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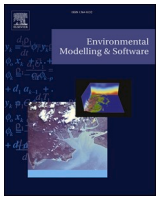
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Twenty years of the ODD protocol: development, usage, extensions, and lessons learned about modelling standards development

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ABSTRACT

The ODD (Overview, Design Concepts, Details) protocol began in 2006 as a standard for describing agent-based ecological models and is now widely used in many disciplines. Updates in 2010 and 2020 provided detailed usage guidance. Numerous extensions have customized ODD for specific disciplines and model types. ODD has proven valuable for guiding model design and development by providing a checklist of concepts to think about explicitly, and for reviewing models. The ODD experience indicates that successful standards focus on specific parts of the model life cycle, have a clear purpose and facilitate communication within and outside of the modelling team. Future directions may include developing ODD-like standards for other model types and coupled modelling systems. The lessons from ODD point to a need for modelling standards across all areas of science, providing a common foundation for greater transparency, reproducibility, communication, responsibility, and coherence in scientific modelling.

1. Introduction

The ODD (Overview, Design Concepts, Details) protocol is a standard format for describing agent-based models (ABMs, also referred to as individual-based models in ecology; Grimm et al., 2006). Twenty years on from its introduction, this article traces how ODD has been used, extended, and critiqued across disciplines, and distils lessons learned for the design of future modelling standards, from both its creators and its users.

ODD was developed to address one of the biggest initial challenges of ABMs, that model descriptions were often incomplete and lacked a clear structure or rationale, making them difficult to understand and nearly impossible to replicate the model and its results (Rouchier, 2003; Will and Hegselmann, 2008). The ability to replicate published studies, however, is a defining element of the scientific method (Freese and Peterson, 2017). ABMs were thus criticized as black boxes fully documented only by their computer code, which was typically unavailable or difficult to understand.

To overcome this situation, the ODD protocol was proposed. Initial ideas for ODD were presented in Grimm and Railsback, 2005, Chapter 10.3), then further developed and tested using 19 models at a workshop in Bergen, Norway, in 2004 (Grimm et al., 2006). The protocol required citing the ODD publication, making it possible to monitor its use. This tracking record informed two subsequent revisions — in 2010 (Grimm et al., 2010) and 2020 (Grimm et al., 2020a). These revisions refined the protocol's wording and consolidated the questions, limitations, and issues that had arisen from a decade and a half of use. The second revision came with an extended supplement providing detailed guidance for these issues, including examples and warnings about common misunderstandings or omissions. This iterative refinement kept pace with, and was made possible by, ODD's growing use: in terms of citations, and therefore usage, ODD has become one of the most widely adopted standards in the modelling literature (see Sect. 3). Today, it is used far beyond its original field of application, ecological modelling (Vincenot, 2018). Economic, epidemiological, and sociological models, among others, are also frequently described using ODD. This standard showed a surprisingly rapid and widespread adoption, especially given that most modelling standards generally see limited uptake (Jakeman et al., 2024; Rosello et al. 2026), and given the initial resistance ABM developers showed toward adopting a shared descriptive format. Such resistance was partly rooted in disciplinary differences in terminology and modelling culture that make cross-community standardisation inherently difficult (Bracken and Oughton, 2006). ODD has now been used long enough and in such a wide range of disciplines and contexts that we consider it worthwhile to summarize how and by whom ODD has been used, how and why it has been extended, and its limitations. We then summarize the lessons we, some of the ODD creators and ODD users, and other researchers learned from ODD and how they could inform the development of other standards for good modelling practice and more coherent and efficient modelling across disciplines.

2. The original ODD and its updates

ODD was developed for two main purposes: 1) to provide a consistent way to report and describe ABMs for both model developers and users; and 2) to ensure that readers can understand a model's purpose and functionality and have sufficient information to replicate the model. ODD provides a standard template and terminology (Table 1), which separates a narrative description of the model, the *Overview*, from a technical description, the *Details*. These two elements are augmented by the *Design Concepts*, a checklist of ten concepts, drawn from Complexity Science (Railsback, 2001), that are important to consider when designing an ABM. Example concepts include the way interactions among agents are represented and whether agent behaviour is based on endogenous decision-making algorithms or imposed by empirical rules.

The two updates to ODD in 2010 and 2020 were mostly minor and meant to resolve common misunderstandings of some ODD elements. For example, the original element “Input” was changed to “Input data” to clarify that it refers to data representing external drivers over simulated time, such as weather in ecology, not input used to set initial conditions and parameter values.

The main change in the 2020 paper concerned ODD's first original element, “Purpose”: that 2020 update distinguishes the overall model purpose (e.g., for demonstrating concepts, understanding the inner

Table 1
Main structure of an ODD model description.

ODD	ODD element	Content and purpose	
Overview	1. Purpose and patterns	Explains the overall aim of the model, the research questions it addresses, and patterns observed in reality that are used to claim the model is realistic enough for its purpose.	
	2. Entities, state variables, and scales	Describes the types of agents and other entities, their attributes, and the spatial and temporal scales of the model.	
	3. Process overview and scheduling	Outlines the sequence of processes in the model and how they are scheduled within the model's time step: ● Submodel A ● Submodel B ● . ● File output	
Design concepts	4. *Design concepts*	Basic principles	Describes the theoretical and empirical foundations underlying the model.
		Emergence	Explains which agent behaviours arise from their implicit or explicit decision making.
		Adaptation	Describes if and how agents change their behaviour in response to conditions.
		Objectives	Specifies the goals or fitness criteria that drive agent decision making and behaviour.
		Learning	Explains whether and how agents acquire or update knowledge over time.
		Prediction	Describes whether agents anticipate future states or outcomes to evaluate their options.
		Sensing	Specifies what information agents can perceive from their environment.
		Interaction	Describes how agents interact with each other.
		Stochasticity	Explains the role of randomness in agent behaviour or processes.
		Collectives	Describes the formation and role of groups or collectives of agents.
		Observation	Specifies what data are recorded from the model and how outputs are measured.
Details	5. Initialization	Describes the initial conditions of the model, including agent states and environment setup.	
	6. Input data	Specifies any external data used to drive the model during simulations.	
	7. Submodels	Provides detailed descriptions of the rules and mechanisms governing agent behaviour and system dynamics: ● Submodel A: … ● Submodel B: … ● . ● File output: ….	

workings of the model, or predicting response to environmental change or management; Edmonds et al., 2019) from the more specific research questions. The motivation for this was to prevent models from being used for purposes for which they were not designed (Grimm et al., 2020a). Another important change in 2020 was renaming the first element "Purpose and patterns" and adding to it empirical information or patterns used to claim that the model is suitable for its purpose (Grimm and Railsback, 2012; Gallagher et al., 2021).

The 2020 update also suggested a "visual ODD" to accompany the written model description (Grimm et al., 2020a), and such a vODD has now been established as a standardized, domain-independent framework for illustrating the core narrative of simulation models (Szangolies et al., 2024). A key motivation for vODD was to help readers quickly form a coherent mental picture of the model structure and process flow (cf. Müller et al., 2014, Table 1). Visual model representations can bridge the gap between technical rigor and quick comprehensibility by summarising a model's overarching narrative in an intuitive graphical format. vODD therefore complements the written ODD, providing an immediate, high-level visual overview. By establishing a fixed, predictable arrangement where specific model features occupy the same relative positions, vODD acts as a template that shapes viewers' expectations and understanding of model functioning, much as the written ODD for text-based model documentation.

An example vODD (Fig. 1) represents a model of small mammal community dynamics in fragmented landscapes (Szangolies et al., 2025). This vODD integrates model entities, submodel processes and scheduling, and final observations, while remaining visually appealing through effective use of icons, example figures and colour. This visualisation enables readers to grasp the model's structure within a few minutes, far more quickly than by reading a full textual description. Szangolies et al. (2024) provides detailed instructions on creating a vODD, including the structure of the visualisation, examples, and ready-to-use templates (templates can be accessed at:
https://github.com/visual-ODD/Templates.git).

3. The usage of ODD

In order to document the extent to which the ODD protocol has been used to describe agent-based/individual-based models in publications, we searched the Scopus database for all articles referencing "agent-based/individual-based modelling" and determined the proportion of these articles referencing one or more of the three original ODD publications (Grimm et al., 2006, 2010, 2020a) or ODD + D (Müller et al., 2013). The details of this analysis and its results are available in the Supplementary Data.

The ODD adoption seems highest in the environmental and social sciences but never exceeds 30%. This remains the case if only publications from 2020 onwards would be considered (see Supplementary Data, Fig. S1). The relatively high proportion of ODD usage in domains with fewer than 1000 articles may be an artefact of small sample sizes (e.g., a handful of ODD-citing papers can produce a large percentage in a low-volume field) rather than genuinely higher adoption; we nonetheless included these domains to illustrate that ODD is known and used in virtually all scientific fields (Fig. 2).

Although ODD may be the most widely adopted modelling standard, the 'ODD story' should be told modestly. There is still much room for improvement. Funding bodies could, for instance, require an ODD (or at minimum its Overview section) as a condition of proposal submission or final reporting for any project developing an ABM, echoing recent calls for funders and journals to set clearer expectations around good modelling practice more broadly (Micheletti et al., 2024). Early examples of this kind of funder engagement include the German Research Foundation's involvement with the Research Software Alliance and the US NSF's POSE program (Micheletti et al., 2024).

Journals could play a key role in a wider adoption of the protocol. As Fig. 3 shows, the proportion of ODD uses in specific journals can exceed 30% (see also Supporting Data). This is not only the case in modelling journals such as *Environmental Modelling and Software* and *Ecological Modelling*, but also in domain journals such as the ecology journal *Oikos* and across-domain journals such as *PLoS One* and *Scientific Reports*. It is also encouraging that the proportion of ODD uses has increased in most journals since 2020, plausibly reflecting the added clarity and guidance provided by the 2020 update (Grimm et al., 2020a) together with the broader rise of FAIR and open-science expectations in ecological and environmental research over this period, although disentangling these factors would require further study.

While none of these journals recommend or require the use of ODD to

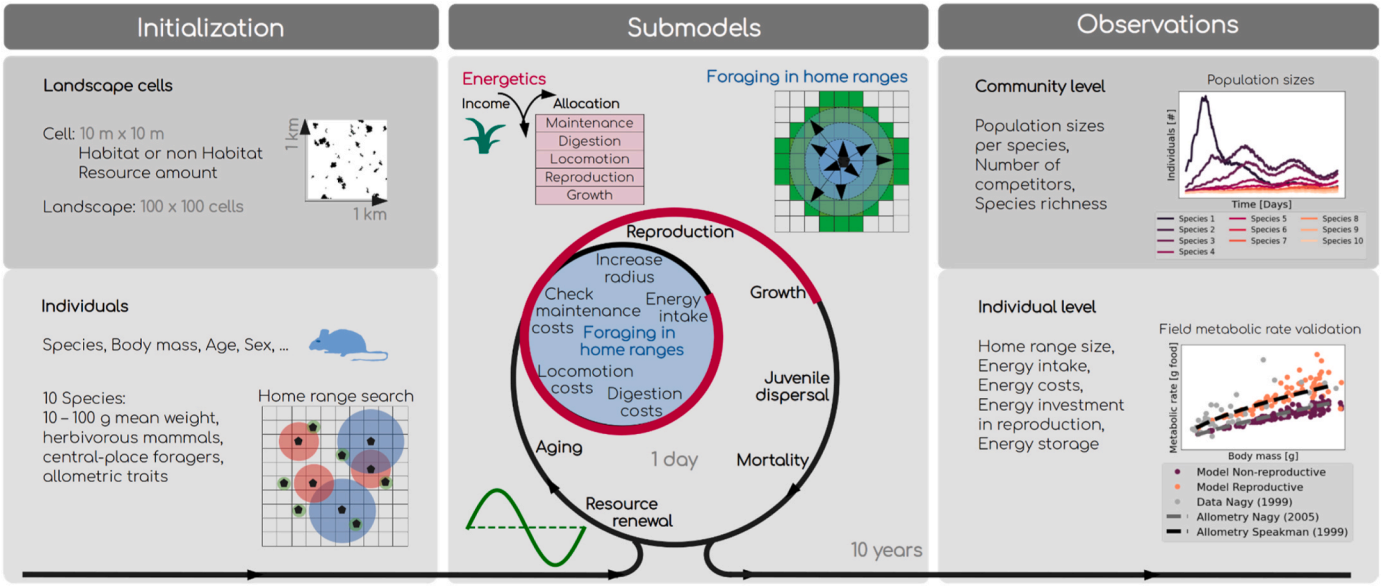


Fig. 1. Example of a vODD representing a spatial metabolic model of a small mammal community, where individuals of varying body mass form home ranges in a fragmented landscape, forage, and allocate energy to metabolic processes, shaping survival and reproductive success of species and thus community dynamics (from Szangolies et al., 2025). The visualisation is structured into the core panels Initialization, Submodels, and Observations. Additional optional panels (Purpose and Scenarios) have been omitted here, to focus on the core vODD.

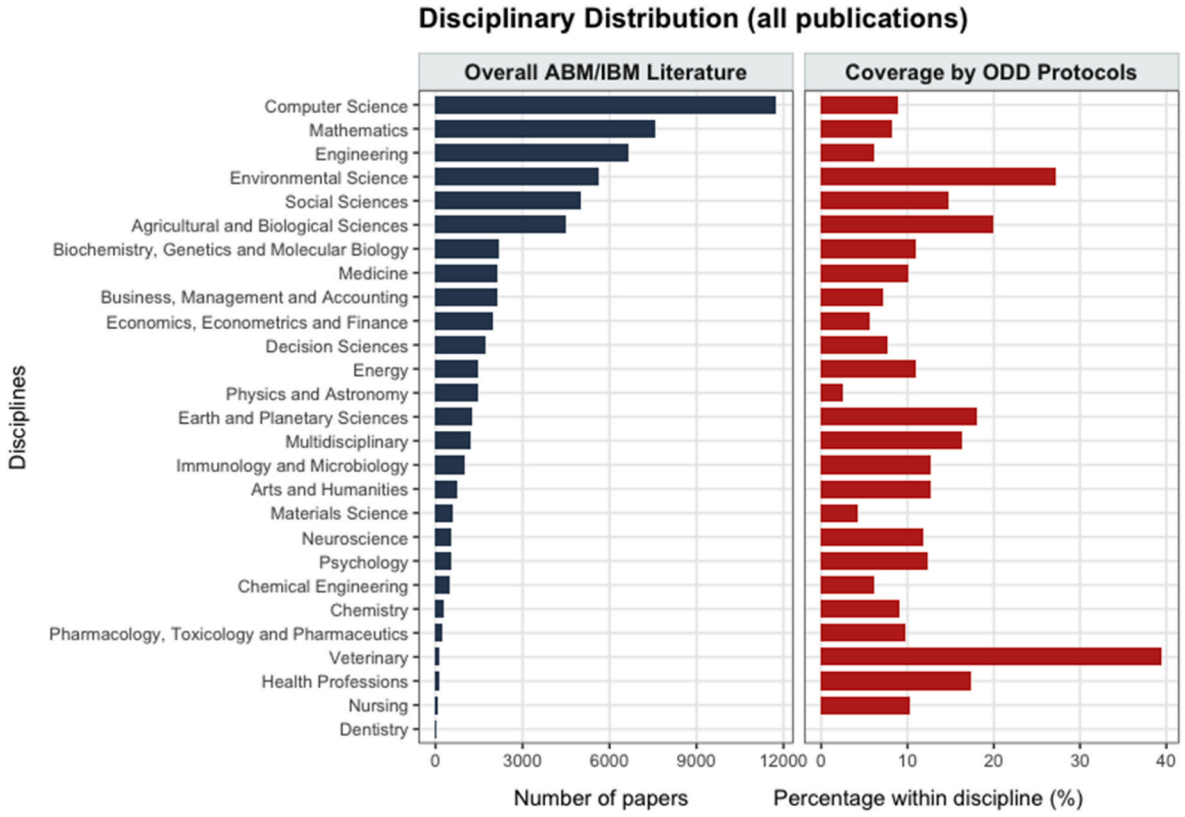


Fig. 2. Number of articles referring to "agent-based/individual-based modelling" in different domains, and the proportion of these articles that also refer to ODD/ODD + D. The domains are defined by the All Science Journal Classification (ASJC) system used by Scopus. Each article can have more than one classification, which explains the large number of articles filed under "Computer science". Analysis based on data fetched from Scopus on June 23, 2026.

describe the ABM employed, publications on ODD have appeared in *Ecological Modelling* (Grimm et al., 2006, 2010) and the *Journal of Artificial Societies and Social Simulation* (JASSS; Polhill et al., 2008; Grimm et al., 2020a). The ODD + D protocol has also been published in *Environmental Modelling and Software*. By publishing these articles, these journals have indicated their interest in and openness to ODD standards, which has certainly played a role in the high level of ODD adoption. In light of these findings, the Open Modelling Foundation (OMF) intends to

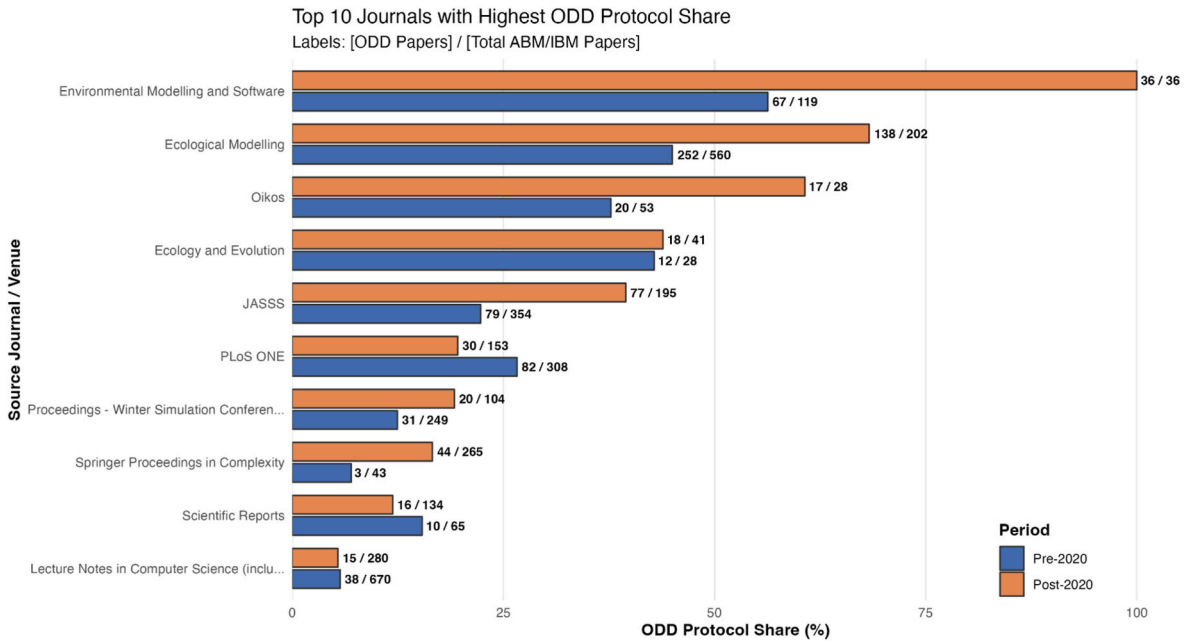


Fig. 3. The proportion of articles referring to both "agent-based/individual-based modelling" and ODD/ODD + D in the ten scientific journals with the highest proportions of ODD uses. Analysis based on data fetched from Scopus on June 23, 2026.

invite journal editors to discuss the adoption of ODD as a recommendation or potential requirement (see Sect. 7.4).

4. ODD-related standards

The adoption of ODD has inspired related modelling standards (Table 2). Some are extensions, keeping the overall structure and all or most elements of ODD and adding new ones. For example, ODD + D (Müller et al., 2013) adds elements that allow more specific characterization of decision submodels used for human agents. ODD + D was developed during a review of decision making in land-use ABMs (Groeneveld et al., 2017), in which the authors observed that decision-making was often described in an unstructured and incomplete manner, with key elements omitted and the underlying rationale insufficiently explained.

Platas-López et al. (2023) augment ODD elements affected by machine learning methods with additional questions, while M-ODD (Savić et al., 2022) introduces additional design concepts to better describe ABMs representing networks of mobile phones. There are also extensions that add elements that do not describe the model itself or its underlying design concepts but, for example, the data underlying the model's design, parameterization, and testing (ODD+2D, Laatabi et al., 2018).

Other ODD-related standards combine ODD with another standard. One example is ODdox (Topping et al., 2010), which combines ODD with Doxygen (van Heesch, 1997), a standard for software documentation. Another example is ODD + P (Reinhardt et al., 2018), which combines ODD with OPM (Moreau et al., 2011), a standard for documenting model provenance.

Other ODD-related standards do not use ODD elements but adopt the overall idea of separating a narrative overview from more technical or methodological elements. Seuru et al. (2026), for example, adopted this logic for machine learning workflows by replacing ODD's ABM-specific Design Concepts and Details with Data and Execution elements, thereby adapting ODD's overall idea to data-driven modelling. All these standards have mentioned ODD as a starting point or inspiration for its development (Table 2).

Not all of these standards are widely used. ODMAP (Table 2) and ODD + D stand out, with more than 1000 and 700 citations, respectively, perhaps because they are for widely-used model types. It appears that ODD led to all these ODD-related standards largely because the idea of standardizing model descriptions and the distinction between an overview and the more technical aspects needed for replicability and full transparency were considered useful.

5. Using ODD beyond model documentation

ODD has proven useful for modelling activities beyond documentation. Here, we illustrate two of the most common such uses: reviewing and designing models.

5.1. Using ODD for comparative reviews

Reviews of models addressing the same kind of system usually compare model structure, underlying assumptions, and scope. Such comparisons are easier if model descriptions follow a common structure. Müller et al. (2014, Table 1) suggested ODD for this purpose. The first ODD-based review (Berger et al., 2008) compared three models, FORMAN, KiWi, and MANGRO, which were developed independently to explore long-term dynamics of mangrove forests under different environmental conditions and management settings. The comparison provided important insights, such as shared limitations and specific strengths and weaknesses (Table 3).

Becher et al. (2013, Tables S3 and S4) used an ODD-based review of honeybee colony models to inform the structure of their own model, BEEHAVE (Becher et al., 2014) and identify reusable submodels (Berger et al., 2024; Filatova et al., 2025). Groeneveld et al. (2017) reviewed agent-based land-use change models using ODD + D (Müller et al., 2013; see Sect. 4). Other ODD + D-based reviews were by Jing et al. (2020), who compared autonomous vehicle ABMs. Kremmydas et al. (2018) compared agricultural policy evaluation ABMs, and Fouladvand (2024) compared community energy systems ABMs. Anshuka et al. (2022) reviewed ABMs for flood risk management and assessment; they used ODD as a framework although only 25% of the models were documented with ODD. They added two elements (Model Analysis and Accessibility) considered important for the review.

These examples and related work (e.g., Perryman et al., 2025) illustrate how ODD's common format and language facilitate the

Table 2
ODD-related standards, i.e. modelling documentation standards which are either an ODD extension, a combination of ODD with other standards, or new but inspired by ODD.

	Given name, or short description	Purpose, or reason given	Added/kept elements	Extension, combination, ODD-inspired
Topping et al., (2010)	ODdox[b]	Facilitate documentation of large object-oriented models, including updates as software is developed	ODD completed and augmented by extracting comments from the source code	Combination
Nguyen et al., (2011)	CoODD	Facilitate scientist interactions during simulation by adding new features on Collaboration design	Adds four elements: Simulator, User's profile, Application aspect, Collaboration	Extension
Stepney (2013)	Combine CosMoS and ODD[c]	Include ODD in CosMoS for understanding and building confidence in simulations	All ODD elements are integrated in the CosMos framework	Combination
Müller et al., (2013)	ODD + D[d]	Better understand and compare how human decision is represented	Overview: 3 questions *Design concepts*: > 20 questions (including a new Design Concept on Heterogeneity) Details: new element "Implementation Details"	Extension
Laatabi et al., (2018)	ODD+2D[e]	Specify data usage inside a model to determine application domain and facilitate reuse	Input data: Data overview, structure, Mapping, and Patterns	Extension
Reinhardt et al., (2018)	ODD + P[f]	Add information about how the model was developed to increase trust in quality and validity	Combine ODD with OPM (Open Provenance Model; Moreau et al., 2011, a standard for provenance description)	Combination
Grimm et al., (2020b)	POE[a] [g]	Pose three questions about model purpose, organization, and evidence to screen models for decision support	Keeps most Overview elements of ODD, provides "Evidence" of the models realism and validity.	Inspired
Slayton et al., (2020)	MInD-Healthcare Framework[h]	Improve quality of evidence generated by ABMs of infections and multidrug-resistant organisms	Keeps all ODD elements, albeit in different order, with a subset of ODD's design concepts, and adds elements on model verification, calibration, and validation.	Extension
Zurell et al., (2020)	ODMAP[i]	Describe Species Distribution Models	The distinction between Overview and other elements was kept.	Inspired
Grueau et al. (2021)	Add metadata to ODD	Combine ODD with concepts from Darwin Core and Codemeta	Keeps ODD structure and adds elements CodeDescription and DocumentDescription	Combination
Planque et al., (2022)	OPE[j]	Standardize and report model evaluation practices.	Keeps an organization into three blocks which include 22 questions.	Inspired
Savić et al., (2022)	M-ODD[k]	Describe simulations of mobile ad hoc networks[b]	Keeps the ODD structure, but has different categories for DD	Extension
Troost et al., (2023)	KIA[l]	Assist assessment of context-adequacy of model validation and inference	A list of guiding questions, organized into 12 steps, covering both statistical and mechanistic models	Inspired
Platas-López et al., (2023)	ODD for ABMs including or using machine learning	Describe uses of Machine Learning (ML) in supporting agent-based modelling.	ODD elements that can be affected by ML are modified: Input Data and the design concepts "Learning" and "Observation"	Extension
Jung et al., (2025)	ODPSCP[m]	Facilitate assessment of the scope and comprehensiveness of Systematic Conservation Planning exercises.	Keeps the distinction between an Overview and more specific and detail elements (Design, Specification, Context, Prioritization)	Inspired
Wang et al., (2025)	5D[n] protocol	Guide the design and implementation of ABMs in food microbiology	Keeps the first two ODD elements, the then uses different categories on conceptualization, model building, simulation, and validation	Inspired
Bell et al., (2026) [a]	PAVE[o]	Provide more compact model description for both developers and other users	Keeps the distinction between Overview and more technical aspects	Inspired
Seuru et al., (2026) [a]	ODE[p]	Standardize use of machine learning in environmental, social and related interdisciplinary sciences	Keeps the distinction between an Overview and the details about Data and Execution	Inspired

[a] VG coauthor.
[b] A combination of ODD and Doxygen (van Heesch, 1997).
[c] CoSMoS (Complex Systems Modelling and Simulation infrastructure) is a framework and methodology for developing, documenting, and validating computational models of complex systems. CoSMoS helps researchers build simulations that can be more easily understood, verified, and reused by others (Andrews et al., 2010).
[d] "D" for "decision making".
[e] An extension of ODD + D, 2nd D for "Data".
[f] "Provenance information about a simulation model is information about people, artifacts, and processes that have contributed to its generation." (Reinhardt et al., 2018, p.727).
[g] Purpose, Organization, Evidence.
[h] Modelling Infectious Diseases in Healthcare Network.
[i] Overview, Data, Model, Assessment, Prediction.
[j] Objective, Patterns, Evaluation.
[k] Mobile ad hoc Networks (MANETs) are networks of mobile phone users without using fixed infrastructure.
[l] Keep it adequate.
[m] Overview and Design Protocol for Systematic Conservation Planning.
[n] Define, Dissect, Develop, Deploy, and Demonstrate.
[o] Purpose, Assumptions, Validity, Exploration.
[p] Overview, Data, and Execution.

Table 3
ODD-based comparison of three models of mangrove forests (reprinted from Berger et al., 2008, with permission from Elsevier).

	FORMAN	KIWI	MANGRO
Differences in purpose(s)	Applied to particular sites in Florida, Louisiana, and Colombia	Applied to theoretical issues, and particular sites in Brazil and Belize	Applied to the Everglades (Florida, USA)
Differences in variables	No explicit stem position, leaf area	Stem position, size and shape of FON, no leaf area	Stem position, crown dimension, leaf area
Differences in spatial scales	Forest stand (matrix of gaps 500 m^2 each)	Forest stand with variable extension and shape	Landscape as matrix of squared forest stands (default size 1 ha)
Differences in resource description	Nutrients/salinity homogeneous within a gap. Light availability per height class	Nutrients/salinity heterogeneous. Light availability implicitly	Salinity/soil quality homogeneous within stand. Light availability per tree
Differences in design concepts	*Interactions of trees*: light competition through sum of leaf areas per height class. *Sensing of trees*: nutrients/salinity within gap, neighbors via total leaf area above, number of degree days	*Interactions of trees*: competition for all spatial distributed resources phenol-menologically via FON. *Sensing of trees*: nutrient/salinity at stem position, neighbors in spatially explicit constellation, no temperature sensing	*Interactions of trees*: competition for growing space and light explicitly. *Sensing of trees*: flooding/salinity/stand quality at stand unit, neighbors via distance and azimuth
Differences in initialization	Saplings	Saplings	Seedlings
Differences in submodels	No explicit saplings dispersal. *Tree growth* affected by nutrients, light, and temperature defined growth period. *Tree mortality* due to age and growth suppression, gap creation by a reduction of total leaf area	Explicit saplings dispersal. *Tree growth* affected by nutrients, neighbor competition (FON overlap). *Tree mortality* due growth suppression, gap creation spatially explicit	No explicit seedlings dispersal. *Tree growth* affected by flooding, crown volume, light. *Tree mortality*: due to growth suppression, gap creation spatially explicit

systematic comparison and integration of model designs and their consequences. None of these reviews used the full ODD or ODD + D protocol but focussed on certain ODD elements–usually the *Overview* or certain design concepts–which were considered the most important.

5.2. Using ODD for model development

The following discussion draws primarily on the collective experience of the authors as ODD users and developers rather than on systematic survey evidence. We explicitly acknowledge the experiential basis of this discussion and consider a structured survey of the wider modelling community to be a valuable area for future research. Based on our experience, we will also suggest a workflow using ODD to make model development more systematic and transparent.

Many model developers use ODD as a checklist or framework for designing models. By occupying a middle layer between informal conceptual models and computer code, ODD acts as a framework for structured thinking. Early and continuous engagement with the protocol promotes a "concept-first" approach to modelling, rather than retrofitting explanations to existing code. This encourages more conceptual clarity early on by requiring modelers to explicitly answer fundamental questions: what is the purpose of the model, what entities exist, what state variables matter, what processes are essential, and at what temporal and spatial scales? This helps prevent the common trap of "coding first, thinking later", thereby reducing risks of feature creep, inconsistent or implicit assumptions, unclear causal mechanisms, and hidden dependencies.

Each component of ODD's *Overview* element aligns directly with a key modelling decision. The "Purpose and patterns" element forces the explicit articulation of the overall purpose, the research questions, and the criteria for the model's realism. These support separating scientific questions from technical choices, and to avoid accidently optimizing software architecture instead of explanatory power. "Entities, state variables, and scales" element explicitly defines system boundaries and levels of organization. "Process overview and scheduling" clarifies causal structures and temporal dynamics. Finally, "*Design concepts*" encourages explicit reasoning about mechanisms such as adaptation, emergence, sensing, learning, and stochasticity.

A major strength of ODD during development is that it reveals assumptions that would otherwise remain hidden within the code. Without such a standard protocol, discussions about specific models often rely on unstructured mental summaries or low-level implementation details. Structuring the modelling process around ODD ensures that teams continuously define their agent state variables, monitor structural shifts across iterations, and justify why specific features were added or removed.

Using ODD during model development demands that teams explicitly articulate conceptual assumptions such as whether agents are perfectly informed, whether they optimize or use bounded rationality (Groeneveld et al., 2017), whether they learn, whether interactions are local or global, and whether randomness represents intrinsic variability or merely measurement noise. Exploring and documenting these assumptions early improves internal consistency, enables critique, and prevents accidental contradictions in the model's logic. By doing so, conceptual decisions are made deliberately rather haphazardly during coding. It encourages modelers to think more about the processes involved in the model and which mechanisms generate observed macro-patterns, which interactions matter, and which abstractions are defensible.

Modelling agent-based complex systems is inherently collaborative, usually requiring teams with domain scientists, statisticians, software developers, and decision-makers (Grimm et al., 2005; An et al., 2021; Nguyen et al., 2011). Documentation in a common format can facilitate collaboration, as it provides a common language (Martinez-Moyano, 2012; Nahar et al., 2022; Nugroho and Uehara, 2023). When used from the outset, ODD can be a tool for cross-disciplinary co-creation. While code is inaccessible to many collaborators, ODD provides a shared structure and language that improves communication and enables specific, targeted critiques: ecologists can critique biological mechanisms, sociologists can critique behavioural assumptions, and programmers can critique implementation feasibility. It can also help establish clear roles within the team, where domain experts work on the "Purpose/patterns" and *Design concepts*, scientists of different disciplines work on different "*Details*", and programmers work from the "Process overview and scheduling" and "*Details*" elements.

To maximize its utility, ODD is best used as a living design document that evolves alongside the model (Railsback et al., 2026). During development, teams can repeatedly ask whether a specific mechanism belongs in the model, whether a process matches the overall purpose, and whether outputs are properly linked to target patterns. This practice parallels software engineering practices of documentation-driven development (Zhang et al., 2004) and the "weaving" and "tangling" steps of literate programming (Knuth, 1984; Luqi et al., 2004), which actively support transparency, reproducibility of intermediate stages,

and onboarding of new collaborators. Version control systems like Git can also be used for shared ODD documents, tracking changes including added mechanisms, removed processes, and changes in scale or resolution, and the rationale for such changes (Reinhardt et al., 2018).

A proposed workflow for use of ODD in model development (Box 1) has four phases. The phases are not strictly sequential: teams often cycle through them repeatedly as understanding deepens and the model evolves.

An important benefit of using ODD for model development is that "Good Modelling Practice" (GMP) can be effectively promoted by developing and establishing standard documentation formats. Although there is general agreement about how modelling should be done, few modellers explicitly follow good practice (Schmolke et al., 2010). Experience with ODD led to the conclusion that GMP can be promoted by standardized formats for documenting the entire modelling process, such as TRACE documents (Schmolke et al., 2010; Grimm et al., 2014; Ayllón et al., 2021, Sect. 9.1, below).

6. ODD's challenges

The history of ODD reveals several challenges, most of which have been addressed by updates and extensions. Here we discuss three of the most prominent challenges and how they have been addressed.

6.1. Accurate implementation

As a standard, ODD's value is greatly diminished when users do not follow it completely or consistently. The updates to ODD were largely intended to reduce implementation problems. Misunderstanding of terms is a common problem. ODD uses specific definitions of terms such as "entities," "state variables," "input," "submodels" and "emergence". Words, however, never have a fixed meaning that is understood and used unequivocally, as Aristotle elaborated in his *Categories*. It is thus not surprising that ODD users often used its terms incorrectly, especially in its first years. For example, "state variable" is a clearer concept for natural scientists who quantify characteristics numerically than for, e.g., social scientists who describe characteristics such as opinions, personalities, or memories. Some scientists use the term "parameter" for what ODD calls a state variable. "Input" was often misinterpreted as all data read in, not specifically data describing how some exogenous variable changes over time. Terminology clarification and refinement can address these issues, e.g., by replacing "Input" with "Input data".

Incomplete specification of submodels is another common problem. Whether its description is complete enough to make a model reproducible hinges on the details in "Submodels", which is less specified than other ODD elements. One high-level process can have substantially different detailed designs. This problem is not a limitation specifically of ODD, and in fact should be reduced by ODD. Whether or not model replication is supported by ODD has not yet been systematically tested, despite the value of replication (Thiele and Grimm, 2015). Grimm et al. (2025) used ODD to first rewrite the descriptions of 18 existing models from different disciplines and then reimplement those models. In 15 cases, original model results could be reproduced, indicating that ODD reduces but does not eliminate replication challenges. Complete specification could be supported by further standardisation of the "Submodels" element; the "nested ODD" introduced in Grimm et al. (2020a) – an ODD-like description of individual submodels – is one approach.

There also are common errors in formatting – for example using *Overview*, *Design concepts*, and *Details* as section titles (instead, ODD model descriptions have seven numbered *elements*; Table 1). Often, information is provided in the wrong place, such as by including initialization data as "Input data" and describing submodel behaviour in "Process overview and scheduling". Important details, such as all parameters definitions, units, ranges and default values, and the sources of values, are often missing.

The ODD update of Grimm et al. (2020a) provides detailed guidance in its Supplement S1. This guidance should have come sooner. The lesson is that any modelling standard should come with three things: a template for application; a guide explaining in detail the meaning and rationale of each element, with examples, typical mistakes, and frequently asked questions; and a glossary where the exact meaning of each key term is specified. Given the extensive guidance now available for ODD, misimplementation now appears to result from authors not finding and following the guidance. That limitation may best be addressed by reviewers and journals continuing to expect a reasonable level of rigor in how authors use ODD.

6.2. Summary descriptions

One comment on model description standards like ODD was that "their uptake by the ABM community is inhibited by their sometimes excessive level of detail" (Daly et al., 2022, p. 1). Length is indeed an issue, but also the reason why ODD has the *Overview* part. After reading an overview, a reviewer or potential user should have a good idea of what the model is and does and can then decide what parts of the model to look at in more detail. Still, summaries are often clearly needed, e.g.,

Box 1
Proposed iterative workflow using ODD to support *model development*

Phase 1. Purpose, patterns, entities and scales: Before writing any code, the team drafts the *Purpose and patterns* to specify the overall purpose, the research question, and the criteria for claiming the model's realism. They define *Entities, state variables, and scales* to draw a hard boundary around what exists in the simulation. If a domain expert suggests adding, for instance, a new demographic trait, the team checks the *Purpose*—if the team agrees that it is unlikely to have a strong effect on the model's purpose it is excluded (but this decision documented, as it might be reconsidered at a later stage).

Phase 2. Process overview and scheduling: Programmers and domain experts build flow diagrams and algorithms mapping out the sequence of events (Bodine et al., 2020). They ask critical scheduling questions, such as whether sensing happens before or after movement, and write this logic into the ODD. As the model evolves, this phase is revisited frequently to adjust processes or resolve inconsistencies.

Phase 3. *Design concepts*: The team fills out the *Design concepts*, agreeing on the theoretical mechanisms. They establish whether agents learn, whether interactions are local or global, and whether a certain behaviour can be imposed or should emerge from the agents' decision making. As new insights or needs arise, these are refined and re-aligned with the *Purpose and patterns*.

Phase 4. Details: Domain experts fully design, explore, and document each submodel, often by implementing them in separate software. Programmers write the full code from the ODD, identifying ambiguities and errors (e.g., algorithms that produce run-time errors) that are resolved in the ODD, ensuring that documentation stays synchronized with the code. This phase often triggers returns to earlier phases when discrepancies reveal conceptual gaps.

for journal publications. The 2020 update (Grimm et al., 2020a) therefore includes a template for fully narrative summary ODDs, and recommendations for writing ODDs of modified models (i.e., "delta ODD") without repeating previous descriptions. The vODD graphical representation (Szangolies et al., 2024; see Sect. 2) is another form of summary description.

6.3. Links to code

Experience illustrates that developing, testing, understanding, and revising models is easier when it is easy to find the computer code implementing each part of an ODD. The 2020 update recommends clearly linking the model description to the code by using the same names for variables and procedures, and by tagging model equations and algorithms in both the ODD and code.

7. Discussion

Here, we discuss the potential of ODD to facilitate the extension of legacy models, the potential of AI to support the proper writing and use of ODD model descriptions, the lessons learned from the "ODD story" for the development and establishment of modelling standards, and - last but not least - the possibility to extend the scope to other, if not all, model types, which would be a major step in establishing a "lingua franca" for all modellers and model users.

7.1. Extending legacy models

Legacy models, i.e., applied models that have existed for decades and are widely used within specific application domains, are often complex and therefore hard to extend to incorporate new data or adapt to related but new purposes and applications. For instance, atmospheric dispersion models such as the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Stein et al., 2015) were originally developed for non-biological applications, e.g., dispersion of dust particles, but are now widely used in aerobiology to investigate the atmospheric dispersal of biotic particles. To improve the realism and accuracy of simulations for aerobiological applications, external submodels are developed to represent biological processes, e.g., the dispersion of fungal spores or small insects, and provide submodel-specific parameterisations (Wang et al., 2021, 2026).

Applying ODD here is not without friction: HYSPLIT and similar legacy models are not agent-based, so notions such as "entities," "state variables," or "emergence" do not map cleanly onto their grid- or trajectory-based architecture, and documenting them with ODD requires reinterpreting or omitting ABM-specific elements rather than applying the protocol unchanged. Despite this friction, ODD could still provide a structured and transparent way to document external added submodels, and where and how they plug into the legacy architecture. This would reduce the risk of using legacy models for purposes they were not designed for, and improving the understanding, reproducibility, and effective use of legacy models across disciplines.

7.2. Using AI for writing ODD model descriptions

One suggestion that often comes up when discussing how using ODD could be facilitated, is by making it machine-readable or by using AI, in particular Large Language Models (LLMs). The tool ODD2ABM developed by Xanthopoulou et al. (2019) formalizes ODD so that it can be semi-automatically translated into a NetLogo program. More recently, the potential of LLMs to automatically generate ODD structured text from model source code is being explored. Initial experimentation with this using Claude, ChatGPT, NotebookLM and Gemini (Kunkel et al., 2025) are encouraging in that even without fine-tuning or other specialized training, LLMs can prepare at least a first draft of an ODD from (NetLogo) model code. It is also possible that well-structured code – a benefit also for human readers – would facilitate an LLM in improving its drafting of an ODD. Similar studies include Khatami and Frantz (2025) and Fachada et al. (2026).

Despite the encouraging performance of automated ODD generation, several technical risks remain unresolved, including the tendency of LLMs to hallucinate plausible-sounding but incorrect descriptions of submodel logic, to misinterpret ODD-specific terminology in ways inconsistent with established usage (see Sect. 6.1), and to produce descriptions that appear complete while silently omitting edge-case behaviour present in the code, i.e. how a computer program handles extreme, rare, or boundary conditions that fall outside of its typical, everyday operating parameter.

Care should be taken that through this development ODDs do not become merely a *post hoc* product of completed code. ODD was designed for people, not for computers. It encourages both model developers and users to think about the model's assumptions, rationale and its underlying functioning. AI can still be useful when used carefully, particularly as part of a responsible, human-in-the-loop process in which LLM outputs are treated as provisional aids rather than substitutes for modeller judgement (Nabavi et al., 2026). Given the increasing use of LLMs, guidance on their application in ODD documentation may therefore be warranted to ensure that their use complements the purpose of the ODD to support model development.

7.3. Lessons for the development of modelling standards

The ODD experience offers several lessons for the development of future modelling standards. The first lesson is that successful modelling standards do not need to cover the whole model life cycle, which includes model development, implementation, testing, use and maintenance (Hamilton et al., 2022; Rosello et al. 2026). They may be most useful when they provide a clear and practical intervention at a specific point in the model life cycle. ODD responded to a common and concrete ABM issue around incomplete and inconsistent model descriptions, and subsequent difficulties in supporting understanding, replication, review or reuse (Grimm et al., 2010, 2020a). ODD thus addressed an important gap at the point where the ABM community needed a shared structure to describe their models.

A similar logic can be seen in the development of ODMAP (Table 2) for reporting species distribution models (Zurell et al., 2020). Like ODD, ODMAP addresses a recognised problem in a community where models were widely used for ecological assessment, conservation planning and decision-making, but where documentation and standardisation of modelling protocols remained limited. ODMAP provides a structured checklist and modelling protocol to make modelling decisions more explicit and help assess whether those decisions were aligned with research objectives and intended applications (Zurell et al., 2020).

The second lesson is that the adoption of modelling standards depends not only on their conceptual soundness, but also on their perceived usefulness, implementability, and fit with the practices of communities they are intended to support. ODD operates primarily as a normative documentation and communication standard, balancing structure with flexibility. It provides a stable reporting structure and shared terminology, while still allowing room for disciplinary and model-specific judgement (Grimm et al., 2010, 2020a).

More broadly, work on community standards suggests that uptake depends on standards being useable within the practices, infrastructures, and incentives of the communities expected to apply them. More recently there have been initiatives prompted in response to the recognised need for conditions to support standards uptake, including *FAIRsharing* and *COMBINE*. *FAIRsharing* was established as a community resource that connects standards with databases, repositories, journals, funders and data policies to make standards more visible, easier to discover, and easier to embed in existing research architectures and community practices (Sansone et al., 2019). Similarly, the *COMBINE* initiative in systems biology coordinates a family of community

standards for computational modelling, including standards for model representation, simulation experiments and graphical notation. These examples illustrate that uptake often depends on coordination across related standards, tools and user communities, rather than on the conceptual strength of any single standard alone (Hucka et al., 2015).

This balance between structure, flexibility, and community fit is also reflected in several ODD extensions and ODD-inspired standards. (see Sect. 4). These developments suggest that the usefulness of a standard may depend not only on the strength of its original structure, but also on whether it can be extended, combined or adapted in ways that remain meaningful to specific modelling communities. For example, one of the most widely used standard, the *CONSORT* guideline for reporting randomized controlled trials in medical studies (Begg et al., 1996), has seen not only several updates but also numerous extensions.[1]

The third lesson is that modelling standards can facilitate communication of the model and its inner workings among modelers as well as with relevant scientists, reviewers, users, and potential re-users (Section 5.2). Its use in model reviews (Section 5.1) illustrates how a common descriptive structure can support comparison of model assumptions, scope and design choices across related models (Berger et al., 2008; Groeneveld et al., 2017; Anshuka et al., 2022). In this sense, ODD works not only as a documentation template, but also as a communication device that helps us ask more precise questions about how a model works and why particular design choices were made.

Fourth, the ODD experience illustrates why future standards should be explicit about their purpose, intended users, and place in the model life cycle. No single standard should be expected to support all requirements of good modelling practice or FAIR-aligned modelling. ODD contributes strongly to model documentation, communication, and, indirectly, model design. But other parts of the model life cycle may require additional standards, protocols, or guidance. Examples include model evaluation, provenance, software implementation, model sharing, governance, maintenance, or decision-support use. This lesson is consistent with recent work on modelling standards, which suggests that standards differ in their types, functions, principles, intended stakeholders and contribution across the model life cycle (Rosello et al. 2026). Making these distinctions explicit helps to clarify whether a modelling standard is mainly intended to support transparency, communication, evaluation, interoperability, software implementation, governance, reuse, or another function.

7.4. Outlook: towards an ODD for other model types

Although ODD was originally designed for documenting ABMs, its provision of an accessible overview of the model appears transferable to a wider range of model types. Similar documentation challenges arise across Earth-system, environmental, and coupled human–natural systems modelling, where model purpose, boundary judgments, assumptions, uncertainties, and intended use are often difficult for users, reviewers, and collaborators to reconstruct (Chen et al., 2026). In this broader context, generalising ODD should be guided not by transferring ABM-specific terminology wholesale, but by preserving its underlying documentation logic: making explicit why the model exists, what system boundaries it draws, what assumptions and processes it includes or excludes, and what uncertainties matter for its intended use. This is consistent with recent calls for integrated modelling to give greater attention to model purpose, boundary judgment, warranted system complexity, and critical uncertainties (Razavi et al., 2025).

The *Overview* section helps readers to understand a model's purpose, scope and basic operation before engaging with more technical details, and it also provides a useful entry point for navigating the fuller description. Similarly, making key design concepts explicit can support quality assurance by requiring modellers to identify important assumptions, organising principles and modelling choices. However, extending ODD beyond ABMs requires caution, because what can be generalised is ODD's rationale and structure, not necessarily the categories developed for ABMs. While the *Overview* section may be broadly applicable across model types, the *Design Concepts* and *Details* sections are likely to require different categories, terminology and emphasis depending on the modelling formalism, purpose and community of practice. A generalised ODD should therefore not impose a single universal vocabulary for all models. Instead, it could provide a common high-level structure while leaving room for modelling communities to develop more specific standards or extensions for particular model types, such as discrete-event simulations, network models, system dynamics models, or other modelling approaches.

For example, in deterministic process-based models, documentation may need to emphasise governing equations, state variables, forcing data, boundary conditions, and numerical solvers. Whether or not documentation should go beyond documenting the model itself and also include, e.g., parameterization, calibration, and validation procedures, is to be decided by the corresponding community (for ODD so far it is not included; Grimm et al., 2020a). In system dynamics models, stocks, flows, feedback loops, delays, and policy levers may be more central. In network models, nodes, links, flows, topology, and interaction rules may require greater attention. A generalised ODD should therefore provide a common structure while allowing each modelling community to define the technical elements most relevant to its own modelling tradition.

A further consideration is that many contemporary modelling challenges are no longer addressed by a single model type or disciplinary tradition. In Earth-system, environmental, integrated assessment, and coupled human–natural systems modelling, models increasingly combine components developed in different fields, using different assumptions, spatial and temporal scales, data sources, evaluation criteria, and modelling languages. A generalised ODD should therefore be able to document not only individual models, but also model systems: how component models are connected, what information is exchanged among them, what assumptions are introduced at their interfaces, and how uncertainty, scale mismatches, and boundary judgments propagate through the overall modelling framework. This would extend ODD's role from describing model structure to supporting transparency in transdisciplinary model integration.

For transdisciplinary model systems, a generalised ODD would also need to address semantic interoperability. Different disciplines may use the same terms differently, or attach different assumptions and evidentiary standards to concepts such as uncertainty, risk, validation, scenario, boundary, scale, resilience, feedback, or model coupling (Razavi et al., 2025). Documentation should therefore define key terms, clarify the meaning and provenance of exchanged variables and outputs, and make explicit how concepts are translated across disciplinary and model interfaces. This would help ensure that model integration is not treated only as a technical exercise of coupling code and data, but also as a process of aligning meanings, assumptions, and expectations across communities.

The Open Modelling Foundation (OMF), which includes all the authors of this article, is therefore considering a generalised ODD based on a tiered approach. At a base level, the standard could require an *Overview* section that introduces the model's purpose, scope and operation in a common language. A fuller level could include *Design Concepts* and *Details* sections, while allowing the specific content, terminology and elements to be adapted by relevant modelling communities. For coupled or transdisciplinary modelling frameworks, an additional integration layer could document component models, coupling assumptions, exchanged variables, scale translations, interface uncertainties, and semantic choices. This approach would build on one of ODD's strengths: its ability to maintain a recognisable rationale while being adapted for specific model types, purposes or documentation needs. This is similar to the way reporting guidelines such as CONSORT have developed extensions for particular study designs or contexts (Begg et al., 1996).

[1] Equator network.

Whether a generalised ODD becomes widely used will depend not only on its design, but also on how it is taken up by modelling communities, journals, reviewers, funders and member organisations. The OMF currently includes more than 40 modelling institutes, departments, societies, and journals, which will vote on whether to accept the generalised ODD as an OMF-promoted standard. If accepted, its use within each organization will depend on the priorities and practices of that organization and its representative. At present, ODD functions primarily as a norm (i.e. widely accepted practice) rather than a more formally enforced standard (Rosello et al. 2026), such as the GMP described by the European Food Safety Authority (e.g., EFSA Panel on Plant Protection Products and their Residues, 2014). Enforcing a standard may be particularly valuable for interdisciplinary or transdisciplinary models, where reviewers may not share all of the disciplinary assumptions, terminology, or modelling conventions embedded in the model system.

Journals and reviewers may therefore play a particularly important role. The history of ODD suggests that a standard can become established when reviewers begin to ask authors for it, authors become familiar with its value through use, and some later reproduce these expectations when acting as reviewers themselves. For a generalised ODD, journals could start by encouraging or requiring the base-level *Overview* section, because this would introduce a common language and facilitate a basic understanding of a model's purpose, scope and operation. The fuller ODD could remain optional, recommended, or required only in contexts where detailed documentation is needed for review, reuse or reproducibility.

8. Conclusions

ODD has become a widely adopted standard, evolving from a protocol for documenting models to a communication tool, a comparative framework for evaluating models, a debugging aid, and a scientific reasoning scaffold across disciplines. Lessons from the ODD story suggest that future modelling standards should not attempt to become universal or all-encompassing. Rather, modelling standards may be most effective when they solve a recognised problem, provide a useable structure, support communication among relevant communities, and make clear what they are and are not designed to do. In this way, a plurality (or ecosystem) of standards is a feature of good model communication, not a bug. The ODD experience also shows that uptake in such an ecosystem can be reinforced when a standard becomes embedded in peer-review practices. In this sense, standards become established not only because they are conceptually useful, but because they are adopted within the routines, expectations and incentives of a modelling community. Therefore, future standard-development work could benefit from the ODD experience by positioning standards as complementary resources within a broader standards ecosystem, rather than as competing or self-sufficient solutions. By clarifying how different standards contribute to different parts of the model life cycle, such an ecosystem would not only support technical consistency, but also more coordinated, transparent and reflective modelling practices among the communities who develop, review, use and maintain models (Jakeman et al., 2024; Rosello et al. 2026). Standards such as the ODD promote rigorous design, transparent reporting and communication of models, and their adoption can be critical in establishing good modelling practices as the norm in the modelling community.

CRediT authorship contribution statement

Volker Grimm: Writing – review & editing, Writing – original draft, Conceptualization. **Caroline Rosello:** Writing – review & editing, Writing – original draft, Conceptualization. **Serena Hamilton:** Writing – review & editing, Writing – original draft, Conceptualization. **Cara Gallagher:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Tatiane Micheletti:** Writing – review & editing, Writing – original draft, Conceptualization. **Leonna Szangolies:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Geerten M. Hengeveld:** Conceptualization. **Maria Pierce:** Writing – review & editing, Conceptualization. **Carsten Lemmen:** Writing – review & editing, Conceptualization. **Christian Troost:** Writing – review & editing, Conceptualization. **Allen Lee:** Writing – review & editing, Conceptualization. **Andrew Bell:** Writing – review & editing. **Bruce Edmonds:** Writing – review & editing, Conceptualization. **Cheng-Zhi Qin:** Writing – review & editing. **Marie-Christin Wimmler:** Writing – review & editing, Conceptualization. **Franziska Appel:** Writing – review & editing. **Daniel Ayllón:** Writing – review & editing. **Indushree Banerjee:** Writing – review & editing. **Uta Berger:** Writing – review & editing, Conceptualization. **Donald DeAngelis:** Writing – review & editing. **Changxing Dong:** Writing – review & editing. **Bert Jagers:** Writing – review & editing, Conceptualization. **Anthony Jakeman:** Writing – review & editing. **Julia Kunkel:** Writing – review & editing. **Birgit Müller:** Writing – review & editing. **Ruth Njiru:** Writing – review & editing. **J. Gareth Polhill:** Writing – review & editing, Conceptualization. **Viktoriia Radchuk:** Writing – review & editing, Conceptualization. **Saman Razavi:** Writing – review & editing. **Michael Renton:** Writing – review & editing. **Hugo Salinas:** Writing – review & editing. **Liang-Jun Zhu:** Writing – review & editing. **Luke Christopher Evans:** Writing – review & editing. **Samuel Seuru:** Writing – review & editing. **Xifu Sun:** Writing – review & editing. **Charlotte Thibodeaux:** Writing – review & editing. **Isaac I. Ullah:** Writing – review & editing. **Christian Vincenot:** Writing – review & editing, Formal analysis, Conceptualization. **Ming Wang:** Writing – review & editing. **Fengyuan Zhang:** Writing – review & editing. **Michael Barton:** Conceptualization. **Steve Railsback:** Writing – review & editing, Conceptualization.

Declaration on use of AI

We used DeepL to edit the language of some sections but checked and edited these sections multiple times afterwards. We used undermind. ai to find all relevant extensions of ODD, all reviews using ODD and all papers commenting on ODD. We did not use any of the summaries or evaluations of these articles offered by undermind. ai.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

No data was used for the research described in the article.

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