

[7] E. Paredis, Sustainability transitions and the nature of technology, Foundations of Science 16 (2-3) (2011) 195–225.

[8] E. Trist, The evolution of socio-technical systems, Occasional paper 2 (1981) (1981) 1981.

[9] B. Latour, et al., Reassembling the social: An introduction to actor-network-theory, Oxford university press, 2005.

[10] J. Markard, R. Raven, B. Truffer, Sustainability transitions: An emerging field of research and its prospects, Research policy 41 (6) (2012) 955–967.

[11] J. Köhler, F. W. Geels, F. Kern, J. Markard, E. Onsongo, A. Wieczorek, F. Alkemade, F. Avelino, A. Bergek, F. Boons, et al., An agenda for sustainability transitions research: State of the art and future directions, Environmental Innovation and Societal Transitions 31 (2019) 1–32.

[12] S. O. Hansson, Technology and the notion of sustainability, Technology in Society 32 (4) (2010) 274–279.

[13] R. Costanza, L. Graumlich, W. Steffen, C. Crumley, J. Dearing, K. Hibbard, R. Leemans, C. Redman, D. Schimel, Sustainability or collapse: what can we learn from integrating the history of humans and the rest of nature?, Ambio (2007) 522–527.

[14] M. Lawhon, J. T. Murphy, Socio-technical regimes and sustainability transitions: Insights from political ecology, Progress in human geography 36 (3) (2012) 354–378.

[15] P. Cafaro, Avoiding catastrophic climate change: Why technological innovation is necessary but not sufficient, in: Ethics and Emerging Technologies, Springer, 2014, pp. 424–438.

[16] G. Feola, Capitalism in sustainability transitions research: Time for a critical turn?, Environmental Innovation and Societal Transitions 35 (2020) 241–250. doi:https://doi.org/10.1016/j.eist.2019.02.005.

[17] F. Avelino, J. M. Wittmayer, B. Pel, P. Weaver, A. Dumitru, A. Haxeltine, R. Kemp, M. S. Jørgensen, T. Bauler, S. Ruijsink, et al., Transformative social innovation and (dis) empowerment, Technological Forecasting and Social Change 145 (2019) 195–206.

[18] D. Ihde, The phenomenology of technics, in: R. C. Scharff, V. Dusek (Eds.), Philosophy of technology: the technological condition: an anthology, John Wiley & Sons, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK, 2013, pp. 19–24.

[19] P.-P. Verbeek, Materializing morality: Design ethics and technological mediation, Science, Technology, & Human Values 31 (3) (2006) 361–380.

[20] P.-P. Verbeek, Postphenomenology of technology, in: R. C. Scharff, V. Dusek (Eds.), Philosophy of technology: the technological condition: an anthology, John Wiley & Sons, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK, 2013, pp. 561–572.

[21] P.-P. Verbeek, Toward a theory of technological mediation, Technoscience and postphenomenology: The Manhattan papers (2015) 189.

[22] S. Laakso, R. Aro, E. Heiskanen, M. Kaljonen, Reconfigurations in sustainability transitions: a systematic and critical review, Sustainability: Science, Practice and Policy 17 (1) (2021) 15–31.

[23] F. W. Geels, J. Schot, Typology of sociotechnical transition pathways, Research policy 36 (3) (2007) 399–417.

[24] United Nations, United nations sustainable development goal 14, https://www.un.org/sustainabledevelopment/oceans/, accessed: 2021-09-01 (2021).

[25] G. Walker, N. Stanton, P. Salmon, D. Jenkins, A review of sociotechnical systems theory: a classic concept for new command and control

paradigms, Theoretical Issues in Ergonomics Science 9 (2008) 479 – 499.

[26] N. Guarino, E. Bottazzi, R. Ferrario, G. Sartor, Open ontology-driven sociotechnical systems: Transparency as a key for business resiliency, in: M. De Marco, D. Te'eni, V. Albano, S. Za (Eds.), Information Systems: Crossroads for Organization, Management, Accounting and Engineering, Physica-Verlag HD, Heidelberg, 2012, pp. 535–542.

[27] F. E. Emery, Characteristics of socio-technical systems, in: L. E. D. . J. C. Taylor (Ed.), Design of jobs, Penguin Books, 1972, p. 157–186.

[28] E. Mumford, The story of socio-technical design: Reflections on its successes, failures and potential, Information systems journal 16 (4) (2006) 317–342.

[29] S. Sawyer, M. H. Jarrahi, The Sociotechnical Perspective, Vol. 2, CRC Press, 2014.

[30] G. D. Baxter, I. Sommerville, Socio-technical systems: From design methods to systems engineering, Interact. Comput. 23 (1) (2011) 4–17. doi:10.1016/j.intcom.2010.07.003.

[31] B. Latour, Where are the missing masses, sociology of a few mundane artefacts, In Shaping Technology-Building Society. Studies in Sociotechnical Change (1992).

[32] P. Dourish, Hci and environmental sustainability: the politics of design and the design of politics, in: Proceedings of the 8th ACM conference on designing interactive systems, ACM, 2010, pp. 1–10.

[33] R. Owen, J. Stilgoe, P. Macnaghten, M. Gorman, E. Fisher, D. Guston, A framework for responsible innovation, Responsible innovation: managing the responsible emergence of science and innovation in society 31 (2013) 27–50.

[34] M. Willis, On agonism and design: dialogues between theory and practice, Ph.D. thesis, University of Trento (2019).

[35] P. Verbeek, Artifacts and attachment. A post-script philosophy of mediation., Amsterdam University Press, Netherlands, 2005, pp. –, open Access.

[36] T. Fry, Design futuring, University of New South Wales Press, Sydney (2009) 71–77.

[37] M. Horkheimer, Critical Theory: Selected Essays, Continuum, 1972.

[38] S. Bardzell, J. Bardzell, J. Forlizzi, J. Zimmerman, J. Antanitis, Critical design and critical theory: the challenge of designing for provocation, Proceedings of the Designing Interactive Systems Conference (2012) 288–297.

[39] L. M. Hilty, B. Aebischer, ICT for sustainability: An emerging research field, in: L. M. Hilty, B. Aebischer (Eds.), ICT Innovations for Sustainability, Vol. 310 of Advances in Intelligent Systems and Computing, Springer, 2015, pp. 3–36. doi:10.1007/978-3-319-09228-7_1.

[40] B. Walrave, M. Talmar, K. S. Podoynitsyna, A. G. L. Romme, G. P. Verbong, A multi-level perspective on innovation ecosystems for path-breaking innovation, Technological Forecasting and Social Change 136 (2018) 103–113.

[41] P.-P. Verbeek, Cover story beyond interaction: a short introduction to mediation theory, interactions 22 (3) (2015) 26–31.

[42] P.-P. Verbeek, Don ihde: the technological lifeworld, American philosophy of technology: The empirical turn (2001) 119–146.

[43] J. McCarthy, M. L. Minsky, N. Rochester, C. E. Shannon, A proposal for the dartmouth summer research project on artificial intelligence, august 31, 1955, AI magazine 27 (4) (2006) 12–12.

[44] S. T. Luan, The hidden dimensions of human–technology relations, Philosophy and Technology 33 (1) (2020) 141–165. doi:10.1007/s13347-019-00349-8.

[45] P.-P. Verbeek, Materializing morality: Design ethics and technological mediation, Science, Technology, & Human Values 31 (3) (2006) 361–380. arXiv:https://doi.org/10.1177/0162243905285847, doi:10.1177/0162243905285847.

[46] P.-P. Verbeek, Some misunderstandings about the moral significance of technology, in: The moral status of technical artefacts, Springer, 2014, pp. 75–88.

[47] G. Guizzardi, R. de Almeida Falbo, R. S. S. Guizzardi, Grounding software domain ontologies in the unified foundational ontology (UFO): the case of the ODE software process ontology, in: M. Lencastre, J. F. e Cunha, A. Valecillo (Eds.), Memorias de la XI Conferencia Iberoamericana de Software Engineering (CIbSE 2008), Recife, Pernambuco, Brasil, February 13-17, 2008, 2008, pp. 127–140.

[48] P. Kroes, Engineering and the dual nature of technical artefacts, Cambridge Journal of Economics 34 (1) (2009) 51–62. arXiv:https://academic.oup.com/cje/article-pdf/34/1/51/4740491/bep019.pdf, doi:10.1093/cje/bep019.

[49] B. Smith, P. Grenon, The cornucopia of formal-ontological relations, Dialectica 58 (3) (2004) 279–296. arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1746-8361.2004.tb00305.x, doi:https://doi.org/10.1111/j.1746-8361.2004.tb00305.x.

[50] N. Guarino, G. Guizzardi, "we need to discuss the relationship": Revisiting relationships as modeling constructs, in: J. Zdravkovic, M. Kirikova, P. Johannesson (Eds.), Advanced Information Systems Engineering - 27th International Conference, CAiSE 2015, Stockholm, Sweden, June 8-12, 2015, Proceedings, Vol. 9097 of Lecture Notes in Computer Science, Springer, 2015, pp. 279–294. doi:10.1007/978-3-319-19069-3_18.

[51] F. W. Geels, Regime resistance against low-carbon transitions: introducing politics and power into the multi-level perspective, Theory, Culture & Society 31 (5) (2014) 21–40.

[52] T. Hargreaves, Practice-ing behaviour change: Applying social practice theory to pro-environmental behaviour change, Journal of consumer culture 11 (1) (2011) 79–99.

[53] A. Reckwitz, Toward a theory of social practices: A development in culturalist theorizing, European journal of social theory 5 (2) (2002) 243–263.

[54] H. De Jaegher, E. Di Paolo, Participatory sense-making, Phenomenology and the cognitive sciences 6 (4) (2007) 485–507.

[55] M. Merleau-Ponty, Phénoménologie de la perception, Libraqire Gallimard, Paris (1945).

[56] IPCC, Ipcc special report on the ocean and cryosphere in a changing climate, Report, Intergovernmental Panel on Climate Change (2019). URL https://www.ipcc.ch/srocc/

[57] V. Masson-Delmotte, P. Zhai, A. Pirani, S. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, M. I. L. Goldfarb, Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, B. Zhou (Eds.), Climate Change 2021: The Physical Science Basis., Cambridge University Press, 2021.

[58] B. Stevens, C. Jolly, J. Jolliffe, A new era of digitalisation for ocean sustainability?, Tech. Rep. 111, OECD (2021). doi:https://doi.org/https://doi.org/10.1787/a4734a65-en.

[59] The European Marine Observation and Data Network (EMODnet), Emodnet physics map, https://map.emodnet-physics.eu, accessed: 2021-08-31 (2021).

[60] OceanOPS, Oceanops integrated dashboard, https://www.ocean-ops.org/board, accessed: 2021-08-31 (2021).

[61] National Oceanic and Atmospheric Administration U.S. Department of Commerce, National data buoy center, https://www.ndbc.noaa.gov/, accessed: 2021-08-31 (2021).

[62] Lagrangian Drifter Lab, Lagrangian drifter lab gdp array viewer, https://gdp.ucsd.edu/apps/projects/noaa/global-drifter-program.html, accessed: 2021-08-31 (2021).

[63] JERICO-RI , Jerico-ri catalogue, https://www.jerico-ri.eu/jerico-ri-catalogue/#/map, accessed: 2021-08-31 (2021).

[64] F. Selinger, Mitteilungen deutsch eautomatische wetterstationen in der arktis1942-1945, Polarjorschung 55 (1) (1985).

[65] C. Albaladejo, P. Sánchez, A. Iborra, F. Soto, J. A. López, R. Torres, Wireless sensor networks for oceanographic monitoring: A systematic review, Sensors 10 (7) (2010) 6948–6968.

[66] P. Poli, M. Lucas, A. O'Carroll, M. Le Menn, A. David, G. K. Corlett, P. Blouch, D. Meldrum, C. J. Merchant, M. Belbeoch, et al., The copernicus surface velocity platform drifter with barometer and reference sensor for temperature (svp-brst): genesis, design, and initial results, Ocean Science 15 (1) (2019) 199–214.

[67] T. C. Malone, P. M. DiGiacomo, E. Gonçalves, A. H. Knap, L. Talaue-McManus, S. de Mora, A global ocean observing system framework for sustainable development, Marine Policy 43 (2014) 262–272.

[68] GOOS, Essential ocean variables, https://www.goosocean.org/index.php?option=com_content&view=article&id=283&Itemid=441, accessed: 2021-08-31 (2021).
[69] Copernicus, Ocean monitoring indicators, https://marine.copernicus.eu/access-data/ocean-monitoring-indicators, accessed: 2021-08-31 (2021).
[70] The European Marine Observation and Data Network (EMODnet), Emodnet data ingestion portal, https://www.emodnet-ingestion.eu/, accessed: 2021-08-31 (2021).
[71] K. von Schuckmann, P. Le Traon, N. Smith, A. Pascual, S. Djavidnia, J. Gattuso, M. Grégoire, G. G. Nolan, Copernicus marine service ocean state report, Journal of Operational Oceanography 4 (2020).
[72] J. Murdoch, Ecologising sociology: Actor-network theory, co-construction and the problem of human exemptionalism, Sociology 35 (1) (2001) 111–133.
[73] European Commission, Environmental impact assessment - eia, https://ec.europa.eu/environment/eia/eia-legalcontext.htm, accessed: 2022-06-28 (2022).
[74] C. Liquete, C. Piroddi, E. G. Drakou, L. Gurney, S. Katsanevakis, A. Charef, B. Egoh, Current status and future prospects for the assessment of marine and coastal ecosystem services: a systematic review, PloS one 8 (7) (2013) e67737.
[75] E. Commission, Directive 2000/60/ec of the european parliament and of the council establishing a framework for community action in the field of water policy. (water framework directive), Official Journal of the European Communities 327 (2000).
[76] E. Commission, Directive 2008/56/ec of the european parliament and of the council of 17 june 2008 establishing a framework for community action in the field of marine environmental policy (marine strategy framework directive), Official Journal of the European Communities 164 (2008).
[77] World Ocean Day, Happy world ocean day! one ocean, one climate, one future – together, https://worldoceanday.org/, accessed: 2021-08-31 (2021).
[78] PADI, Padi aware foundation, https://www.padi.com/aware, accessed: 2021-08-31 (2021).
[79] Reef Life Survey, Introducing reef life explorer, https://reeflifesurvey.com/, accessed: 2021-08-31 (2021).
[80] Ghost Diving, Ghost diving, https://ghostdiving.org/, accessed: 2021-08-31 (2021).
[81] C. Samantha, D. Matthew, M. Takaaki, S. Tanya, H. Ani, Listening to leaders 2018: Is development cooperation tuned-in or tone-deaf?, Tech. rep., AidData A Research Lab at William & Mary (2018).
[82] J. Bardzell, S. Bardzell, What is "critical" about critical design?, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (2013) 3297–3306doi:10.1145/2470654.2466451.
[83] FAO, Environmental impact assessment and monitoring in aquaculture., Tech. Rep. 527, FAO Fisheries and Aquaculture, Rome (2009).
[84] W. Schmidt, D. Raymond, D. Parish, I. G. Ashton, P. I. Miller, C. J. Campos, J. D. Shutler, Design and operation of a low-cost and compact autonomous buoy system for use in coastal aquaculture and water quality monitoring, Aquacultural engineering 80 (2018) 28–36.
[85] D. B. C. Panel, Ocean data buoy vandalism: Incidence, impact and responses, Tech. Rep. 41, WMO, IOC (2011).
[86] UNDRR, UNESCO-IOC, Limitations and challenges of early warningsystems: A case study of the 2018 palu-donggala tsunami., Tech. rep., United Nations Office for DisasterRisk Reduction (UNDRR), Regional Office for Asia and the Pacific, and the IntergovernmentalOceanographic Commission of United Nations Educational, Scientific and Cultural Organization.(IOC Technical Series N° 150) (2019).
[87] N. Zampoukas, H. Piha, E. Bigagli, N. Hoepffner, G. Hanke, A. C. Cardoso, Marine monitoring in the european union: how to fulfill the requirements for the marine strategy framework directive in an efficient and integrated way, Marine Policy 39 (2013) 349–351.
[88] J. M. Sadler, D. Ames, R. M. Khattar, A recipe for standards-based data sharing using open source software and low-cost electronics, Journal of Hydroinformatics 18 (2016) 185–197.
[89] S. Ali, J. Darsan, A. Singh, M. Wilson, Sustainable coastal ecosystem management–an evolving paradigm and its application to caribbean sids, Ocean & Coastal Management 163 (2018) 173–184.
[90] L. Fanning, R. Mahon, P. McConney, Towards marine ecosystem-based management in the wider Caribbean, Amsterdam University Press, 2011.
[91] M. R. Sobir, Micro-, small and medium-sizedenterprises (msmes) and their role inachieving the sustainable developmentgoals, Tech. rep., United Nations Department of Economic and Social Affairs Division for Sustainable Development Goals (2020).
[92] T. Berg, K. Fürhaupter, H. Teixeira, L. Uusitalo, N. Zampoukas, The marine strategy framework directive and the ecosystem-based approach – pitfalls and solutions, Marine pollution bulletin 62 (05 2015). doi:10.1016/j.marpolbul.2015.04.050.
[93] E. G. Drakou, C. Kermagoret, C. Liquete, A. Ruiz-Frau, K. Burkhard, A. I. Lillebø, A. P. van Oudenhoven, J. Ballé-Béganton, J. G. Rodrigues, E. Nieminen, Marine and coastal ecosystem services on the science–policy–practice nexus: challenges and opportunities from 11 european case studies, International Journal of Biodiversity Science, Ecosystem Services & Management 13 (3) (2017) 51–67.
[94] S. Shephard, S. P. R. Greenstreet, G. J. Piet, A. Rindorf, M. Dickey-Collas, Surveillance indicators and their use in implementation of the Marine Strategy Framework Directive, ICES Journal of Marine Science 72 (8) (2015) 2269–2277. doi:10.1093/icesjms/fsv131.
[95] S. Raicevich, P. Battaglia, T. Fortibuoni, T. Romeo, O. Giovanardi, F. Andaloro, Critical inconsistencies in early implementations of the marine strategy framework directive and common fisheries policy objectives hamper policy synergies in fostering the sustainable exploitation of mediterranean fisheries resources, Frontiers in Marine Science 4 (2017) 316.
[96] S. Wells, C. Ravilious, In the front line: shoreline protection and other ecosystem services from mangroves and coral reefs (2006).
[97] E. F. Granek, S. Polasky, C. V. Kappel, D. J. Reed, D. M. Stoms, E. W. Koch, C. J. Kennedy, L. A. Cramer, S. D. Hacker, E. B. Barbier, et al., Ecosystem services as a common language for coastal ecosystem-based management, Conservation Biology 24 (1) (2010) 207–216.
[98] I. Overland, B. K. Sovacool, The misallocation of climate research funding, Energy Research & Social Science 62 (2020) 101349.

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