

Article

# The Digitalization Sustainability Matrix: A Participatory Research Tool for Investigating Digitainability

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**Abstract:** Rapidly increasing applications of Digitalization and Artificial Intelligence (D&AI) are already impacting our day-to-day life substantially, along with social and economic prospects worldwide. The accelerating utilization of D&AI has stirred the discussion concerning the responsible application of technologies for assisting the implementation of the Sustainable Development Goals (SDGs). D&AI can raise productivity, lower costs, reduce resource intensity, and enable efficient public services. However, there are also risks and downsides that we all must identify and tackle to address any potential short-/long-term undesired impact. Notably, there exists a gap in knowledge about the mutual relationships between D&AI and the 17 SDGs. To address this gap and gather broader perspectives of experts on the potential uses and pitfalls of D&AI for SDGs and their respective indicators, we propose a participatory research approach: the Digitalization–Sustainability Matrix (DSM). The DSM serves as a means for collaborative methods, such as participatory action research (PAR), for the knowledge production process. We exercised the DSM in the Digitainable Thinkathon event, a gathering of experts from diverse sectors and backgrounds for capturing the action-oriented dialogues concerning the use of D&AI technologies for the indicators of SDGs 4 (Education) and 13 (Climate Action). As a tool, the DSM aided in the discussion by systematically capturing transdisciplinary knowledge generated on several aspects, such as: (1) the need for research–practice nexus action; (2) data-capturing efforts and social considerations; (3) collaborative planning for utilizing the power of D&AI; (4) lessons from the diverse community to encourage the purposeful use of technologies. Overall, the proposed approach effectively triggered a discussion on the crucial aspects that need to be considered for D&AI's practices, a step towards deep-rooting the transdisciplinary perspectives for meaningful use of D&AI for SDGs.

**Keywords:** digitalization; artificial intelligence; SDGs; SDG indicators; participatory tools; digitainability; SDG 4; SDG 13

## 1. Introduction

Sustainability is a broad concept focusing on addressing every aspect of the world in which we, as humans, coexist. Sustainability is not only bound to the conservation of the environment, as it also includes notions of preserving economic and social resources [1,2]. The United Nations describes sustainability as a movement for safeguarding a better and more sustainable well-being for all, including future generations. Caradonna [3] points out that sustainability is a comparatively new concept when it comes to its wide use, but its roots reach far back to the 18th century [4]. Sustainability has abundant literature, which helps extensively conceptualize and embody the three fundamental pillars of environmental, economic, and social sustainability [5].

In 2015, the 193 member states of the United Nations (UN) General Assembly adopted the 2030 Development Agenda, intending to move the world onto a sustainable development path by obliging member states to act in a collaborative partnership to support the needs of the present and future generations, ensuring equity and protecting the world's resources. Building on the Millennium Development Goals (MDGs), the 2030 Agenda includes 17 Sustainable Development Goals (SDGs), comprising 169 targets and 212 indicators to be achieved by 2030 and applicable to all countries, regardless of their development status. With no more than a decade left to tackle the SDGs universally and the fact that progress has been insufficient so far, there is a growing need to increase the effectiveness and efficiency of action to support the implementation of the SDGs. To support the speedy attainment of the SDGs, there is an urgent need for strategic enhancements in the process running on the ground at the SDG indicator level to reach beyond the outcomes in the implementation of the Millennium Development Goals (MDGs), where, on average, only 68% of MDG indicators were populated [6]. We face a crucial gap in the literature and practice on strengthening and disseminating the sustainability and transdisciplinary aspects regarding interaction with digitalization. It is recognizable that the significant uptake of transdisciplinary research into practice requires appropriate stakeholders' active involvement [7,8]. However, understanding and practicing the participation from the perspectives of multiple stakeholders remain inadequately addressed. Academic and non-academic stakeholders bring multiple aspects of knowledge and expertise vital to the case scenarios in action-oriented research. Nevertheless, the challenge remains in finding instruments to move towards the transdisciplinary outcome's co-generation, considering the diversity and applicability of stakeholders' perspectives [9,10].

Sachs et al. [11] suggested six key transformations desired within the UN SDG framework to ensure sustainable resources for future generations. Consistently with the European Commission, the six requisite transformations aspire to achieve the Sustainable Development Goals. The goals are (1) advancement in human capacity through improvement in education and healthcare, (2) responsible consumption and production, (3) decarbonization of energy, (4) access to nutritional food and clean water for all, (5) building smart cities, and (6) digital revolution. Among the six transformations described, the digital revolution (Transformation 6) is considered one of the significant forces for furthering the progress of the SDGs. The digital revolution involves the utilization of the benefits obtainable by Digitalization and Artificial Intelligence (D&AI), in which digital information is generated at an unprecedented pace, and machines can "learn, adjust, and perform tasks" [12]. According to Katz and Koutroumpis [13], digitalization refers to the social transformation triggered by the mass adoption of digital technologies that generate, process, and transfer information. Despite controversially discussed uncertainty, technological impacts are likely to be remarkable, and they are impacting us at an unprecedented speed [14]. The currently available 25 zettabytes of data will likely surge to more than 150 zettabytes by 2025 [15]. The increase in global connectivity exhibited by more than 4 billion active Internet users and 3.3 billion social media users by 2018 [15], as well as an increase in global data and communication flows [16], highlights the significant relevance of D&AI for achieving the SDGs.

It is crucial to map the impact of D&AI on SDGs and their indicators. Realizing the constructive aspect of a technology-enabled sustainable development will not occur unguided and non-integrated. Multi-stakeholder contributions are needed to develop transdisciplinary knowledge on relevant SDGs and their respective indicators, trade-offs, synergies, and critical questioning of who might be suffering [17] and who might benefit from applying the disruptive technologies. Instrumental objectives hamper open and reflexive discussion of alternative pathways to sustainability and how participating stakeholders shape the action-oriented research process. These insights help in an interactive dialogue to enable a realization of their transdisciplinary perspectives.

To achieve such an endeavor, this paper proposes a new systematic approach that can help to address a few fundamental questions concerning D&AI and SDGs:

1. How can D&AI be mapped for the SDG indicators?
2. How can the dependencies between indicators of SDGs be identified considering the application of D&AI?
3. How can we include the transdisciplinary perspective considering the Participatory Action Research (PAR) approach in order to map the relevance of D&AI for SDGs?

To address the identified gaps and research questions, we proposed and utilized the Digitalization–Sustainability Matrix (DSM), which helped gather the transdisciplinary perspectives concerning the potential of D&AI for the SDG indicators and for fostering diverse stakeholders to align their interests, which can support the SDGs' progress.

Section 2 of this paper provides a brief background about the complexities in interpreting the SDG indicators and their transdisciplinary interactions with technologies. Section 3 provides the methodology that we have developed and practiced to address the identified research gaps in the sustainability and digitalization transdisciplinary research landscape. Section 4 will discuss the research outcomes, and Section 5 brings forward the discussion section to describe the various relevant aspects, limitations, and standpoints concerning the future work, followed by the conclusion in Section 6.

## 2. Background

A better understanding of how D&AI can help in achieving the SDGs is becoming increasingly relevant. There is a broad consensus that D&AI could be very significant for accomplishing the SDGs as an inevitable driver of change [18,19]. Therefore, it is essential to harness this potential to achieve the goals by 2030, as time is running out. The fundamental objective of sustainable development is to enable individuals, communities, and people to achieve a state for improving their quality of life [20], and this needs to be well considered. Therefore, technology should not be exhausted for any adverse course.

Foreseeing alternative future scenarios, which emphasize the different challenges to variable degrees, can help in working towards implementing the SDGs to realize more of their opportunities and avoid the possible threats of D&AI, such as the digital divide [21]. However, because decisions and actions to advance any one of the SDGs will likely affect the achievement of others, the extensive understanding of the interactions among SDGs and their targets, particularly trade-offs, synergies, and inadvertent consequences, is necessary [22,23]. A particular overarching problem in this context is the digital divide, resulting in rapid digital advancements that fail to put everyone on board, therefore, in turn, causing economic and social exclusion [24]. According to recent literature [19,25], if not tackled urgently, the digital divide will continue not only to be caused by poverty and not only for vulnerable communities and individuals, but also the gap within sectors and economies will be expanded because of digitization, as well as between early adopters and reluctant actors depending on gender, age, and level of urbanization.

To denote the intricate relationship between D&AI, on the one hand, and sustainability, on the other hand, we have coined the noun “digitainability”, a merging of the terms “digitalization” and “sustainability”. It refers to the cross-fertilization between the processes of digitalization and sustainable development. For the initial investigation, the PAR approach, complemented with the systematic exploration tools, could help us find answers to the identified questions. Thus, by developing a transdisciplinary research approach, we investigated digitainability along with the opportunities and uncertainties that are still unknown but could be rapidly crystallized by identifying cause–effect relationships and conceiving solutions for transformative actions. Thus, this helps in exploring the complexity of the Sustainable Development Goals at the indicator level so that key actors can respond promptly.

### 2.1. SDG Indicators and Complexities

As a society, we are experiencing both opportunities and threats from D&AI during its adaptation and innovation [26]. Notably, D&AI could provide the necessary evidence, including tracing indicators and support for implementing the series of solutions for reaching particular targets. However, a critical interrogation of how D&AI can aid us with these overarching goals is fundamental for optimally using the resources [27].

The broadly framed 17 separate and diverse goals and their associated targets and indicators are innately interacting and are a formulation of inseparable parts from an overall perspective. In the currently available literature, some studies exclusively focus on enhancing the knowledge on the interaction of the SDGs and their respective targets. The OpenWorking Group (OWG) prepared an annex document that presented the inter-linkages among 19 focus areas [28]. The Stakeholder Forum looked into the integration and inter-linkages issues even before the SDGs were officially adopted [29]. Additionally, the Organization for Economic Cooperation and Development (OECD) has expressed that the “2030 Agenda requires transitioning from policy coherence for development (PCD) to policy coherence for sustainable development (PCSD)” [30]. The PCSD framework substituted the previously known PCD framework and backed “strategic response to the SDGs”. The framework is flexible to support both OECD members and partner countries for coherence desired for SDG implementation. Research published by the Stockholm Environment Institute approached the issue for cross-sectoral integration of the SDGs, which could help realize the goals [31]. The German Development Institute (DIE) provided a framework for clustering the SDGs by placing the goals in three different layers of concentric circles, where human-centered goals are placed at the core or inner circle, following the goals linked with production, distribution, and delivery of goods and services (middle circle). Finally, the outer circle holds the goals linked to ecosystems and natural resources [27].

Assessing how one SDG target or indicator affects all other SDGs is becoming increasingly important. Various studies, such as the UN Economic and Social Commission for Asia and the Pacific (ESCAP), established a methodological framework to identify the interaction associated with the targets of Goal 6 (clean water and sanitation) with the targets under the other 16 Goals [32]. However, there is almost no literature going even one step further and highlighting the requirement for indicator-level framework as an integrated and transdisciplinary assessment tool to reach the various targets and goals. Using D&AI technologies for a comprehensive transformation towards sustainability does not merely promote just one indicator or indicator of a specific target. Considering the synergies and trade-offs across targets and indicators, D&AI technologies use their disruptive potential to challenge not a singular indicator, but depending on the use cases, impact many others directly and indirectly [25]. This provides a possibility to develop transdisciplinary approaches rather than merely optimizing one technology’s impact on achieving a target in silos. The gap remains in understanding the indicator-level interactions and contextualizing the role of D&AI in the identified interactions for supporting the Agenda 2030.

An enhanced grasp on cooperative interactions among targets and their respective indicators provides the prospect of identifying co-benefits that enable achievement of desirable outcomes through coordination of action rather than trade-offs. Therefore, the indicator-level understanding of the interaction between the technologies and SDGs need to be considered, including synergies and possible conflicts between the SDGs’ indicators [33]. For instance, air pollution is now considered one of the most significant environmental health risks caused by rapid urbanization and industrialization in many countries [34]. Using (satellite) data, affected countries can monitor air quality and fill gaps in regions where data are scarce or non-existent. In this use case application of the Earth observation system, two of the SDG indicators are directly cited—Indicator 11.6.2 (annual mean levels of particulate matter in cities) and Indicator 3.9.1 (mortality rate attributed to household and ambient air pollution) of SDGs 11 (sustainable cities and communities) and 3 (good health and well-being) [34,35]. Big Data presents a largely untapped opportunity for a sustainable development path by linking these indicators. As a sub-set of Big Data, Earth observation data and geospatial information can

considerably reduce monitoring costs for reporting of SDGs within the limited resources available in the context of developing countries [35,36].

## 2.2. Transdisciplinarity for Mapping Interactions and Relevance of D&AI for SDGs

Different disciplines have quite different assumptions about how indicators interact with each other and about what value D&AI technology can add for achieving the SDGs. These differences should not be overlooked, as diversity provides a holistic picture. By understanding, categorizing, and measuring the scope of role, impact, and potential maturity of D&AI technologies on each indicator of the selected SDG from multidisciplinary or transdisciplinary lenses, it is possible to identify the crucial corners of acceleration that synergistically support the transformative process. However, both sustainable development and D&AI are complex and broad topics demanding fundamental knowledge in sustainability and technology along with insights from the social sciences and humanities, environment, and policy domains [37]. Collaborative methods such as Participatory Action Research (PAR) were proposed in the literature to reduce the broadness aspect and to extract the transdisciplinarity of knowledge. PAR provides a framework to bring together interdisciplinary stakeholders in the knowledge production process for the co-development of research, education, and action inter-linkages between science and practice for the issues under study [38].

The standard framework of PAR consists of three main pillars—participation, action, and research. In PAR, effective hybrid choices of participatory research methods, tools, and processes engage the research stakeholders and integrate different knowledge, perspectives, and values to advance research scenario development for translation into apt action [39]. In practice, the PAR approach manifests itself in numerous action-oriented research strategies. By planning an integrative process, interactions can be explicit in each phase of the PAR to provide the opportunity for stakeholders to be involved and co-act [40]. Moreover, the participation, contributions, and collaboration of all stakeholders are the vital guiding principles for the PAR, characterizing an active knowledge-generating alternative for transdisciplinary research [39,41]. Considering the PAR's advantages from a multi- and transdisciplinary perspective, it is potentially possible to investigate and map the implications of D&AI at the indicator level of the SDGs.

This paper introduces an encapsulation of the PAR approach for developing the Digitalization–Sustainability Matrix (described in detail in Section 3.1) in the Digitainable Thinkathon expert event. The paper further presents the outcomes gathered by operationalizing the DSM for two SDGs and their indicators, which embed a combination of participatory and action-oriented approaches as a multi-phase process. By providing opportunities for active participation, this initiates transdisciplinary interaction between sustainability and digitalization. Remarkably, participants' diversity helps overcome biases, enrich the quality of outcomes, and explore promising future collaboration pathways.

## 3. Materials and Methods

### 3.1. Digitalization–Sustainability Matrix (DSM)

This section describes the Digitalization–Sustainability Matrix (DSM) as a basic framework to structure the discussion in the PAR setup. The DSM connects D&AI and sustainability at the SDG indicator level. It is a 2D (two-dimensional) matrix using D&AI themes and respective technologies connected to indicators of a particular SDG to seek the perspective on positive, negative, non-, and unknown relevance for the diverse stakeholders in the discussion. In DSM, we divided the technologies into three broad key themes, considering the recent literature's strategic technology trends.

1. Data-driven opportunities to leverage the potentials provided by mobile internet technology, Blockchain, and IoT;
2. Analytics-driven opportunities provided by technologies such as Big Data, cloud computing, and AI;

3. Design-driven opportunities provided by virtual/augmented reality and adaptive manufacturing or 3D printing.

The themes are classified based on the applicability aspects of the technologies at the SDG indicator level. The DSM-led discussion explores the practical and potential opportunities and challenges of technologies (definitions in Appendix A) and each indicator of the SDG under study.

The DSM intends to stir up the much-needed discussion in the broader digitalization, AI, and sustainability community on matters such as:

- What role could D&AI play at the SDG indicator level?
- How is this practiced, and could this be practiced most effectively, considering both technical and social perspectives?
- What needs to change in the existing processes to facilitate the effective utilization of D&AI?

We utilized the Digitalization–Sustainability Matrix (DSM) to map the potential of D&AI for the SDG indicators and provided examples of how it can be used. To the best of our knowledge, this exploration is the first attempt to carefully examine the scope for using D&AI technologies primarily for the SDG indicators and to assess their potential for providing support—either directly or indirectly—comprehensively or partially for SDG target achievement. The paper sets out the DSM and its application for SDGs 4 and 13 to illustrate the rationale and provides a summary of the results.

The two dimensions of the DSM are: D&AI technologies and the SDG indicators, as can be seen in Figure 1. The matrix’s vertical axis presents the reference wording of each indicator of the SDG under consideration. On the horizontal axis, eight key aspects of D&AI are noted. Though not exhaustive, this list represents a wide array of D&AI sub-disciplines. The eight key technologies of D&AI are grouped under three broad themes. Each of these eight technologies is fully described in Appendix A. The ordinal scale and the respective symbol were assigned to a single category, representing the level of relevance of the D&AI technology (discussed in the next section) on the horizontal axis to the specific SDG indicator on the vertical axis. The DSM with ordinal values helps in the systematic investigation of the potential gaps and opportunities that D&AI provides to monitor/support (directly or indirectly) the technological and social dimensions for each undertaken SDG indicator. The discussion prompted by the DSM as a guiding tool also supports the postulation of a “big picture” of the potential impact of inter-linkages, trade-offs, and synergies between SDG indicators to address individual SDG indicators with D&AI technologies efficiently.

8 Indicators

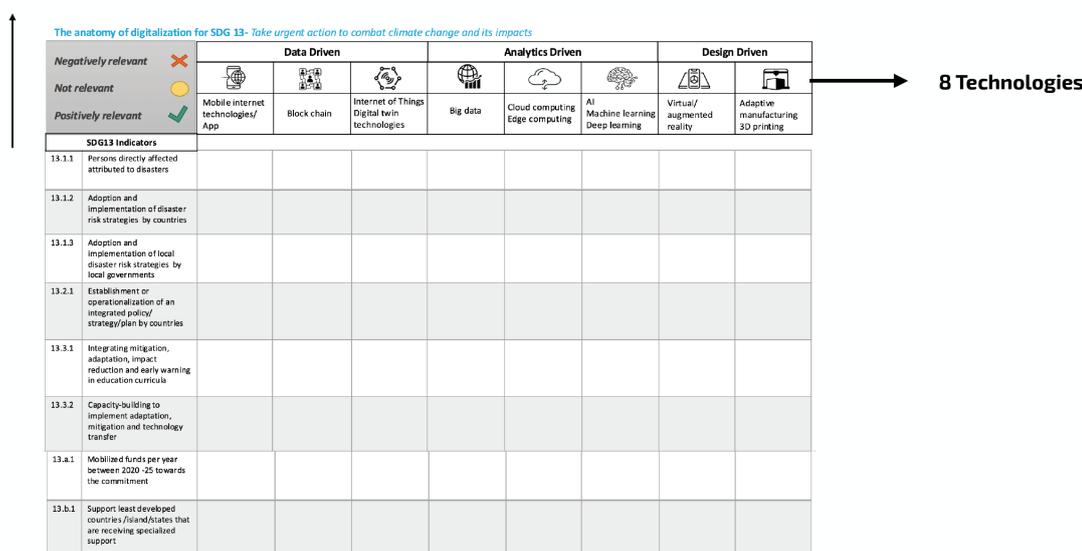


Figure 1. Digitalization–Sustainability Matrix (DSM).

### 3.2. Utilizing the DSM for Participatory Inputs: Thinkathon

In April 2020, we hosted a one-day Digitainable Thinkathon expert event in a virtual format. The Thinkathon expert event was structured to provide a basis for dialogue on the intersection of sustainable development and D&AI. The event aimed to discuss ideas, research findings, and proposals that contribute to the vision of sustainable digital transformation by delivering a stepping stone toward bringing together a community of experts who work on interdisciplinary research and action agendas concerning the opportunities that D&AI provides as well as the challenges it poses to society, energy debates, and the environment in the era of sustainable development. In doing so, the Thinkathon gathered experts who work at the junction of digitalization and sustainable development to exchange and integrate knowledge among a community of professionals. It included experts from academia, industry, non-profit organizations, the private sector, and funding and governance agencies. During the Thinkathon, the discussions were concentrated on mapping the relevance of D&AI technologies for SDGs 4 (education) and 13 (climate change).

The overall Thinkathon event consisted of six phases in a process depicted in Figure 2. Each of these phases consisted of a set of activities, from design to implementation, based on the PAR approach, data collection method, and interaction features. A detailed description of the design process of the whole event is mentioned in Appendix B. The Thinkathon design and implementation process evolved and was conducted within six months, starting from the event announcement and open registration of applications. Before the event day, we administered the DSM via an online poll to the participants for each of the two SDGs under consideration, along with links and factsheets concerning general information on the topics. During the Thinkathon, we divided participants into two working groups focusing on DSMs for SDGs 4 and 13 to briefly discuss the administered polls' outcomes and to collect the responses' reasoning. A panel discussion was conducted at the end of the event to extend the gathering, deliberation, and structuring of facts, ideas, and values discussed in the working groups. Following the Thinkathon, a feedback survey was developed and carried out to understand the participants' views. In the last phase, the conclusively filled DSMs of both SDGs 4 and 13 were presented in the feedback session, as were the outcomes of the polls and experiences with various platforms used in the event along with the feedback survey results.

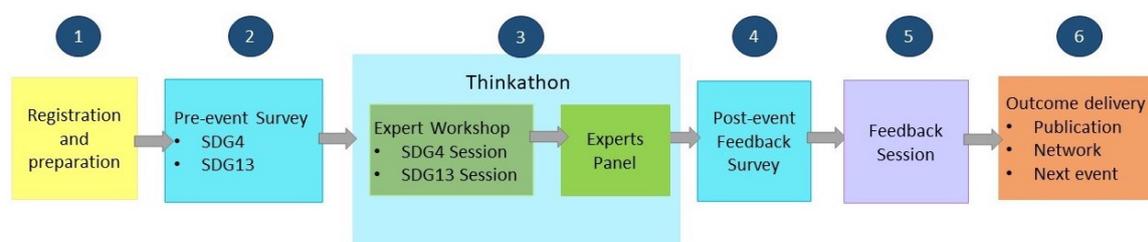


Figure 2. Overall Thinkathon event and implementation process.

### 3.3. Deployment

The analytical framework developed for the Thinkathon encompasses and consolidates the various steps and associated phases of an integrated multi-method PAR approach for implementing the processes of developing collective schemes and outcomes. In the previous subsection, we looked at the broader facets that characterize the Thinkathon expert event with respect to how it was set up and implemented. We combined communication, a survey, interactive working groups, panel discussions, feedback sessions, and network/community building, thus connecting the interdisciplinary participants for further activities and events. A series of participatory methods were designed and implemented for various phases of the event and throughout the process. Before dividing into the working groups on each of the focused-upon SDGs, participants were given various possibilities to (i) select the preferred SDGs, (ii) reflect about the selected SDGs and the relevance to their work, (iii) identify potential focus areas for intervention, (iv) express their ideas/actions for the

DSM in the pre-event survey, (v) discuss specific inter-sectoral concepts, measures, and strategies in interactive working groups and online platforms, and (vi) receive feedback and evaluation of the concerned content and knowledge being systematically analyzed.

This combination of collective and participatory approaches within PAR, assigned to a specific phase of the Thinkathon, produced an outcome, which served as an input for the next phases (see Figure 3). The action orientation of the PAR applied in the Thinkathon refers to the contribution of the method's significance to an increased understanding of the selected SDGs' contextual digitainability and the promotion of practical interventions that influence the discussed subjects in both research and informed action.

### Thinkathon DSM development process via Participatory Action Research

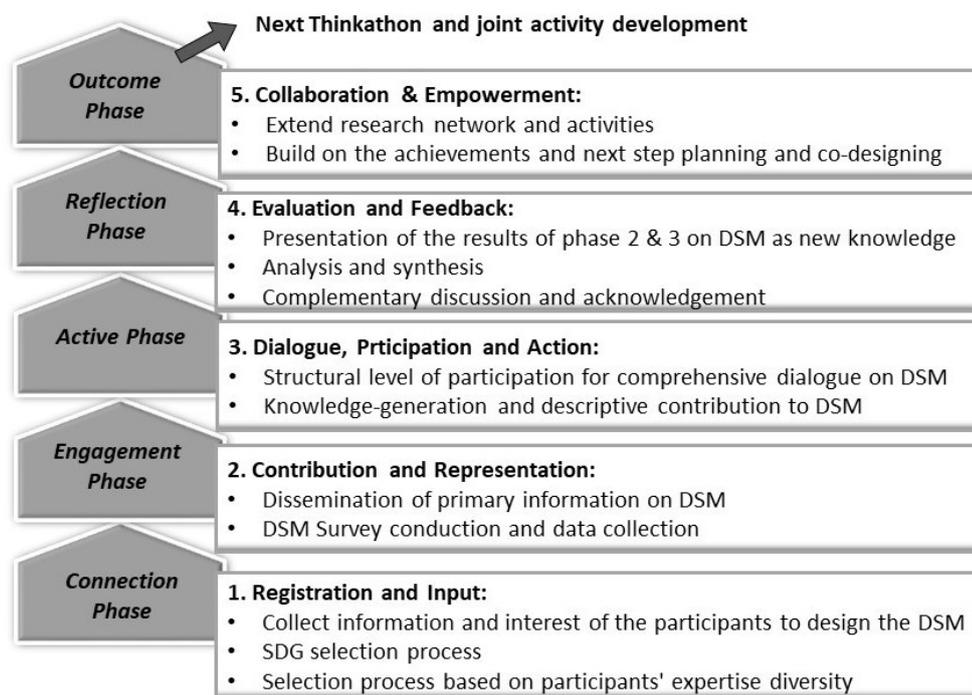
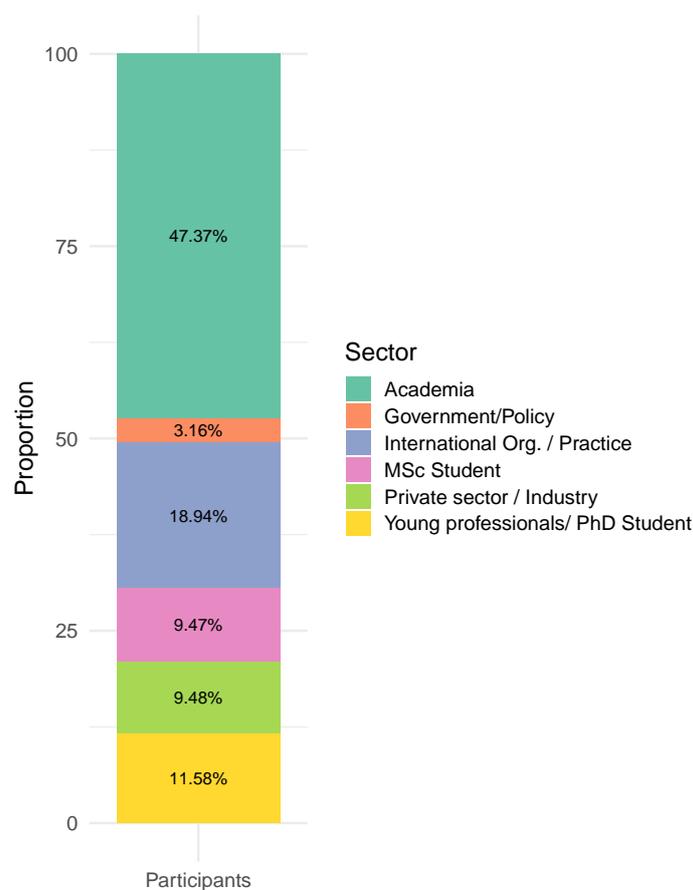


Figure 3. DSM development process.

#### 4. Outcomes

Considering the participants' share and diversity (Figure 4), harmonizing the qualitative information outcome during the transdisciplinary event consisted of polls, group activities, and panel discussions. Furthermore, the diversity of the participants' expertise, professions, and levels of engagement significantly determined the success of content analysis and the further exploration of the suitability of the participatory method. The participants were encouraged to contribute to various forms of communication from their practical perspectives and to bring forth discussions with other participants throughout the event.



**Figure 4.** Overview of the diversity of the participants in the event.

The DSMs were deployed for two SDGs as case studies in the group discussions. The two SDGs, SDG 4 (quality education) and SDG 13 (climate action) were highly preferred SDGs among all the participants when we analyzed the poll results for recognizing the topics of interest for participants in the event. Overall, the participants were divided into two working groups and the discussion was initiated during the event, holding the DSM as the principal tool for (i) initiating discussion, (ii) shaping the sub-topic for discussion, (iii) compelling the flow of discussion toward what is relevant to the particular topic, and (iv) checking on the few opinions beyond the scope of the topic under consideration. Below, we present the findings of the work that we conducted for the two SDGs we tested with the DSM.

#### 4.1. DSM for the SDG 13 (Climate Action) Group

Goal 13 urges for action to be taken to combat climate change and its impacts. The goal has five targets and eight associated indicators to measure the progress towards the goal. As mentioned in the previous section, to understand the participants' conception of D&AI technology's relevance for SDG 13, we conducted a pre-event poll. Figure 5 presents the initial results of the poll for each indicator and the respective technologies. Detailed responses can be accessed in Appendix C.



Figure 5. A glimpse of the pre-event poll results that we captured for Sustainable Development Goal (SDG) 13 ( $n = 32$ ).

The pre-event poll results were then rendered into the DSM inputs for further discussion during the event. The image below presents the rendered version of the pre-event poll results in the DSM. As can be realized from the rendered matrix above, the participants' perspectives about using D&AI technologies could be easily visualized using the DSM. This straightforward interpretation was further fed for initiating the dialogues between multiple stakeholders. The generalized perspective majorly helped in sharing expertise and refining the concerns for interpretations. The red dots in Figure 6 represent the poll inputs. General opinions about the positive/negative relevance were not reached with the majority in the pre-event poll outcome.

The anatomy of digitalization for SDG 13- Take urgent action to combat climate change and its impacts

SDG13 Indicators	Data Driven			Analytics Driven			Design Driven	
	Mobile internet technologies/ App	Block chain	Internet of Things Digital twin technologies	Big data	Cloud computing Edge computing	AI Machine learning Deep learning	Virtual/ augmented reality	Adaptive manufacturing 3D printing
13.1.1 Persons directly affected attributed to disasters	✓	●	✓	✓	✓	✓	●	●●
13.1.2 Adoption and implementation of disaster risk strategies by countries	✓	●	✓	✓	✓	✓	●	✓●
13.1.3 Adoption and implementation of local disaster risk strategies by local governments	✓	✓	✓	✓	✓	✓	✓	●
13.2.1 Establishment or operationalization of an integrated policy/ strategy/plan by countries	✓	✓	✓	✓	✓	✓	✓	●
13.3.1 Integrating mitigation, adaptation, impact reduction and early warning in education curricula	✓	✓	✓●	✓	✓	✓●	✓	✓●
13.3.2 Capacity-building to implement adaptation, mitigation and technology transfer	✓	✓	✓	✓	✓	✓	✓	●
13.a.1 Mobilized funds per year between 2020 -25 towards the commitment	●	✓	✓	✓	✓	✓●	✓●	●
13.b.1 Support least developed countries /island/states that are receiving specialized support	✓	✓	✓	✓	✓	✓	✓●	●●

Figure 6. DSM matrix translated from the pre-event poll results for SDG 13.

While discussing the gaps identified (red dots in Figure 6), the DSM also helped pinpoint the potential synergies and trade-offs between other SDG targets and their respective indicators during the event. Since the audience was a mix of experts from multiple sectors and backgrounds, the comprehensive dialogues supported by the DSM led to appending more specific perspectives on the poll's understanding. For example, while discussing the relevance of using virtual reality/augmented reality (VR/AR) technologies for Indicator 13.1.2, the participants asserted the use of particular technologies for timely capacity building in developing countries, which was also featured as an essential tool for climate-related education and awareness (Indicator 13.3.1). The discussion on Indicator 13.1.2 led to a change in the pre-event poll matrix for VR/AR applications from a red dot with no clarity for participants to a status of "positively relevant" (Figure 7). Furthermore, the discussion also highlighted the negative relevance of the VR/AR technologies for energy consumption and infrastructure needs (Indicators 7.1.2, 7.2.1, and 7.a.1).

A similar change was also observed while discussing the relevance of mobile technologies for Indicator 13.1.1, where participants pointed out the negative impact of mobile data by breaching the privacy of the user and asserted the interdependencies with SDG 10 on economic and social affairs, along with inequality in access to mobile phones between men and women (Figure 7). During the discussion, contrasting perspectives were added on various occasions, thus changing the DSM's entries.

The discussion driven by the DSM in this example demonstrates the advantage of leading intuitive discussions on specific topics of SDG indicators and digital technologies.

Negatively relevant  Not relevant  Positively relevant 	Data Driven			Analytics Driven			Design Driven			
										
	Mobile internet technologies/ App	Block chain	Internet of Things Digital twin technologies	Big data	Cloud computing Edge computing	AI Machine learning Deep learning	Virtual/ augmented reality	Adaptive manufacturing 3D printing		
SDG13 Indicators										
13.1.1	Persons directly affected attributed to disasters									
13.1.2	Adoption and implementation of disaster risk strategies by countries									

Figure 7. DSM changes (in red-colored boxes) that occurred during the discussion in the Thinkathon for SDG 13.

By utilizing the variations in perspective identified by using the DSM, we used a brief time during the event more effectively by making it inclusive for multiple sectors and multiple stakeholders. Considering the complexity and broadness of the digitalization and SDG indicator topics, the DSM serves as a tool fit for the purpose. Dialogues led by the DSM assisted inputs for encouraging conscious topic-centric knowledge-gathering from a diverse range of expertise. The recent literature suggests the urgent need for such a dialogue process, more specifically in climate action [42].

#### 4.2. DSM for the SDG 4 (Quality Education) Group

Within the comprehensive 2030 Agenda for Sustainable Development, education is articulated as SDG 4—ensure inclusive and equitable quality education and promote lifelong learning opportunities for all—with seven outcome targets, three means of implementation, and eleven global indicators [43]. A DSM was developed for SDG 4 as one of the preferred SDGs selected by the participants of the Thinkathon to understand the correlation of the SDG 4 indicators with the eight groups of digital technologies. To perceive the participants’ level of awareness, preparedness, and their speculation on each of the interactions among the indicators and technologies, we utilized the pre-event poll results for the SDG 4 DSM.

As was done for SDG 13, the results of the pre-event poll (Figure 8) were converted into the SDG 4 DSM, as shown in Figure 9. We used the poll result as the facilitator of the discussions during the event. We identified the gaps, uncertain responses, and less-replied-to questions to initiate conversations and bring in insight from various stakeholders. Based on these poll results, we encouraged the participants to interpret more for those responses with a higher number of opposing opinions. These responses are identified with the red dots on the SDG 4 DSM. For instance, the interactions among AI/machine learning technologies and Indicators 4.a.1 and 4.c.1 were identified as both ‘positive’ and ‘not relevant’ with the same number of responses. We asked participants to support their responses with additional information, case-based evidence, and relevant experience. This communication and information exchange helped build a shared understanding of specific interactions in the DSM and enhanced the level of awareness and knowledge co-generation in discussions.

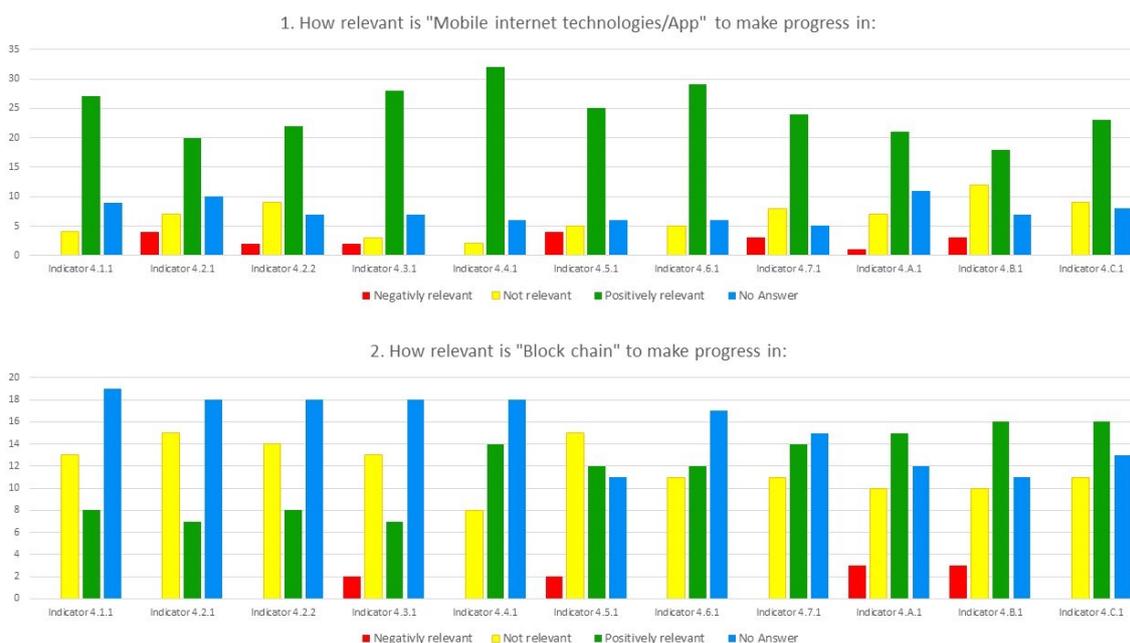


Figure 8. Glimpse of the pre-event poll results that we captured for SDG 4 (n = 40).

The anatomy of digitalization for SDG4: Ensure inclusive & equitable quality education & promote lifelong learning opportunities for all

SDG4 Indicators		Data Driven			Analytics Driven			Design Driven	
		Mobile internet technologies/ App	Block chain	Internet of Things Digital twin technologies	Big data	Cloud computing Edge computing	AI Machine learning Deep learning	Virtual/augmented reality	Additive manufacturing 3D printing
4.1.1	Complete free primary and secondary school for all, by sex	✓	●	●	●	✓	✓	✓	●
4.2.1	Access to early childhood education and care for all, by sex	✓	●	●	✓	✓	✓	✓	●
4.2.2	Participation rate in pre-primary for all, by sex	✓	●	●	✓	✓	✓	✓	●
4.3.1	Access to affordable and quality technical, vocational, tertiary and university	✓	●	●	✓	✓	✓	✓	●
4.4.1	Proportion of youth and adults with technical and vocational skills for employment and entrepreneurship	✓	●	✓	✓	✓	✓	✓	✓
4.5.1	Gender disparities in education and equal access to all levels of education for all	✓	●	✓	✓	✓	✓	✓	●
4.6.1	Percentage of population proficiency in literacy and numeracy skills, by sex	✓	✓	●	✓	✓	✓	●	●
4.7.1	Extent knowledge ad skill for sustainable development in curricula and teacher education	✓	✓	✓	✓	✓	●	●	✓
4.a.1	Proportion of schools with safe learning environment and access to adequate technology, facilities and infrastructure	✓	✓	✓	✓	✓	●	●	✓
4.b.1	Volume of official development scholarships for higher education	✓	✓	✓	✓	✓	●	●	●
4.c.1	Proportion of teachers with access to quality training pre-service or in-service for teaching at the relevant level	✓	✓	✓	●	✓	●	●	✓

Figure 9. DSM translated from pre-event poll results for SDG 4.

Due to the diverse combination of knowledge and expertise of peers attending the event, the participants gained a knowledge-based and experience-based perspective on the overarching topics at the junction of education and digital innovation during the group and panel discussions. According to the participants’ feedback, some of the specific subjects and interrelations in the DSM that received ‘no answer’ in the poll due to lack of information transformed into a more concrete standpoint after the knowledge exchange and dialogue throughout the event. For example, after discussing the interconnection of innovations in blockchain technologies and virtual reality for all indicators of SDG 4, as well as detailed information on the applications of such technologies in organizational and teaching content development in the education sector, a new set of information and use cases were shared.

During the working group discussions, the discussion driven by the DSM formed knowledge- and experience-sharing prospects for the topics of the SDG 4 indicators and digital technologies. An example of perspective changes during the event was the impact of AI/machine learning on the education system, specifically on the access to adequate technology, facilities, and infrastructure in administration and curriculum development (Indicator 4.a.1). Experts indicated their perspectives on how artificial intelligence (AI) allows for automation of classification and processing of paperwork and infrastructure, which led to a positive change in the response. In addition, the discussion on how AI and machine learning provide benefits for teachers and improve teaching techniques resulted in positive changes in the responses for Indicator 4.c.1. Regarding scholarship in higher education (Indicator 4.b.1), virtual and augmented reality can be used to make the scholarship system interactive, transparent, and efficient, causing a significant shift from its old-fashioned institution. These exchanges with transdisciplinary co-generation of knowledge and ideas worked as participatory inputs and led to a learning process that follows changed comprehensions and perspectives with respect to a few topics in the SDG 4 DSM (Figure 10).

The anatomy of digitalization for SDG4: Ensure inclusive & equitable quality education & promote lifelong learning opportunities for all

SDG4 Indicators		Data Driven			Analytics Driven			Design Driven	
		Mobile internet technologies/ App	Block chain	Internet of Things Digital twin technologies	Big data	Cloud computing Edge computing	AI Machine learning Deep learning	Virtual/augmented reality	Additive manufacturing 3D printing
4.a.1	Proportion of schools with safe learning environment and access to adequate technology, facilities and infrastructure	✓	✓	✓	✓	✓	✓	✓	✓
4.b.1	Volume of official development scholarships for higher education	✓	✓	✓	✓	✓	○	✓	○
4.c.1	Proportion of teachers with access to quality training pre-service or in-service for teaching at the relevant level	✓	✓	○	✓	✓	✓	○	✓

Figure 10. DSM changes (in red-colored boxes) that occurred during the discussion in the Thinkathon for SDG 4.

### 4.3. DSM as a Tool for PAR

Prior to and following the Thinkathon event, the participants were involved in each stage of the proposed PAR approach by inputting research-informed knowledge and know-how from their practice areas. This process led to co-generation of knowledge and co-learning, which are essential steps in facilitating the event’s effective use of mixed methods within the PAR approach. While encouraging full participation at all stages of the Thinkathon process, however, the involvement degree was not the same for every participant. In transdisciplinary research, some variables influence the extent to which participants prefer to be involved and engaged in the PAR approach’s activities; these range from diverse demographic individualities, institutional characteristics, and incentives for participation. In the Thinkathon, we measured the level of involvement by considering the number of participants who responded to the polls (40 for SDG 4 and 31 for SDG 13), keenly participated in the working group activities by communication and discussion through text, voice, and video, took part in the feedback survey, and participated in the post-event feedback session.

Within the PAR procedure in the Thinkathon, participation in the designed activities fed into action-oriented research, which led to an improved form of participation with an accessible result, thus supporting future action/research. The designed PAR processes, pre-event polls, post-event surveys, and the main event integrated the generated knowledge and validated productive participation. However, this combination of approaches was complementary and successful in accomplishing the event’s initial objectives. For instance, online surveys pose particular communication challenges, since they do not call for factual knowledge, but principally estimate specific issues. Studies suggest that if respondents sense the inability to estimate, they do not provide an answer. Therefore, in the Thinkathon PAR approach, we created a setting to discuss issues in working group discussions and shared the relevant information to overcome the barrier for active involvement. The panel discussion was also coordinated in connection to the other PAR sections to conclude and reflect on the event’s

overall findings. The panel was composed of experts who provided the creative input and ensured that many different viewpoints were well represented.

Overall, our study results provide practical reflections on applying the DSM as a tool to integrate the PAR approach, deriving a systematic methodology for transdisciplinary research, and generating qualitative research outcomes. The participants linked to digitalization and sustainable development in any way were able to participate and access the information shared during the event with more concrete discussion rather than a broader overarching debate. Furthermore, participants could share their expert opinions before, during, and after the event, which made the discussion more inclusive and unfolded the space for further concrete consideration of the meaningful utilization of D&AI for SDGs at the indicator level. The significantly favorable aspects of using the DSM for multi-stakeholder-inclusive discussion can be summarized as follows:

- The DSM helped multi-sectoral participants contextualize technological aspects and consider social and governance perspectives together, which is critical for practical implementations.
- Participants adhered to the explicit topic under consideration and identified new interlinkages and dependencies by utilizing distinctive expert knowledge.
- Inter-sectoral understanding—where theory met practices from all sectors contributing to D&AI and sustainable development.
- Support for transdisciplinary knowledge co-generation and collective action plan mapping.

## 5. Discussion

Recent literature recognizes the significant role D&AI could play in making progress corresponding to the SDG framework [27]. The digital revolution provides unique capacities and serves as a significant force in shaping both the systemic context of global transformative change and eventual solutions; simultaneously, it potentially brings robust societal and environmental disruption if not held with caution. Systematic exploration of values for implementing D&AI using key actors is necessary for realizing the sustainable transformation. Knowledge sharing, particularly with transdisciplinary perspectives, could help us realize the crucial potentials of D&AI for the SDGs. In the Digitainable Thinkathon, we reflected on the constructive relevance that D&AI have and will continue having from both technological and societal viewpoints.

Nonetheless, we are equally aware that the risks and other contrary impacts with which each digital technology group is associated can be aptly monitored and controlled. D&AI is both life-changing and disruptive. To date, D&AI enhances the availability of enormous amounts of digital data, empowers high-tech advances in computational, simulation, and analytical proficiencies, and causes innovative tools and smart models to mimic human intelligence to emerge. Even though digital technologies bring ample benefits to individuals and society, they pose risks and negative impacts, which may be challenging to anticipate, identify, or quantify at this point. Hence, it is essential to shape the operationalization of D&AI in a robust, sustainable, and favorable manner from both technical and social standpoints.

In this paper, we proposed the DSM as an approach to motivate and structure the dialogue on the conscious use of D&AI technologies for the SDGs at the indicator level. The DSM also undertakes the three main pillars of PAR, namely: the degree of participation, action-oriented dialogue and intervention, and transdisciplinarity, which were modified based on the application in the Thinkathon. The research outcomes are appropriate indicators for measuring the success of the PAR implementation in the Thinkathon. In addition, a fundamental part of the designed PAR approach for the Thinkathon was aimed at science–action community-building. Having a diverse group of stakeholders for a D&AI and sustainable development action planning is essential for the Agenda 2030.

As can be interpreted from the outcomes we gathered from the event, the DSM as a tool with the PAR approach helped address the questions and existing gaps discussed in the initial part of the paper. Notably, the DSM helped aid in:

1. Mapping the relevance of D&AI for SDG indicators considering the diverse perspectives from experts.
2. Realizing the certain interdependencies between indicators of the SDGs along with interdependencies between D&AI technologies.
3. Generating knowledge collectively with a transdisciplinary perspective for the thoughtful deployment of D&AI technologies for SDG indicators.

The DSM served as a valuable tool for promoting rich dialogues with transdisciplinary perspectives and promoting science-backed evidence for collective sustainable transformation. Such practices can also help in clarifying the individual discipline's and stakeholder's own ethical and epistemic values, which help in defining the accountability and transparency for collective action planning.

Furthermore, we would like to acknowledge that the research we have conducted and the tools we have introduced may have certain limitations. Firstly, the DSM is significantly based on generally agreed-upon indicators and digital technologies; the participants' inputs can have some degree of subjectivity. Even though it was advised during the pre-poll survey and during the event to contribute based on practical and concrete experience, subjectivity in inputs cannot be overlooked. Secondly, the participants may have inferred unintended meanings during the pre-poll survey, as there were eight questions (one for each technology under consideration) associated with each indicator. Thirdly, technologies may have a certain degree of overlap. For example, Big Data, cloud computing, and machine learning work synergistically in some circumstances. This context-based incertitude may bring inputs that do not accurately depict the relevance of D&AI for the SDG indicators and their respective interdependencies. Some participants could also anticipate more importance of one specific technology or indicator, which may lead to isolated inputs. Such inputs could be considered a limitation as well as an advantage, as the participation of multiple sectors and multiple stakeholders balances this isolated vision and, at the same time, adds in-depth knowledge about a particular context. There are further possible explanations for these limitations. Initially, the Thinkathon was designed to take place in a face-to-face arrangement, but because of the COVID-19 pandemic, we readjusted it in an online-only format. Deployment of the DSM in a face-to-face discussion arrangement with experts might bring in new prospects. Further iterations are required to address some of these limitations and make the proposed approach more beneficial.

Despite these limitations, our approach would lend itself well for use in a workshop setting with representatives from diverse backgrounds; it could also be useful for individual participants to gather a holistic viewpoint about using technologies at the individual indicator level or broadly at the SDG level, making it easy for informed participation in action planning. We believe that designing workshops where discussions are induced with the DSM as a tool could help understand dynamics across nexus systems [44]. The matrix could be filled in an iterative fashion, considering multiple contexts and disciplines by individuals, or in breakout groups to start an informed dialogue on how technology could affect the delivery of the selected SDGs, supporting planning processes at large. The DSM enables easy compilation of the technology application and identification of inter-linkages at the indicator level of the SDGs, which might help organize thoughts clearly within the context of a particular case study or project for evaluation. The DSM can also serve as a useful tool in educational settings, enhancing deep-rooted considerations and sustainability awareness.

The utilization of the DSM for two case studies (SDGs 4 and 13) also helped identify gaps and redundancies that need to be further improved. Future work will attempt to overcome some of these gaps and certain limitations. Though the DSM is intended to apply widely to indicators of different nature, not all aspects have been well considered. For example, considering socio-technical conflicts in technology usage could help in more concrete action planning. Extensions of this nature could be made in the next version of the DSM. Future work should also include possible ways of adding visual assistance in grasping the inter-linkage maps. It may also be beneficial for updated versions to include a section that can help identify recommendations in a particular context and quantitatively use the

knowledge generated in a more action-oriented way. Ultimately, the DSM presented in this work is the first version of a continuously evolving framework for examining how D&AI can support sustainable transformation considering the science-backed multi-stakeholder and multi-sectoral perspectives. As a tool, the DSM can help in the systematic exploration of values we need to consider for using D&AI for society, the environment, and the economy, a much-needed topic not just to achieve Agenda 2030 in general, but also to leverage the knowledge and strength to overcome the inequalities that impair the potential for a more sustainable, inclusive, and equitable future for all.

## 6. Conclusions

This research presents a participatory research tool, the Digitalization–Sustainability Matrix (DSM), which can help in measuring the “digitainability” of the Sustainable Development Goals (SDGs) at the indicator level. We presented the outcomes obtained by deploying the DSM during a multi-sectoral and multidisciplinary expert event for SDGs 4 and 13. The DSM helps address the existing gap in the current research landscape on the cross-section of digitalization and sustainable development by contributing as a tool that helps identify the SDG-indicator-specific relevance of Digitalization and Artificial Intelligence (D&AI). The information gathered using the DSM could serve as a valuable starting point for diverse stakeholders from multiple disciplines in accessing the practical implications of D&AI for supporting the SDGs’ progress considering their potential interlinkages. By sharing the framework from this open-access perspective, we expect that more sustainable transformation action planners/takers will validate and enrich the proposed tool by utilizing it in different contexts, which will help identify the areas where refinement and improvement are desired for measuring the meaningful use of D&AI. Comprehensively, the contributions of the DSM as a participatory research tool are threefold: firstly, in unraveling and critically reflecting on the technical and social needs for the application of D&AI at the SDG indicator level; secondly, in spelling out the values that need to be considered for utilizing D&AI; thirdly, in gaining transdisciplinary perspectives and potential common grounds on how D&AI could be used for the attainment of the SDGs.

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## Abbreviations

The following abbreviations are used in this manuscript:

DSM	Digitalization–Sustainability Matrix
SDGs	Sustainable Development Goals
D&AI	Digitalization and Artificial Intelligence
PAR	Participatory Action Research

## Appendix A

### *D&AI Technologies*

The utilization and incorporation of D&AI technologies are affecting all walks of life as well as extensive parts of organizations, companies, and beyond. Potential applications and benefits of D&AI are manifold and include increases in productivity, rapid innovations, and novel forms of

interaction among stakeholders, which can well serve the Agenda 2030. Given the broader set of D&AI technologies fostering sustainable transformation strategies, we have broadly classified the technologies into eight groups. The grouping was done while recognizing the worldwide discussion on digital transformation strategies and high-impact technologies that are paving the way for successful transformations. Brief details and definitions of each technology group we used in the DSM are discussed below.

**Mobile internet technologies/apps:** Mobile technologies are those who go where the user goes. They are based on portable two-way communication devices, computing devices, and the networking technology that connects them. These days, mobile technologies are internet-enabled devices like smartphones, tablets, and watches. These latest innovations include two-way pagers, notebook computers, mobile telephones, GPS navigation devices, etc. The communication networks enable mobile devices to share voice, data, and applications (mobile apps).

**Blockchain:** Blockchain is a data structure technology that allows people and organizations to reach agreement on and permanently transparently record transactions and information without a central authority. It has been recognized as an essential tool for building a fair, inclusive, secure, and democratic digital economy. This has significant implications for how we think about many of our economic, social, and political institutions.

**Internet of Things/digital twin technologies:** The Internet of Things (IoT) is a network of billions of interconnected devices or systems ('things') that can be remotely controlled over the Internet. These devices collect and exchange data that can be analyzed and aggregated to monitor, maintain, and improve processes to deliver products and services to consumers. Furthermore, digital twin technologies are the digital replicas of products or systems that are maintained as a virtual equivalent throughout the physical product's lifespan. Digital twin technologies utilize the IoT for creating the digital twin.

**Big data:** Big data refers to large amounts of data produced very quickly by a high number of diverse sources. Data can either be created by people or generated by machines, such as sensors gathering climate information, satellite imagery, digital pictures, and videos, purchase transaction records, GPS signals, etc. It covers many sectors, from healthcare to transport and energy.

**Cloud computing/edge computing:** Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.

In edge computing, the massive data generated by different types of IoT devices can be processed at the network edge instead of transmitting them to the centralized cloud infrastructure, owing to bandwidth and energy consumption concerns.

**Artificial intelligence/machine learning/deep learning:** Artificial intelligence is the use of science and engineering (software or hardware) to create intelligent machines that can make and/or act on decisions that usually require organic intelligence. As Max Tegmark said, "Intelligence that is not biological". The image in the annex provides a brief overview of the applications of AI.

**Machine learning:** Machine learning is the process of training a machine by developing algorithms to find patterns in massive amounts of data. Moreover, here, data encompass many things—numbers, words, images, and clicks. If it can be digitally stored, it can be fed into a machine-learning algorithm.

Deep learning is a subset of machine learning where algorithms are created and function similarly to machine learning, but there are many levels of these algorithms, each providing a different interpretation of the data it conveys. This network of algorithms is called an artificial neural network. In simple words, it resembles the neural connections that exist in the human brain.

**Virtual/augmented reality:** Virtual reality (VR) implies a complete immersion experience that shuts out the physical world. Using VR devices such as HTC Vive, Oculus Rift, or Google Cardboard,

users can be transported into a number of real-world and imagined environments, such as the middle of a squawking penguin colony or even on the back of a dragon.

Augmented reality (AR) is the visualization technology that adds digital elements to a live view, often by using the camera on a smartphone. Examples of augmented reality experiences include Snapchat lenses and the game Pokemon Go.

**Adaptive manufacturing or 3D printing:** Adaptive manufacturing or 3D printing is a process of making three-dimensional solid objects from a digital file. The creation of a 3D-printed object is achieved using additive processes. An object is created by laying down successive layers of material in an additive process until the object is created. Each of these layers can be seen as a thinly sliced horizontal cross-section of the eventual object.

## Appendix B. Thinkathon

The Thinkathon process consists of six phases:

**(1) Preparation and registration:** The Thinkathon event was initially conceived as a “two-leg” event, consisting of physical meetings in Bonn and the possibility for connecting remotely via Livestream. The Coronavirus outbreak forced us to discover virtual alternatives and move beyond ‘business as usual’ event set-ups while we were in the last stages of the preparation phase for the onsite event. The physical meeting size was limited to 50 participants, and we had 17 applications for remote participation. Under the impact of the COVID crisis, which made it impossible to conduct physical meetings, we started the format transformation process after the first announcement of the event. The scientific component of the event was shaped during the registration of the applicants in the early phase. We asked in the registration portal about the three most relevant SDGs to applicants’ expertise and interests. SDG 4 (quality education) and SDG 13 (climate action) received the highest numbers of votes.

**(2) Pre-event survey:** As a kick-off to start to the event and warm-up step, we shared a link to a two-part survey on the overarching topic of the event: cross-cutting concerns of D&AI and Sustainable Development Goals, based on the DSM design, for the SDG 4 and SDG 13 indicators. The survey was accessible two days before the event, along with an introductory video and material to inform the participants about the envisioned Thinkathon program and platforms.

### **(3) Thinkathon:**

**(a) Event:** We started by introducing the event concept and procedure, as well as a short talk on the “digitainable” project. After that, we divided the participants randomly into two groups and guided them into two breakout rooms. Two moderators facilitated each of the event sessions with the context designed for the interaction among participants focusing on SDG 4 and SDG 13. Working groups shared insights and exchanged information on the deliberated-upon topics by commenting, texting, and interacting via audio.

**(b) Expert panel:** As the concluding stage of the event, our guest experts conducted a roundtable/panel remotely. The panel started with a short introduction by the moderators and continued with experts’ introductory opinions on the focused-upon topics. The main discussions and highlights of the working groups were reflected upon and concluded in the webinar. The webinar had a wide range of functionality, including reminder/invitation emails, a short introduction of the panelists, transcription and reporting of the context, and engaging platforms for questions and idea exchanges. The scientific framework and outcome of the Thinkathon event are described in the next parts of the article.

**(4) Post-event survey:** Right after the event ended, a link to the second survey was shared with participants as a short feedback questionnaire. We gave participants a few days to respond to the feedback survey questionnaire. The result of the survey contributed to the formation of the feedback session.

**(5) Feedback session:** Very unique in its design, the feedback session took place three weeks after the Thinkathon expert event (virtually). We organized a reflection and feedback session where we

interacted with the Thinkathon participants once more. In the feedback session, we presented the outcome of the scientific discussions on D&AI and sustainable development in the cases of both SDG 4 and SDG 13. Moreover, we highlighted the questions and issues which remained unresolved, restrictions that need to be addressed, and the ways forward for collaboration and networking.

**(6) Outcome delivery:** Further in this paper, the Thinkathon expert event results are presented. We explored some fundamental aspects of digital transformation in the area of knowledge and action for sustainable development, research, and higher education, as well as a view on collaborative community-building. We aimed to look behind the scenes of the emerging digital technologies and innovative solutions for highly complex tasks of the selected SDGs, as well as the potential risks and opportunities that may be proposed in that domain. In addition, the participants discussed some of the ethical concerns involved in the specific case-based applications of digital technologies.

## Appendix C. Poll Results

### Appendix C.1. SDG 13



Figure A1. SDG 13 poll results 1.

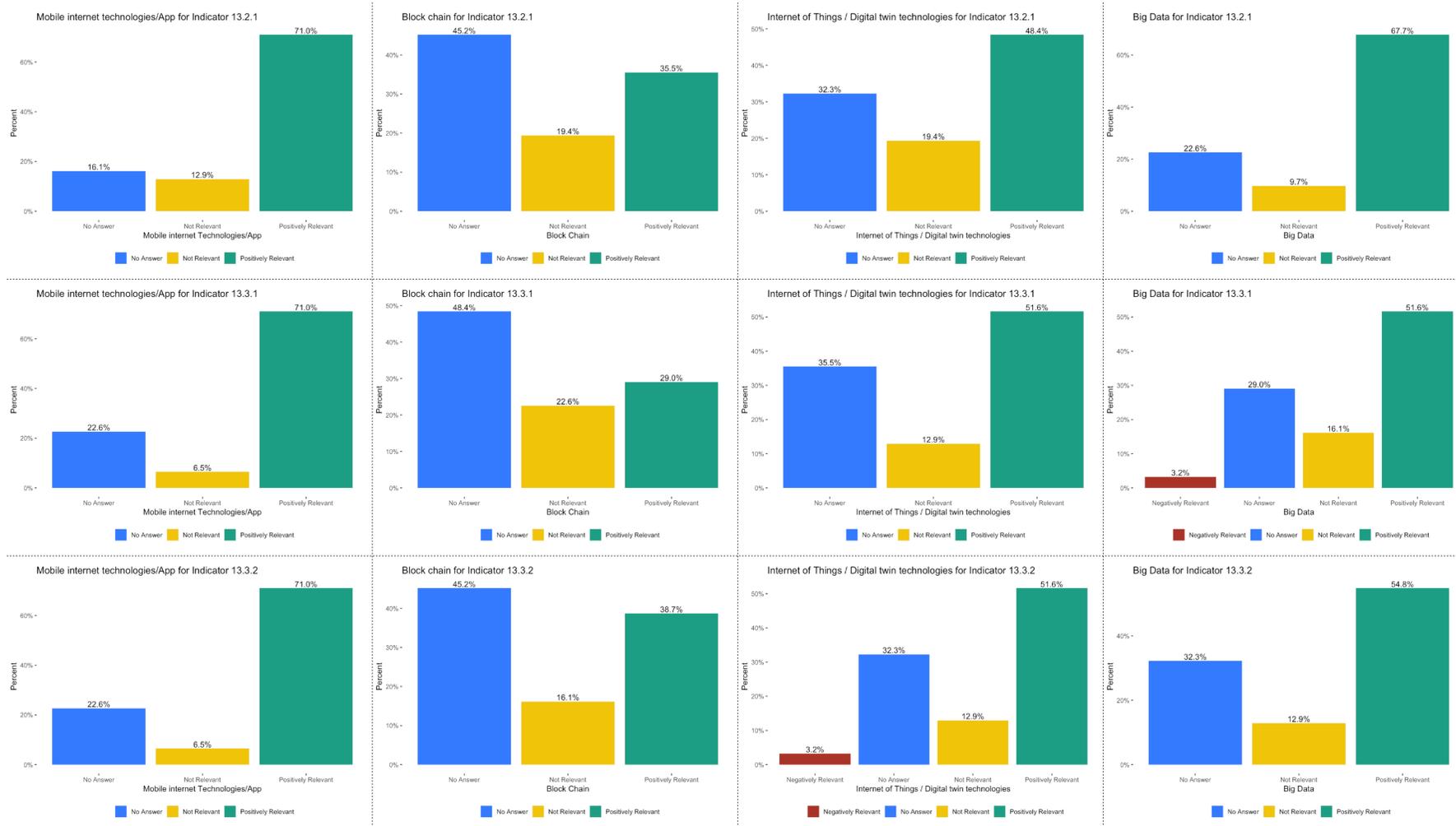


Figure A2. SDG 13 poll results 2.

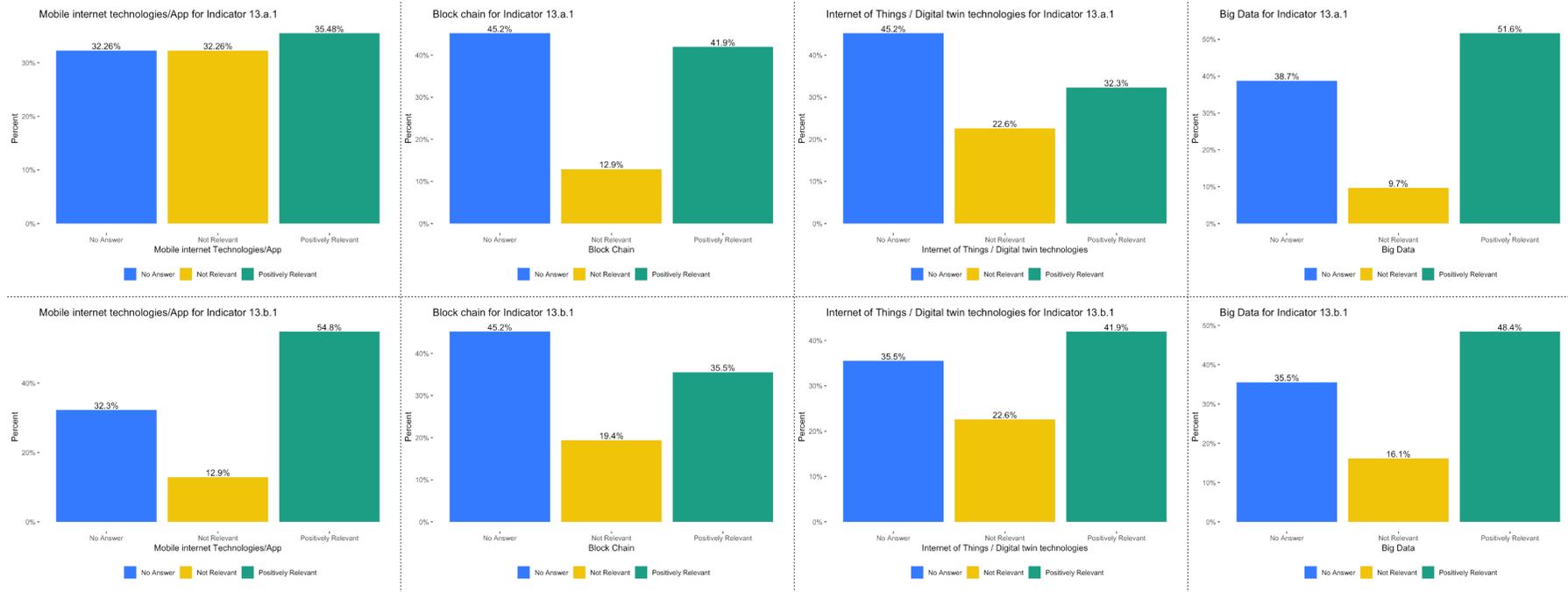


Figure A3. SDG 13 poll results 3.

Appendix C.2. SDG 4

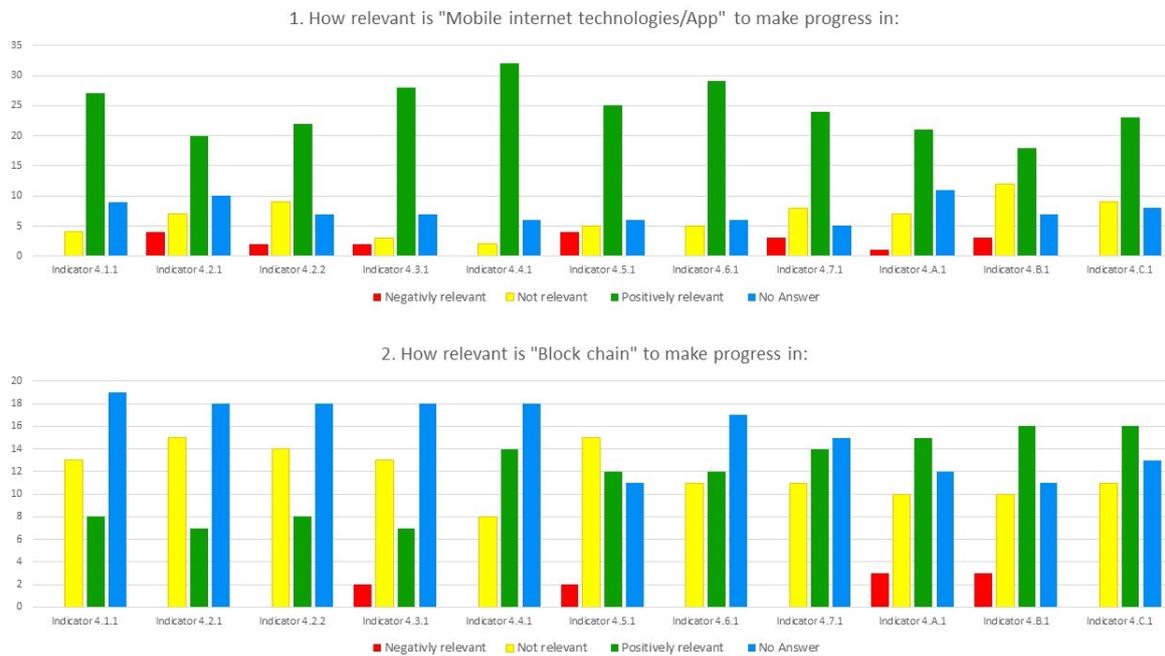


Figure A4. SDG 4 poll results 1.

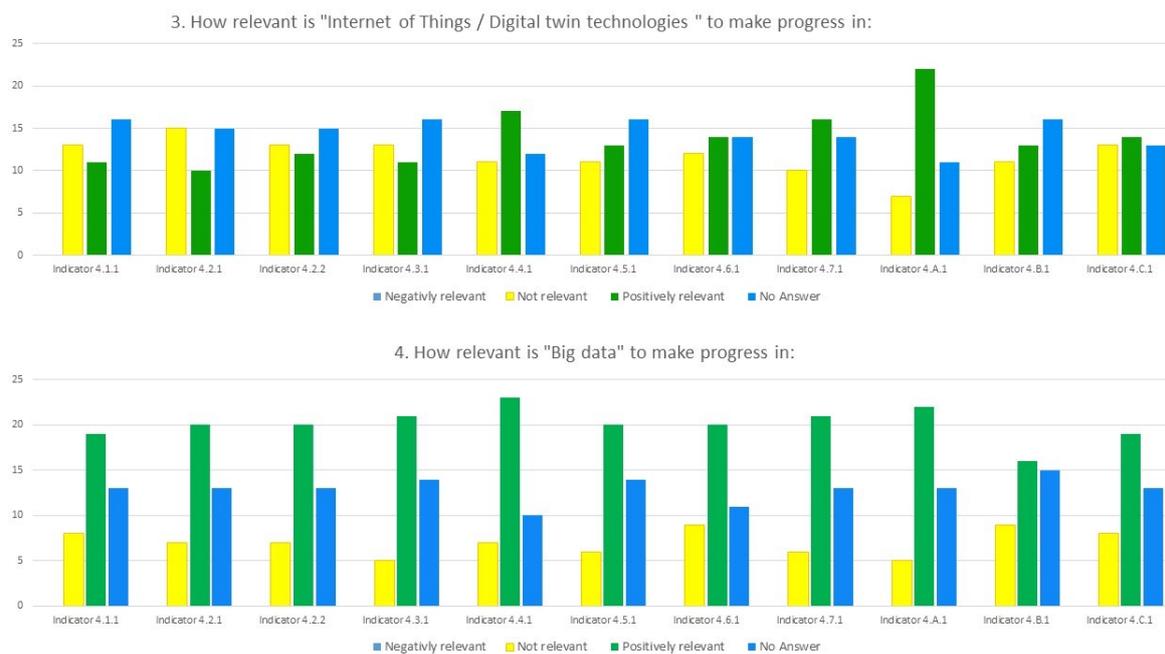


Figure A5. SDG 4 poll results 2.

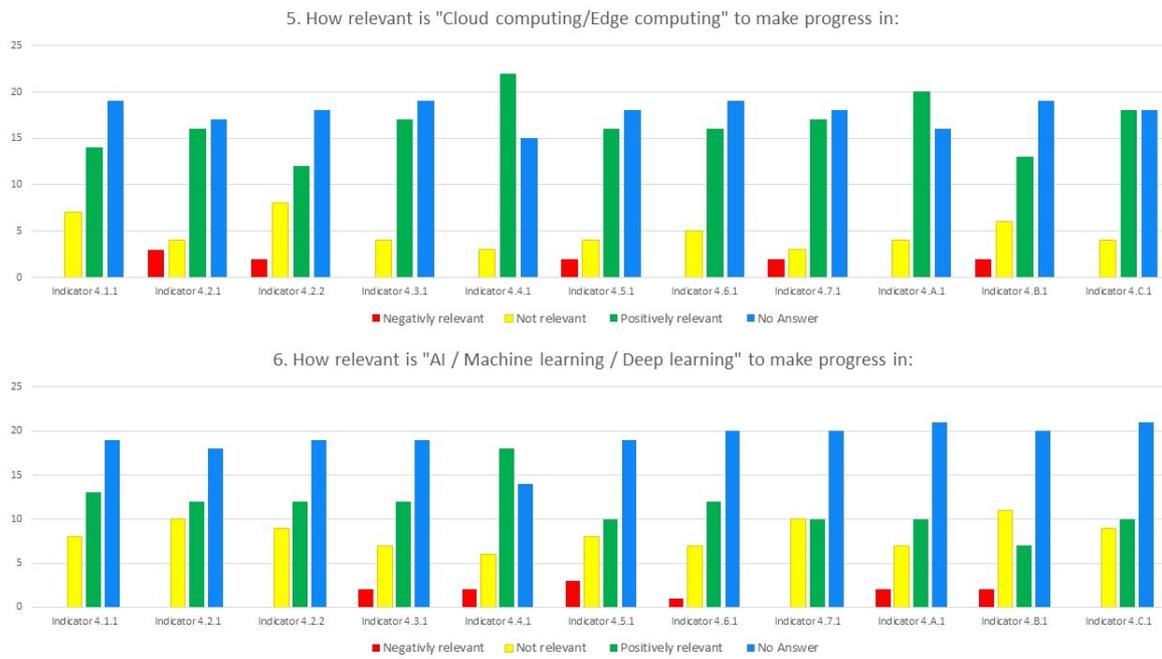


Figure A6. SDG 4 poll results 3.

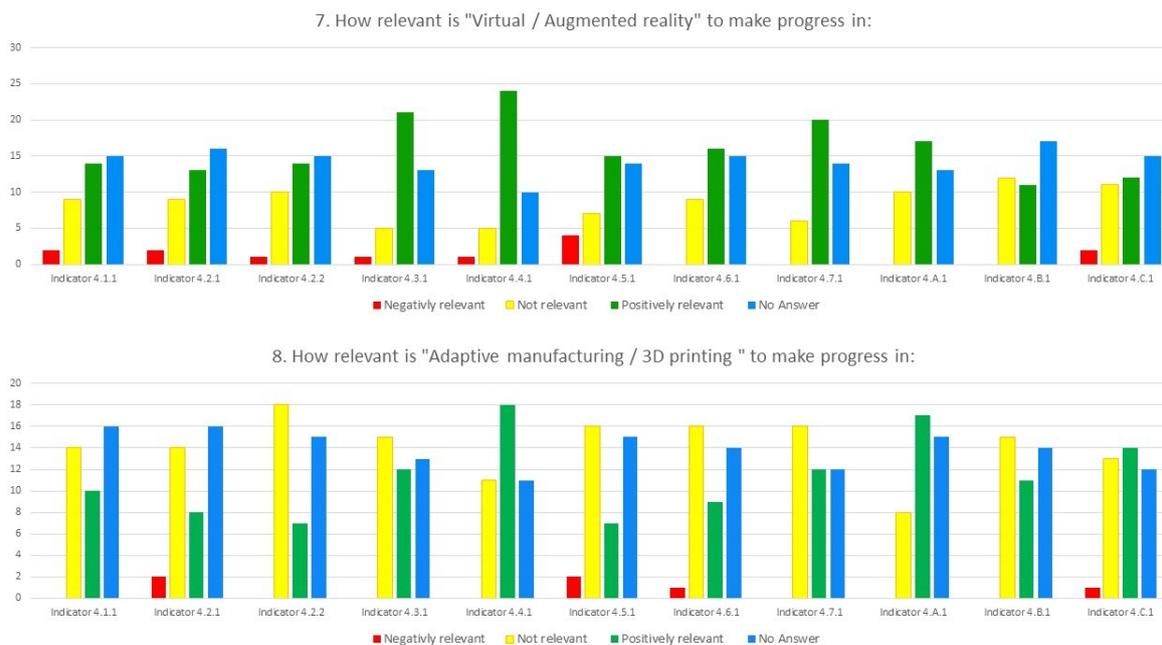


Figure A7. SDG 4 poll results 4.

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