DIGITAL TWIN TECHNOLOGY AND ADAPTIVE MANAGEMENT SYSTEMS FOR DEEP SEA MINING

Limitations and the Risk of Self-Regulation

DSMC
Deep Sea Mining Campaign

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ABBREVIATIONS

AI	Artificial Intelligence
AMS	Adaptive Management System (AMS)
CCZ	Clarion Clipperton Zone
DSM	Deep Sea Mining
DT	Digital Twin
(IMFe)	Information Management Framework for Environmental Digital Twins
ISA	International Seabed Authority
TMC	The Metals Company

EXECUTIVE SUMMARY

Digital Twin (DT) technology, defined as virtual representations of physical entities, is heralded as revolutionising industry by providing real-time data-driven insights to optimise operations and reduce risks. While advances have been made, the technology is still in its infancy. Its capacity to monitor and mitigate the impacts of deep sea mining (DSM) would appear several decades premature. For the foreseeable future, the data assimilated by a DSM DT is likely to relate to equipment performance and a small number of readily measured environmental parameters. This is an insufficient proxy of the wide-ranging mining impacts predicted. The broad scope of the early-stage Trident project (Section 3.1) illustrates the significant challenges to be overcome.

The deep sea is a complex and poorly understood environment and DSM is an unprecedented industry, thus potential impacts are characterised by a high level of uncertainty. The scientific consensus suggests that these would be severe, long term and potentially irreversible in human time frames.[1] The ability of digital modelling tools to ever accurately predict such impacts in a complex environment is viewed by independent scientists with caution.

DSM aspirant, The Metals Company (TMC) has partnered with Norwegian multinational technology company, Kongsberg Digital, to develop a DT that will visualise aspects of its DSM operations. TMC promotes the DT as a tool for transparency, "providing eyes and ears to the regulator and stakeholders."[2]

TMC claims to have deployed Kongsberg's patented Dynamic DT (Kognitwin) during test mining in its Nauru sponsored (NORI-D) exploration licence area. This is in an area of international water in the Pacific Ocean known as the Clarion Clipperton Zone (CCZ) which stretches between Hawai'i and Mexico. But with no public disclosure of the data collected or the performance of the DT, this serves to highlight the control companies will have over the information revealed. It is notable that during this same mining test, TMC failed to report a pollution spill from its support vessel until a video leaked by scientists on board forced it to do so.[3]

TMC maintains that the DT will be a core component of the company's Adaptive Management System (AMS) which will aim "to ensure operations remain within environmental impact thresholds".[4]

The validity of the AMS concept for DSM is itself dubious. It will be decades before enough is known about deep sea ecosystems, their role in broader oceanic processes such as nutrient cycling and carbon sequestration, and their relationships with other marine species, to set meaningful environmental impact thresholds.[5]

Furthermore, the effectiveness of AMS in mitigating DSM impacts is contingent on the accuracy and reliability of the data provided by the DT. In deep sea environments, sensors would degrade due to extreme pressures, temperatures, and corrosion, potentially resulting in data inaccuracies, which would undermine the reliability of the DT simulations and predictions.

In the absence of mandatory standards, the application of adaptive management and digital twins to DSM would provide this unprecedented industry with a facade of cautious environmental management, while in fact trusting companies with the strongest of vested interests to self-regulate and to set critical determinants of environmental management. These would include the environmental parameters they would measure, the level of impact they deem unacceptable, the response they would action to address impacts and crucially the data they would share.

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1 WHAT IS A DIGITAL TWIN?

Image: Adobe Stock/KikkyCNX generated with AI

DTs are virtual representations of physical entities. These can be an object (such as a building, ship, or gas well), a system of objects (such as a mining or engineering project), a system of objects plus services (such as a factory, city, or hospital), or an environment (such as an ocean).

These virtual representations are created and updated using data from sensors connected to the physical objects. The DT then uses a digital interface (the “internet of things”) to integrate simulations, machine learning and artificial intelligence (AI) to analyse the data. DTs can be used to predict the physical object’s behaviour under different scenarios, monitor changes in the system and aid decision making. A DT’s performance is entirely reliant on receiving accurate data from the sensors in a timely manner. Advanced DTs incorporate algorithms that flag when sensors are not functioning optimally.

However, there are few examples of ‘mature’ stage DTs with the majority providing data-collection or error analysis functions rather than enabling more complex autonomous or adaptive systems. [6]

Classification of DTs has become more precise over time. Reviewers note that the term “DT” is sometimes incorrectly applied to describe any computer program that models the physical system, such as a simulation or replica. Simulations or replicas are more correctly termed digital shadows.[7] They can represent the physical object in a static form but are unable to monitor changes in real-time. The key difference between a DT and a digital shadow is the real-time dynamic flow of data – from the physical to the digital and back again.[8]

Simulations and AI (including “deep learning” or “machine learning”) are important components of DT. These technologies, while capable of generating complex data, do not interact directly with the physical object in real-time.

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2 WHERE ARE DIGITAL TWINS USED?

In recent years, the application of DTs to maintain equipment and to optimise operations and supply chain management has grown across a wide range of industries. These include construction, health care, maritime, automotive, aerospace, defence, resource extraction and energy generation.

More recently, interest has grown in developing complex and dynamic DT technology within the environmental sciences and in large scale environmental mapping projects. There has also been interest in using DT for the spatial mapping of agricultural land use and in "smart city" design initiatives.[10, 11]

DTs have been deployed in the offshore oil and gas industries since around 2017 to visualise and optimise operations in challenging and inaccessible environments.[12, 13] Rather than environmental management, the key focus in this sector has been monitoring asset integrity, project planning and life cycle management.[14, 15, 16] Some challenges to the use of DTs in this sector include cybersecurity, sensor deterioration and the lack of standardisation between digital models.[17] Due to sensor decay, DTs must incorporate internal monitoring to ensure that the digital system performs to standard.

DTs are increasingly used to reduce supply chain and productivity risk in various industries particularly via predictive maintenance, for example by predicting mechanical component failure. However, these DT systems face significant technical challenges in tracking complex physical systems.[18] True dynamic DTs are yet to be developed for large scale engineering projects. The existing data-driven AI approaches are not considered capable of predicting failures sufficiently in advance to trigger corrective actions in close to real-time.[19]

DTs have also created much excitement in the aerospace and defence industries as evidenced by industry blogs and media releases. However, confusion between DTs and digital shadows (simple replicas) suggests that dynamic DTs are not yet commonly used in these industries.[20]

2.1 Large-scale Environmental Digital Twins

Interest is growing in mapping and managing data across whole ecosystems to better understand global meta-problems such as climate change and ocean degradation. The complexity of such systems requires dynamic DTs that interact with the environment and closely follow changes over time producing a "process understanding". Such DTs would enable the interrelationships between ecological variables to be mapped and scenarios to be predicted.[21]

A consortium of experts, led by the UK's National Oceanography Centre have published An Information Management Framework for Environmental Digital Twins (IMFe) that outlines the building blocks required to realise the potential of environmental DTs. The IMFe emphasises the need for agreed standards to facilitate inter-operability of DTs, data sharing and verification as part of broader digital modelling efforts.[22]

The ambitious EU-funded "DT of the Ocean" was launched in 2022. It aims to create a digital map of the world's oceans to measure and visualise key sustainability issues and communicate this information widely. As part of this, the Iliad Consortium has created a range of tools for scientists and the public to access ocean environmental data in an interactive way.

A "virtual ocean" with the technological capacity for two-way data flow across systems will require unprecedented cooperation between diverse institutions, industries, and disciplinary fields. Monitoring environmental impacts in the ocean requires data to be integrated across three dimensions: depth, spatial area, and time. Current obstacles include insufficient knowledge of marine processes, limited data sharing and data compatibility, and cost.[23]

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3 DIGITAL TWIN AND ARTIFICIAL INTELLIGENCE INNOVATIONS IN DEEP SEA MINING

The published literature on the application of DTs and AI for DSM suggests that the research to date has focused on:

- The use of DTs to solve DSM engineering problems such as self-tuning of the kinematic systems, or optimising the speed control, trajectory tracking and obstacle avoidance of remotely operated mining vehicles[24, 25]
- The utility of AI and machine learning tools (not dynamic DTs) for analysing deep seabed biodiversity data and investigating the impact of DSM on benthic fauna, and
- Digital modelling to predict the dispersal of sediment plumes generated by DSM operations.

One study concluded that while promising, there are currently significant limitations in the use of digital technology for visualising deep sea environments, analysing biological distributions, and classifying deep-sea organisms. These are due to a lack of ecological data, many environmental variables with complex and unpredictable interactions, and the need for interdisciplinary approaches. The visualisation and quantification of fauna living inside deep-sea sediments also remain challenging due to the lack of interdisciplinary and multidimensional systems capable of analysing the volume of video data from existing ocean observations.[26]

A sense of the difficulties in compiling reliable deep seabed biological databases is provided by a study utilising traditional sampling and species identification methods that found that even minor anomalies in collection or observation can lead to misclassification of biota.[27]

Sediment plume dispersal was examined for a hypothetical polymetallic sulphide mining scenario in the North Mid-Atlantic Ridge and a small-scale nodule mining trial conducted within the German exploration licence area in the Clarion Clipperton Zone (CCZ) of the Pacific Ocean.[28, 29] The latter study found that the digital model was able to predict actual plume dispersal patterns with an acceptable degree of accuracy. However, these technologies are

at a very early stage and would need to be coupled with interdisciplinary and complex ecological DTs to meaningfully predict impact.

The modelling of sediment plumes was combined with digital representations of seabed disturbance to understand impacts on benthic nematode populations resulting from polymetallic nodule collection trials by Belgian company Global Sea Mineral Resources. The study indicated a loss in biodiversity in the short term but cautioned that increased replication, larger spatial coverage, and long-term monitoring were required to draw meaningful conclusions.[30]

The MiningImpact international research project investigating the potential environmental impacts of DSM has used a variety of digital tools to synthesise photographic surveys, hydro-acoustic mapping, benthic biodiversity data, sediment biogeochemistry and sediment plume dispersal. Its research program going forward will continue to explore and refine the use of AI and machine learning to understand the impacts of DSM.

3.1 The TRIDENT Project

The early stage TRIDENT project aims to develop and test dynamic DT technologies and advanced AI to monitor impacts associated with seabed mining of polymetallic nodules, ferromanganese crusts, and polymetallic sulphides. It seeks to provide a 'tool for sustainable, transparent, deep sea mining exploration and exploitation.'

Launched in 2023 and supported by a consortium of European partners, the €16 million project is planned to run for five years hosted by the private Portuguese research association INESC TEC (Institute for Systems and Computer Engineering, Science and Technology).

This exceedingly ambitious project will necessitate the establishment of baseline data for a wide range of environmental parameters, a network of sensors attached to remote-controlled submersible robots operating under extreme conditions at depth, and the capacity to reliably transmit and display monitoring data generated by small scale mining tests;[31] objectives that do not seem achievable within a five-year timeframe. The project aspires to eventually use this data to calculate and predict the impacts of commercial scale DSM. The data and technology requirements would suggest that this may yet take decades, especially as information and understanding about relevant environmental parameters is only just emerging.

Image opposite: Humpback whale, Adobe Stock/Jamesteohart. Image below: Modified by Nat Lowrey.

4 THE METALS COMPANY, DT TECHNOLOGY AND ADAPTIVE MANAGEMENT

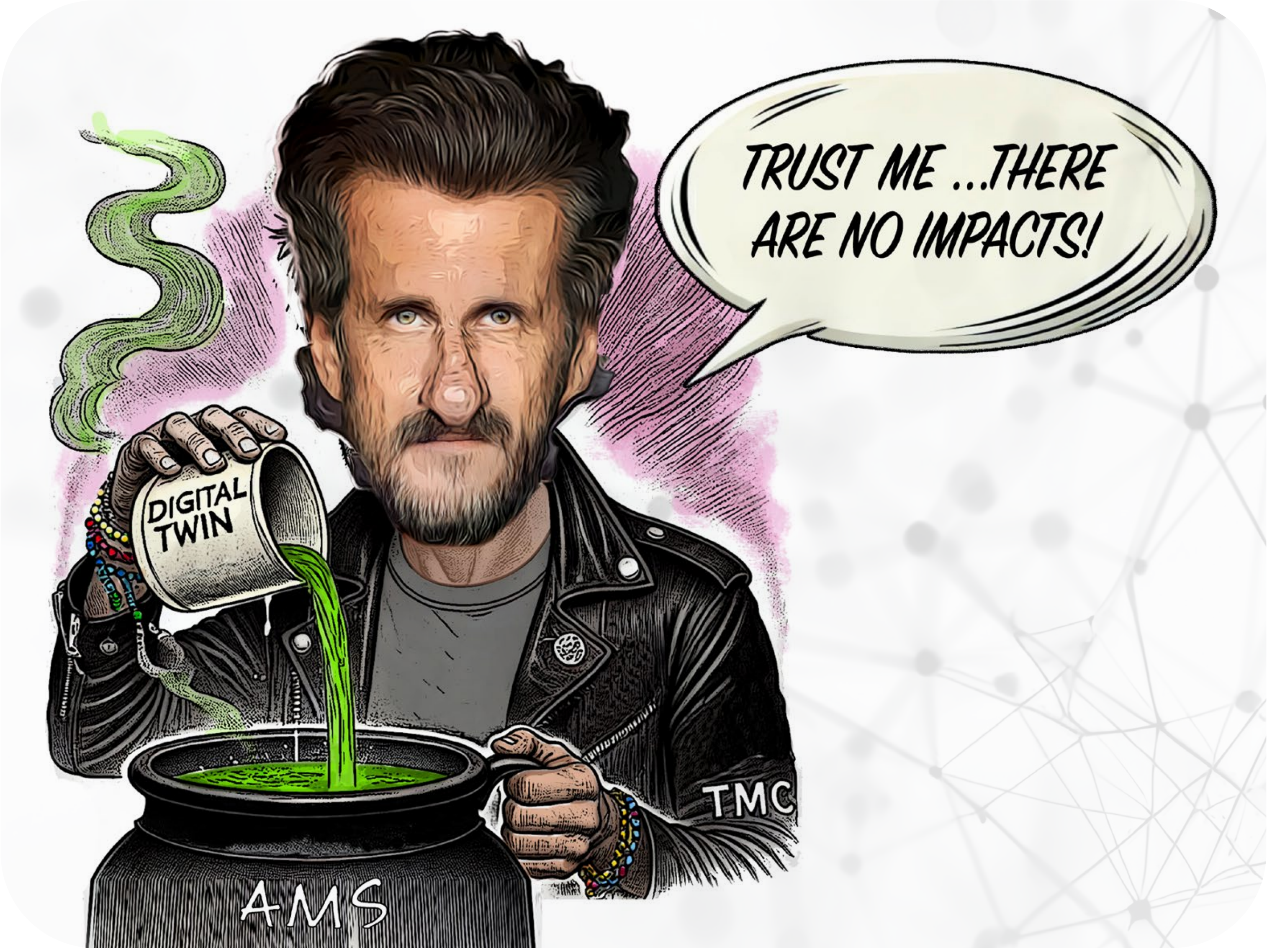

Image: TMC CEO, Gerard Barron and his push for digital twin technology for deep sea mining. Generated with AI by Nat Lowrey.

4.1 AMS in DSM: Learning by destroying

The Metals Company (TMC), arguably the most presumptuous of the small number of companies proposing to mine the deep seabed, hopes to start mining the Pacific Ocean floor by early 2026. As a start-up company with limited funds, its rush to begin commercial mining is driven by financial imperatives.[32] The company has no time to wait for science to catch up with its financial ambitions and for government decision-makers and society as a whole, to better understand the impacts of this unprecedented industry and determine whether it should proceed. Instead, TMC argues it will develop an Adaptive Management System (AMS) to "mitigate operational impacts in the deep-sea environment as much as possible." TMC has stated that its DT will be a core component of the AMS.[33]

AMS is an experimental "learning by doing" approach to project management in which data is collected and operations are adapted during the course of a project.[34]

In effect, the adaptive management of DSM would establish the world's deep oceans – the common heritage of humankind – as the living experimental laboratory of DSM companies.

AMS evolved in the fields of ecology and systems biology for the purpose of natural resource and conservation management due to the complexity of interactions between ecology, hydrology and geology.[35] There is only limited evidence that the approach leads to improved resource management and mitigation of impacts by extractive industries.[36]

Indeed, the validity of AMS has been challenged for projects that could rapidly result in serious harm to ecological systems or where impacts last for a very long time. It is argued that the inherent complexity of environmental systems renders it implausible for any modelling tool to achieve sufficient accuracy to guide decision making or mitigate impacts, especially while the project is actively causing destructive changes within that system.[37]

Furthermore, the effectiveness of an AMS that is reliant on a DT as its data source is contingent on the accuracy and reliability of the data provided. In deep sea environments sensors would degrade due to extreme pressures, temperatures, and corrosion, potentially resulting in data inaccuracies, which would undermine the reliability of the DTs simulations and predictions.

The application of AMS and DT to DSM would offer this unprecedented industry the opportunity to mine world oceans under a facade of cautious environmental management. It would mask the paucity of knowledge about deep sea ecosystems, the broader roles these play in stabilising planetary systems, and the likely cascade of impacts DSM would create.

4.2 The Kognitwin: its capacities and limitations

Kongsberg Digital, a subsidiary of the Norwegian Kongsberg Group, is a provider of digital technologies including its Kognitwin DT, to the defence, aerospace, maritime, manufacturing, and renewable energy sectors.

According to Kongsberg, Kognitwin integrates information from various sources, including sensors, internet of things devices, and historical data to create a dynamic replica of physical assets.[38] Key features include real-time data visualisation to monitor physical assets; predictive models to forecast operational problems; and scenario simulations to help optimise processes. The integrated data is displayed on a digital workspace.

The capacities described for Kognitwin do not extend to the analysis of the cascading and inter-related environmental impacts that are predicted to result from DSM.[39] The data assimilated by Kognitwin relate largely to equipment performance and a small number of readily measured environmental parameters. The broad scope of the early-stage Trident project (Section 3.1) clearly illustrates the many significant challenges that must be overcome before digital technologies can analyse DSM impacts with an acceptable degree of accuracy.

4.3 AMS + DT = Environmental Self-Regulation

A partnership between Kongsberg and TMC was announced in 2021 to develop a DT for "dynamic mine planning, scenario modelling, and impact forecasting" and to make operational and environmental data publicly available via an online dashboard. It is suggested that such data may include the collection system's location, certain tracked ecosystem variables and their comparison to baseline environmental values as determined by TMC's research.[40]

While this attempts to convey an aura of technical proficiency and transparency, this proposition appears to leave critical determinants of the environmental logic underpinning the Kognitwin and the AMS solely to TMC's discretion. This scenario also assumes TMC possesses a high level of scientific expertise and corporate integrity.

TMC advised that a Kognitwin was deployed in nodule collection trials in its Nauru sponsored (NORI-D) exploration licence area in the CCZ in the Pacific Ocean – an area of international water stretching between Hawai'i and Mexico.

According to TMC the deployment of the DT involved "...an array of over 50 subsea sensors on seafloor landers and mid-water moorings to continually monitor sediment plumes and noise generated by the nodule collection operations."[41]

To date, no information has been shared on the performance of the DT or the data it collected.

Notably, it was during this same mining test, that TMC failed to report unauthorised pollution from its support vessel until forced to do so by a video leaked by scientists who were contracted by TMC. Their footage shows wastewater containing rock debris and sediment sucked up from the seabed directly discharged at the ocean surface, with unknown toxicity and ecological impact. The scientists also reported that flaws in the scientific program's monitoring system, poor sampling practices, equipment failure, and inappropriate instrumentation for sediment plume measurements rendered the data collected meaningless.[42]

Currently, no independent oversight, regulations or industry standards exist for the deployment of DTs, the parameters that DTs should measure to determine ecological impact, the transparency of data collected and the stakeholders it will be shared with. There is also no agreement about what constitutes effective protection of the marine environment, serious harm to the marine environment including from the cumulative impacts of DSM, 'acceptable' levels of impact, and who determines these criteria and on what basis.[43] Decades of coordinated research is likely to be required to close current 'monumental' scientific knowledge gaps and to address these fundaments of environmental management for DSM.[44]

The regulations that would enable DSM exploitation are yet to be finalised by the International Seabed Authority (ISA) through a process of negotiation amongst its 168 state members.[45] Many important aspects of the draft regulations are far from settled.[46] These critical environmental questions are still a focus of active and often contentious discussions.

Despite this, TMC through its subsidiary Nauru Ocean Resources Inc. (NORI), invoked a clause under the UNCLOS agreement in 2021 (the 'two- year rule'), pressuring the ISA to finalise the regulations by July 2023 or be forced to provisionally approve mining plans. This deadline has passed and there are still many barriers to TMC gaining a commercial mining licence.[47] However, this action highlights TMC's rush to begin mining, prioritising their corporate interests over the protection of the marine environment and the well-being of human communities.

TMC is asking society to overlook its direct financial interest and to trust in its integrity and capacity to self–monitor and to self-regulate: to determine which environmental variables to measure, how much harm is acceptable, how it will respond to unacceptable impacts, and whether it will allow public access to information about the damage its causes.

Proceeding with DSM under the smokescreen offered by AMS and DTs would facilitate a regulatory free-for-all. It would not enable the high standard of management appropriate for an environment recognised by intenational law as the common heritage of humankind.

CONCLUSION

The application of digital twin technology and adaptive management systems to DSM is fraught with risks due to the limitations of the technology and the significant gaps in knowledge about deep sea ecosystems. These mean that for the foreseeable future, the predictive capacity of DT models such as the Kognitwin that TMC hopes to deploy, will be constrained to equipment performance and a few readily measured environmental parameters. These would not provide an accurate indication of the interconnected ecological harms predicted to result from DSM.

The ability of a DT embedded in an AMS to protect the deep sea from catastrophic DSM damage is only at the concept stage. The challenges to be overcome in complex and dynamic ocean environments and extreme conditions at depth are illustrated by international collaborations such as the DT of the Ocean (Section 2.1) and the TRIDENT project (Section 3.1). These projects, the IMFe (Section 2.1) and current scientific understanding suggest that the following are minimum capacities for DTs to be of value in the context of DSM.

- Integration of data from a wide range of measured environmental parameters, including but not limited to physical oceanographic and biological variables, plume generation and dispersal, sedimentation, noise, and indicators of ecotoxicology related to metals and alpha radiation.
- Simulation and analysis of real-time changes in these variables while mining is underway and for several decades following mining.
- Model validation and verification.
- Integration of data from comprehensive, independently verified baseline studies completed before mining begins. (Noting that if baseline data is inadequate, even the most advanced DT will be unable to analyse mining impacts).
- Connection to a digital workspace that offers inter-operability for multiple teams including for verification by independent scientists
- Data transparency to regulators and civil society stakeholders.

Science-based mandated standards developed with the input of researchers independent of the DSM industry would be required to ensure quality and consistency within and across DSM DTs. These would need to be incorporated into any regulations finalised by the ISA for commercial DSM.

TMC seeks to begin commercial mining by 2026. This does not align with the time required to close knowledge gaps relating to deep sea ecosystems and their roles in oceanic and planetary processes and to develop the standards and capacities for DTs and AMS to have any meaningful application in preserving these ecosystems.

At the time of writing, 32 countries support a moratorium or ban on DSM.[48] The disparity between the timelines pushed by DSM companies and the time needed for research to ensure the wellbeing of all who depend on the ocean, strongly supports a moratorium.

Proceeding with DSM in the near term under the smokescreen offered by AMS and DTs would facilitate a regulatory free-for-all: allowing the very companies with the most to gain from this unprecedented industry to set the critical determinants for its environmental management and protection.

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