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Towards reusable building blocks for agent-based modelling and theory development

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A R T I C L E I N F O

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A B S T R A C T

Despite the increasing use of standards for documenting and testing agent-based models (ABMs) and sharing of open access code, most ABMs are still developed from scratch. This is not only inefficient, but also leads to *ad hoc* and often inconsistent implementations of the same theories in computational code and delays progress in the exploration of the functioning of complex social-ecological systems (SES). We argue that reusable building blocks (RBBs) known from professional software development can mitigate these issues. An RBB is a submodel that represents a particular mechanism or process that is relevant across many ABMs in an application domain, such as plant competition in vegetation models, or reinforcement learning in a behavioural model. RBBs need to be distinguished from modules, which represent entire subsystems and include more than one mechanism and process. While linking modules faces the same challenges as integrating different models in general, RBBs are “atomic” enough to be more easily re-used in different contexts. We describe and provide examples from different domains for how and why building blocks are used in software development, and the benefits of doing so for the ABM community and to individual modellers. We propose a template to guide the development and publication of RBBs and provide example RBBs that use this template. Most importantly, we propose and initiate a strategy for community-based development, sharing and use of RBBs. Individual modellers can have a much greater impact in their field with an RBB than with a single paper, while the community will benefit from increased coherence, facilitating the development of theory for both the behaviour of agents and the systems they form. We invite peers to upload and share their RBBs via our website - preferably referenced by a *DOI* (digital object

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identifier obtained e.g. via Zenodo). After a critical mass of candidate RBBs has accumulated, feedback and discussion can take place and both the template and the scope of the envisioned platform can be improved.

1. Software and data availability

RBB website: https://www.rbb4abm.com/

2. Introduction

Agent-based models (ABMs, also called individual-based models) are widely used in environmental, social, and computational sciences whenever the problem or system addressed involves adaptive agents, such as organisms, people, or institutions, their behaviour and interactions (Grimm and Railsback 2005; Squazzoni 2012; Heppenstall et al., 2012; Gilbert 2019). It took nearly two decades for agent-based modelling to develop from its pioneer state, moving from stylized toy models to advanced models relevant for management of Social-Ecological Systems (SES), from by *ad hoc* model designs to theory- and data-grounded designs, and from limited transparency to a mature and more coherently used scientific tool (Grimm 1999, Schlüter et al., 2017).

Indicators of this maturation are standards for documenting ABMs and their development (ODD, Grimm et al., 2006, 2020, Müller et al., 2013; TRACE, Schmolke et al., 2010, Grimm et al., 2014; Barton et al., 2022a, 2022b, Roxburgh et al., 2022), their use of data (RATS, Achter et al., 2022), software environments and programming languages specifically designed for ABMs (e.g., NetLogo, Wilensky, 1999; Wilensky and Rand 2015; GAMA, Amouroux et al., 2007; Agents.jl, Vahdati 2019), tools for designing simulation experiments and sensitivity analyses (e.g., openMole, Reuillon et al., 2013; *nlrx* R-package, Salecker et al., 2019; DOE, Lorscheid et al., 2012), strategies for exploring the robustness of key mechanisms (Grimm and Berger 2016), and protocols for coherent validation, model inference and uncertainty analysis (Troost et al., 2023).

Still, both development and coherence of ABMs are limited by the common practice of developing most ABMs largely from scratch. To improve this situation and to advance ABM development, including its use for theory development of Social-Ecological Systems (SES), this paper aims to revive the concept of reusable building blocks (RBBs) by providing a template for their description, and examples of RBBs to serve as a starting point for their collaborative development.

The concept of RBBs, prevalent in software engineering and applications like computer games and movie animations, is not new. Reusable model components for ABMs have been initiated before, exemplified by Bell et al. (2015) land-use modelling primitives (LUMPs) and agent-based modelling primitives (AMPs), as well as the generic micro-behaviour libraries in BehaviourComposer 2.0 (http://m.modelling4all.org/). However, it seems that the complexity of ABM for SES has complicated the development of RBB so that it has been discussed and tried for decades, leading to “oceans of ink” that have been devoted to this topic (Tucker and Gross 2013, p.1).

So far, the term “reusable building block” refers to many different things ranging from functions to submodels or even entire models (Balci et al., 2011). There is agreement in the literature that with increasing complexity of the building block, the context in which the block was developed plays an increasing role, so that either reusability is limited, or the risk increases that the block is used for purposes for which it was not designed. For example, Tucker and Gross (2013) note “A key unsolved model/simulation reuse problem is how to discover and express assumptions, limitations, and suitable uses – the contexts within which a simulation may be used, in contrast to the context within which it has been used.” (p.2).

When trying to foster the development and use of RBB for ABMs in the environmental science, it is therefore important to avoid the pitfalls that were identified in the field of “Modelling & Simulation” (Balci et al., 2011; Tucker and Gross 2013; Robinson et al., 2004). Likewise, when it comes to combine or integrate different environmental models, Voinov and Shugart (2013) warn that the availability of a model warehouse that provides software components for reuse as black boxes leads to "integronster" models that are hard to understand and hence trust.

We thus suggest distinguishing RBBs from “modules” that represent entire subsystems or include a whole set of mechanisms or processes. Following Robinson et al. (2004) who envisage RBBs as having “a defined interface, providing limited functionality and able to be used within a defined architecture” (Robinson et al., 2004, p. 482), we define an RBB for an ABM to be a *submodel that* represents *a particular mechanism or process that is relevant across many agent-based models in a certain application domain*. The two main features of this definition are that we focus on basic mechanisms (we refer to an RBB as being “atomic”) and that we include the context, i.e. the domain of application. Nevertheless, the purposes of the ABMs in which an RBB is used may be different, but the specific purpose of the RBB should be the same, and therefore narrower. Examples include the description of plant competition in vegetation models, or of reinforcement learning in a behavioural model which can be included in various models applied to understand the response of the particular system to different disturbances. The entire book by O’Sullivan and Perry (2013) on “spatial simulation” is devoted to the idea of providing building blocks, which are all made available and updated on the Internet.[1]

We would also like to emphasise that, similar to Davis and Anderson (2004), we do not require the ideal of a "plug-and-play" RBB as part of our definition. Even for RBBs that represent basic mechanisms, adjustments to the reused RBB may be necessary depending on the context and, for example, the availability of new data. In this sense, an RBB can be seen as a recipe or algorithm for describing a process, rather than a fixed block of code restricted to a particular programming language. Indeed, it is this aspect, as we conceive of RBBs, that links them to theory development: RBBs used in different ABMs, and thus in different larger contexts, can lead either to the development of a single tested "theory" of a particular process or behaviour, or to a limited set of theories that correspond to different contexts.

In this way, distributing useful submodels as RBBs could establish community standards that are needed to reduce ambiguities around the translation of theories on the behaviour of agents into code (Groeneveld et al., 2017; Muelder and Filatova 2018; Schlüter et al., 2017; Huber et al., 2018; Wijermans et al., 2023). So far, the narrative formulations of many existing theories of behaviour often are insufficiently detailed and rigorous, leading to different, sometimes even contradictory, algorithms for operationalizing the same theory in ABMs (e.g., the *Theory of Planned Behaviour,* Ajzen (1991)). It is important to systematically explore and evaluate the consequences of such different algorithmic implementations for simulation outcomes as demonstrated by Schwarz et al. (2020). This would significantly advance the development of rigorous and more useful theories for social and ecological systems (Muelder and Filatova 2018). If modellers would not only develop and test their implementation of a theory within their own ABM, but also make it available in a standardised way as an RBB, others could use and test that theory implementation in new contexts and for new questions. For example, such systematic evaluation of alternative algorithms could ultimately demonstrate that a single implementation of the Theory of Planned Behaviour will be most useful, or alternatively that different sub-versions are needed, depending on the context.

[1] https://dosull.github.io/pattern-and-process/.

Our search for RBBs echoes recent initiatives to make both software development (Barker et al., 2022) and the use of data (Wilkinson et al., 2016) more rigorous and efficient by following the FAIR principles: *findability*, *accessibility*, *interoperability* and *reusability*. However, although modelling and software development overlap, they are not the same, and FAIR principles for scientific modelling are still under development (Barton et al., 2022a). As reported above, for modelling the issues of interoperability and reusability are challenging and, with the exception of the High Level Architecture for models simulating battles (Dahmann et al., 1997) developed by the US Department of Defense, have not yet been resolved.

Hence, no community-wide strategies and standards exist for identifying and evaluating potentially useful RBBs, for distributing and maintaining RBBs, or for providing incentives for individual modellers to invest the time and energy needed to develop and disseminate them. In the following sections, we outline a possible strategy for collaborative development and use of RBBs for ABMs. To do this, we first describe examples of RBBs of ABMs from ecology and social science. We then discuss the benefits to modellers who provide RBBs and how these benefits can be supported by cyberinfrastructure, such as web repositories. We also discuss the challenges to developing RBBs, because it is important to be aware of them to avoid possible pitfalls. Finally, we propose a web-based workflow that hopefully serves as a starting point for discussion and further development. Please note that this is not a classical research paper. Rather, it is a perspectives article, or essay, that emerged from several workshops and conference sessions, and is based on the experience of the authors as well as insights into the challenges linked to RBBs that we found in the literature, although a systematic review of this literature was beyond our scope.

3. Two examples of existing building blocks in agent-based models in social sciences and ecology

Although our above definition of RBBs for ABMs is meant to be clear and comprehensive, in our discussions with each other and with other modellers we realized that we need examples to make our notion of RBBs less abstract. Luckily, there are already a few building blocks for ABMs that match our RBB definition. Here we provide one example each from the social sciences/economics and from ecology. Please note that here we provide narrative descriptions, which still play an important role for communicating the rationale of models in general, and for RBBs in particular. Descriptions following the template for RBBs that we will introduce later are to be found on the website related to this article, https://www.rbb4abm.com/.

3.1. Learning classifier systems – an example from social sciences

The Learning Classifier Systems (LCS) approach *represents agent learning and adaptation* based on feedback (see Holland 1975, 1995) and can be applied to a broad range of entities such as human decision makers, organisations or animals. An LCS is a set of rules consisting of a condition component and an action component, which are updated based on feedback and the use of a genetic algorithm to create new rules. The rules specify actions, i.e. what the agent will do given their perception of the environment. For example, depending on the agent's perception of whether it is rainy or sunny weather, the agent can choose to carry an umbrella or not when going for a walk. In this example the agent would have a set of four possible rules. The basic mechanism can be described as follows: the agent has a set of rules that it can choose from to act. At the beginning, the agent might only have two rules: (1) if sunny weather, then do not carry an umbrella and (2) if rainy weather, then do not carry an umbrella (the second rule obviously makes no sense).

The agent then perceives information about the environment, compares the information with the condition component of the rule (sunny or rainy weather?), and selects the most appropriate action rule from the rule set (see Meyer and Hufschlag (2006) for a more technical description). Given its action, the agent receives some feedback from the environment, which then can be evaluated. In our example, the agent would get wet or not, with wet being considered unfavourable. Based on the feedback, the agent then updates the weights for the rules used, which determine the probability of a specific rule to be chosen in the future. For example, the rule with the condition "rainy weather" and the action "do not carry an umbrella" gets a lower weight once the agent gets wet. Finally, to generate new rules, a genetic algorithm modifies some of the rules in the set and adds them to the rule set. For example, the agent could add the rule (3) if rainy weather, then carry an umbrella.

The LCS approach has been applied to a variety of questions and is in line with alternative theories about the basic processes of learning and adaptation (see also Fig. 1). An early application in economics is Marimon et al. (1990), who use it to model trade and consumption decisions of consumers in a market. Marengo (1992) uses LCS to model managers in an organisation who have to coordinate their production decisions given changing demand outside the organisation. Butz and Hoffmann (2002) use LCS to study the role of anticipations in controlling the behaviour of rats.

Given the generic features and wide usability of LCS, Meyer and Hufschlag (2006) suggest an approach similar to RBB to foster and standardise the usage of LCS. Based on the identification of the generic elements of an LCS, they provide a JAVA-based library based on a strict object-oriented approach. Their aim was to increase the ease of use of LCS and to avoid reinventing the wheel with every new application. At the same time, the library provides a good flexibility to adapt the modelling of agents to the particular modelling purpose. It is inspired by the method of decreasing abstraction by Lindenberg (1992), i.e., it starts with a simple core model, which is subsequently differentiated with reference to the purpose of the model.

3.2. Zone-of-influence approach – an example from ecology

The Zone-of-Influence (ZOI) approach represents competition among plants (e.g., Berger et al., 2008b; Lin et al., 2013). Plants consume above- and below-ground resources, such as light or water and nutrients, within an area defined by their canopy or roots. Assuming that this area, or ZOI, is of a circular shape is a reasonable approximation. The radius of this ZOI increases while a plant is growing, so that at some point the ZOIs of neighbouring plants overlap. In the overlapping area, plants compete for resources so that the growth of the competing plants will be slowed down. One can then assume that (1) competing plants get equal shares of the resources (complete symmetric competition - often assumed for roots and the uptake of below-ground resources), (2) the larger plant gets all the resources and thus does not feel any competition (complete asymmetric competition - often assumed for the canopy and the competition for light), or (3) plants share resources according to a ratio which might depend on their relative sizes.

The basic idea of this approach is more than 40 years old (Gates and Westcott 1978; Wyszomirski 1983) but was made popular by making it a RBB when a grid-based algorithm provided by Weiner et al. (2001) made implementing the ZOI approach straightforward. Weiner et al. (2001) not only developed and used this approach, but added the code implementing it in a supplement to their paper so that this building block could be reused and adapted by others (e.g., May et al., 2009; Lin et al., 2013; García 2014; Backmann et al., 2019).

The ZOI approach has been used for a wide range of theoretical and applied questions because it is about a fundamental process driving the structure and dynamics at higher levels of organisation of plant populations and communities. Its limitations are also well-known because as a phenomenological approach it does not explicitly represent the specific resources and mechanisms of competition.

The community benefits of ZOI as an RBB are obvious: numerous models that included plant competition but addressed a wide range of different questions could build their design on ZOI and its tested

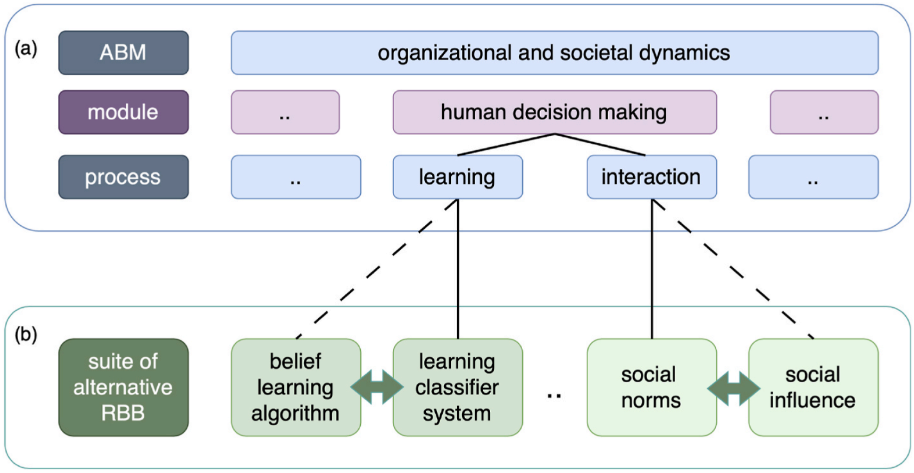

Fig. 1. Exemplary representation of the structure of a model describing several processes of human behaviour (a). Each process can be described according to several theories or concepts, each implemented in its own RBB (b). According to this description, RBBs like the learning classifier system described in the main text have the potential to be replaced by an alternative RBB serving the same purpose. RBBs are therefore predisposed building blocks for a systematic selection of the most appropriate concepts and the development of a general theory about the functioning of complex social-ecological systems.

implementation instead of coming up with their own solutions. Reviewers and peers became familiar with ZOI and its scope and limitations, which facilitated reviewing and understanding. Moreover, the existence of the ZOI RBB stimulated the scientific discussion on new theoretical concepts of local neighbourhood interactions ranging from asymmetric versus symmetric competition (Bauer et al., 2004; Peters et al., 2016), facilitation (Lin et al. 2012, 2016), or the competitive/facilitative use of above- and below-ground resources (Lin et al., 2014; Peters et al., 2016). This led to the rise of a set of follow-ups RBBs like the Field-of-Neighbourhood (FON, Berger and Hildenbrandt, 2000; Berger et al., 2008a) or the Double-ZOI (May et al., 2009; Lin et al., 2014), providing new options for tailored forest simulation models suitable to systematically test alternative concepts on resource use of sessile organisms (Fig. 2). The main benefit for Weiner et al. (2001), who made their implementation available, is that their article's impact was much higher than for a particular case study it could be.

4. Why should we use building blocks in agent-based modelling?

The two examples in the previous section illustrate some key ideas and potential benefits behind RBBs, such as reduced development effort and re-evaluations increasing RBBs' transparency and reliability. Sharing RBBs within and across disciplines, however, has further potential for what we call 'agent-based theory development' as long as we use it as a coherent and iterative process of testing, learning, and improvement just like the classic hypothesis-testing cycles that drive theory development in physical sciences. Given that agents and their behaviour are, by definition, the building blocks of agent-based systems (Wijermans et al., 2023), this simply requires that we use ABMs more frequently as virtual laboratories in which the building blocks representing contrasting or alternative theories of agent behaviour are reused and systematically tested for their ability to reproduce multiple observed patterns (Fig. 3).

Testing alternative theories of human decision-making is strongly recommended by Wijermans et al. (2023), but a tournament of building blocks is still rarely used as a research strategy but see also Railsback and Harvey (2002); Grimm and Railsback (2012); or Hegselmann and Flache (2000). In ABMs of land use and land cover change (Groeneveld et al., 2017), e.g., the "expected utility" was the most frequently used theory for describing land use decision-making. A few models were then used to systematically compare alternative decision models, for example by asking: What do we lose and what do we gain by using a model structure of, e.g., "belief-desire-intention" instead of "expected utility"?

In ecology, Cortés-Avizanda et al. (2014) provide another powerful example: Griffon Vultures (*Gyps fulvus*) often search for a long time

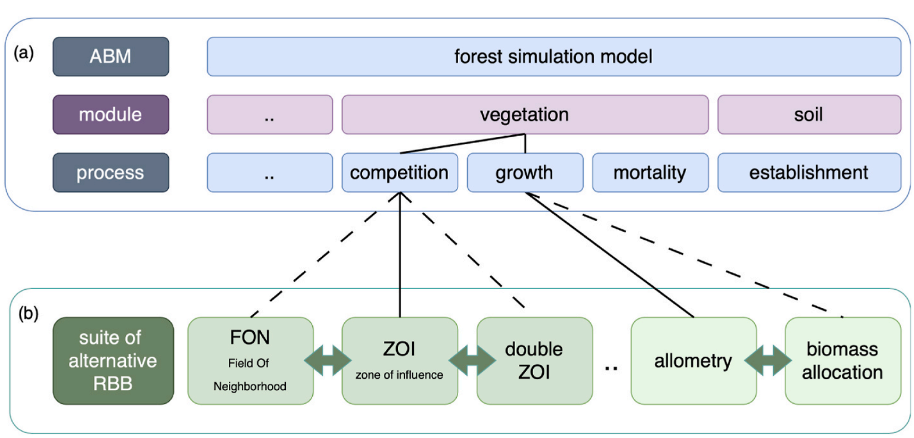

Fig. 2. Exemplary representation of the structure of a forest model. (a) Different modules can be used to describe parts of the system (e.g. vegetation, soil, groundwater). Each module describes several processes belonging to the respective context. (b). Each process can be described according to several theories or concepts, each implemented in a separate RBB.

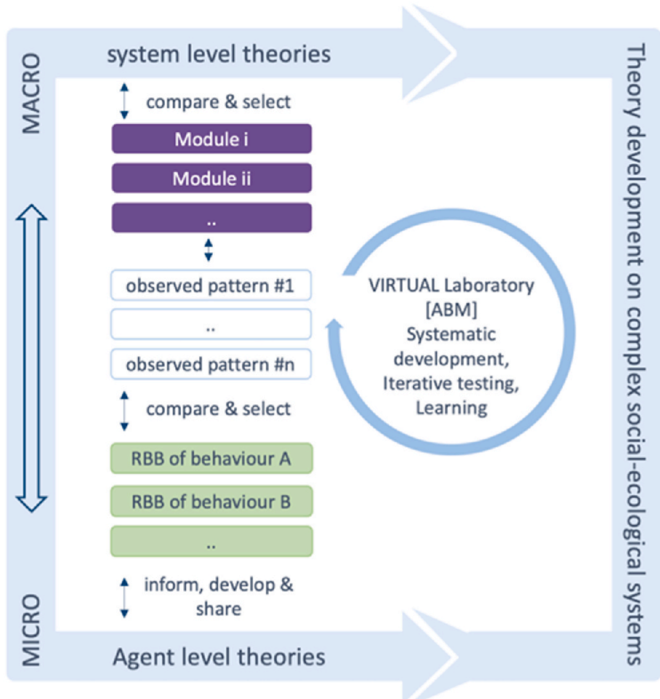

Fig. 3. Each RBB can be replaced by an alternative one that serves the same purpose. They are thus building blocks for a systematic selection of the most appropriate concepts explaining observed patterns, to build modules; and to develop a general theory about the functioning of complex social-ecological systems by a systematic, hypotheses driven approach.

before they find a carcass to feed on, but then dozens of vultures arrive quickly at the same carcass. There are two contrasting theories, how this well-known pattern can be explained: (1) if the finder (vultures that detected a carcass) starts flying straight toward the carcass, other vultures identify this kind of movement and follow, producing a "chain of vultures" (Jackson et al., 2008). (2) Searching vultures only detect the fast descent of finders near the carcass, and fly straight to the food ("local enhancement"). These two theories, and a null theory assuming no information transfer at all, were implemented as building blocks (BB) in an ABM and its results compared with observed patterns. Key for contrasting the alternative theories of agent behaviour were patterns in the number of vultures at a carcass. The chain-of-vulture BB often led to unrealistically high numbers, the null model yielded too few, but the local model matched the observations well. Still, the latter did not match all observed patterns (e.g., the minimum number of vultures), indicating that further experiments, in the field and *in silico*, were needed to refine the model. This demonstrates how agent-based theory development is readily linked with empirical science to gain knowledge about the functioning of complex systems being the base for predictive, cumulative science.

5. Challenges to developing reusable building blocks

Making building blocks re-useable is necessary for the research strategy discussed above and it might be straightforward to use them within specific domains (e.g., regarding human decision making in land use models, local competition for resources among plants, food detection strategies of vultures). Examples for domain specific community efforts are the pioneer modelling platform Community Surface Dynamics Modeling System (CSDMS, https://csdms.colorado.edu/wiki/About_CSDMS), pyMANGA (https://github.com/pymanga, Wimmler et al., 2024) which provides various RBBs including ZOI and FON to assemble plant population models, GSTools v1.3: a toolbox for geostatistical modelling in Python (Müller et al., 2022a,b), or CORMAS (http://cormas.cirad.fr/indexeng.htm) which aims to facilitate the development of ABMs and the monitoring and analysis of simulation scenarios to understand the relationships between societies and their environment. The latter has even taken another innovative direction, namely the collective development of models and interactive simulations. Although such examples show that agent-based theory development via the strategic use of RBB could be powerful for identifying general principles of ecological, social, economic, and political systems, it still has not developed its full strength. To learn from each other, we need to facilitate collective learning and to standardise the theory-building process. For this, alignment of modelling concepts is necessary to recognize similar approaches and to share RBB (Axtell et al., 1996; Schlüter et al., 2017). We have to manage different levels of challenges which relate to the (1) development, (2) sharing, (3) reviewing and (4) reusing of RBB (Fig. 1b).

(1) development

Different programming languages, application programming interfaces or modelling frameworks, are challenges for RBB development only on the first glance. Much more important are different ontologies, unclear semantics, different concepts of time or spatio-temporal resolutions when transferring algorithms and concepts from one context to another. We therefore need guidelines for the design and abstraction of RBBs. Minimum essential requirements for RBBs include a clear documentation of their code, their analysis, and their behaviour all in common languages (Vincenot 2018). Modellers should understand the behaviour and limitations of the RBB to be reused. Providing comprehensive documentation, a simple practical example of the RBB in use and, ideally, benchmarks for the RBB output under defined settings of use, will help users familiarise themselves with how the RBB works, reducing the likelihood that they will be misunderstood and misapplied. This also adds to the credibility of the RBB, as it has been tested independently by other researchers. Such an analysis is in line with previous work, which emphasised the importance of a separate analysis of submodels (Railsback and Grimm, 2019; Railsback et al., 2020; Troost et al., 2023).

(2) sharing

If we consider that processes and the behaviour of agents are often described by specific submodels, candidate building blocks are developed all the time, but making them reusable requires an initiative which has to come from the individual modeller, or team of modellers. They typically will have invested quite some time to develop a representation of a certain process that proved to be useful within a larger ABM. Of course, when the ABM is published and made openly accessible, so are its submodels, but it is unlikely that others will readily recognize them as building blocks and then be able to extract and reuse them in their own ABM. Rather the developers need to ask themselves: could our solution or implementation be useful in other ABMs? If so, the idea of RBB is to make this submodel available as a building block by itself, separately from the ABM for which it was originally developed. To make such consideration a common practice, we need not only the willingness of the contributors, but also file repositories to find RBBs; as well as accessible tools to support their testing, further development, and dissemination (Vincenot 2018). Previous initiatives have been often dependent on the energy of enthusiasts and are thus permanently endangered by a loss of resources which can, for example, abruptly terminate their long-term maintenance. So far, we are missing incentives to share abstract building blocks beyond the particular research project (s) of the contributing scientists.

(3) reviewing

Reviewing RBBs is essential for their credibility and the assurance of their quality. Unfortunately, at present the incentive for modellers to review other people's RBBs is still much lower than the incentive to develop their own RBBs. Nevertheless, this can only be seen as a community task. It will be worthwhile if individual modellers benefit from the certification and further development of RBBs for their own work, and if the joint effort for quality assurance remains transparent and visible in the long term.

(4) reusing

The dangers of an uncritical reuse of RBBs has been extensively addressed in previous studies (e.g., Lorscheid and Meyer 2016; Troost et al., 2023). A simple "plug-and-play" approach will not work in many cases. A RBB, when reused, is inserted into a new model, i.e., in a new context. When doing so, at least two issues must be considered with respect to the input and output of the RBB (Lorscheid and Meyer 2016). First, the parameter values and ranges which have been calibrated for the use in the original model might no longer be adequate in the new context (see also Troost et al., 2023). For the LCS example, parameter settings specifying the speed of learning are not so important in a relatively static environment. However, this would be different in environments frequently posing novel situations for an agent where a higher speed of learning is required. Second, the output of a building block typically affects other submodels in an ABM. Again, the importance of these outputs might differ from the original to the new ABM where the RBB is implemented. An extreme case could be that a specific RBB output was not relevant for the first model but is relevant in the new one, potentially affecting the behaviour of the ABM crucially. Overall, this means that the input/output behaviour of a RBB has to be checked carefully in the new context, similarly to any model component that was newly developed for that model.

Lorscheid and Meyer (2016) suggest using the term "configure", as this indicates that the submodel has to be prepared to fulfil its purpose adequately in the new context, and propose a systematic approach. To identify interdependencies between different submodels, they suggest, as a first step, a graphical representation of the interfaces between the submodels. Here, the submodels are placed in an order corresponding to the schedule of the simulation (e.g., as described in the ODD element "Process overview and scheduling"). Then, the effects of those interdependencies on other submodels can be investigated. Second, to find adequate parameter values and ranges for the RBB, they suggest a so-called cascaded design of simulation experiments. The basic idea is to run several preparatory simulation experiments in which parameter values and ranges are identified which are adequate for the new context (see Lorscheid et al., 2012; Lorscheid and Meyer 2016). Although no one-size-fits all protocol exists for this task, determining the correct parameter values for the purpose at hand increases the credibility of the model in the sense that one ensures that the RBB behaves in the way it is supposed to behave. Moreover, fixing the parameters at specific values in the sense of benchmarks can reduce the complexity of subsequent analyses of the full ABM.

6. How can the development and use of RBBs for ABMs be promoted?

So far, individual RBBs can be published in journals solely focusing on articles describing research software, such as Journal of Open Source Software (JOSS) or MethodsX. The articles are kept intentionally short and describe the software itself; the peer review process targets the software's functionality, documentation, tests, and the licence. Besides improving the software (the RBBs in this case), publishing it helps developers receive credit for the work. To put it in their own words: "While designed to work within the current merit system of science, JOSS addresses the dearth of rewards for key contributions to science made in the form of software." (Smith et al., 2018).

Another incentive for doing so is that the building block will get a *DOI* (digital object identifier), i.e., a permanent internet address. It can be cited and thus, if used by many others, increase the impact and citation rate of the developers. Even different versions of an RBB can be assigned individual *DOI*s. This helps foster the transparency and reproducibility of the RBB development.

However, publishing RBBs in stand-alone journal articles can be also time-consuming for developers and may result in a fragmentation of ABM RBB documentation across journals - some of which may be behind paywalls. Furthermore, it is likely to lead to disparities in what and how RBB details are conveyed, complicating their use by the research community. What we thus need is accessible support for the release, testing and development of RBBs. Ideally, there would be one place (a website hosting metadata and links, or a repository) on the Internet where ABM developers could upload their RBB. Like with models which currently can be uploaded, e.g., to the Model Library of CoMSES.net, certain standards should be required in terms of formatting and the information about the RBB and its scope.

Next, there should be the option of requesting peer review and of getting a *DOI* (ideally after the peer review was passed successfully). And, last but not least, there should be a forum where pros and cons of existing or possible RBBs can be discussed, so that developers can team up, learn from each other, and jointly further develop specific RBBs, and share their implementation ideally in different programming languages. It should also be possible to scan the history of an RBB and its actual use in the literature.

7. How do we build up RBB libraries for agent-based modelling?

To establish a culture of uploading, using, and developing RBBs, a critical mass of RBBs is needed so that modellers will feel it worthwhile to scan the repository of existing RBBs when developing their own model. They are only likely to do this if they believe there is a reasonable chance of finding an RBB of relevance to their work. To get a critical mass of building blocks, the threshold for uploading an RBB should be relatively low. We therefore suggest an approach where the requirements for uploading are kept to a minimum and are adapted to the skills of the contributing modeller, whereas the peer reviewing process of RBBs and getting the full acknowledgement are stimulated.

Several minimal requirements need nevertheless to be met in order to establish a useful RBB library. Each RBB should have a self-explanatory name and be accompanied by a narrative description of the mechanism or process it represents, as well as how and when it can be used. Further, the RBB needs to be well documented so that a subsequent user can understand what the RBB is doing and how it can be re-implemented or incorporated in its own model. The RBB should also be presented with at least one functioning implementation demonstrating its usage and with benchmarks to check its functionality. Given the background of the ABM community which is more in social and environmental sciences than in computer sciences, a RBB description should be user-oriented and not dependent on specialised IT skills that are exclusive to software developers.

A template that has consistent requirements for provision of essential information about the RBBs can support modellers, facilitate the communication and reduce supply side frictions if it is combined with an online repository. Yet this alone is not sufficient to ensure that the RBBs will be useful to and useable by others. Encouraging the development and sharing of RBBs requires consideration of both supply and demand. Potential RBB users may require information that was not anticipated in advance by RBB authors. Users might also find that submodels that are common to many ABMs are missing from the RBB repository. It is therefore important that there be a feedback mechanism, enabling researchers to signal where further details or contributions are required, thereby signalling demand. Thus, we need to link our repository for RBBs to an online forum in which modellers and would-be modellers may identify what they are looking for, discuss and develop existing RBB contributions, and in doing so help to generate signals of what is working and what is not. Such forums have proven themselves to be highly effective in the development of other platforms, such as Stack-Overflow for the development of the statistical programming environment R.

Platforms like GitHub or Zenodo are ideal for setting up a repository for RBBs. Still, in the early phase of trying to establish a culture for developing and releasing RBBs, we decided to keep the threshold for publishing and discussing RBBs as low as possible (see Fig. 4 for a suggested workflow). We have set up the preliminary website https://www.rbb4abm.com/as a starting platform for sharing RBBs with minimum requirements (basically a short description of the RBB and a link to any repository that might contain a more detailed description, source code or benchmarks, whatever is available). We refer to it as the "RBB Hub", so that all RBBs, plus potentially their different versions, their templates, their tests etc. can be found and searched in one place. Ideally, the links to the particular RBB would use GitHub and/or Zenodo or any domain-specific trusted repository. While the useful but somewhat complicated GitHub release + Zenodo gauntlet is increasingly used (as detailed here https://genr.eu/wp/cite/), with our solution contributors could simply upload files to Zenodo directly by clicking the green "New Upload" button. Platforms or even own websites are, for the time being, welcome as well, although experience shows that they tend to be short-lived (Janssen et al., 2020).

We have also opened a thread in the discussion forum on Comses.net (https://bit.ly/RBB_forum). Anyone wishing to publish an RBB, search for existing ones, or report updates or new tests or applications can also post in the forum. We hope that this will help us reach a wider audience.

When contributing an RBB to https://www.rbb4abm.com/, the authors of this article will check the level of contribution. Depending on the inventory, it will be flagged whether only a description, programming code or even benchmarks are made available. This preliminary website, and its template, are meant as a demonstration of the RBB concepts introduced in this article. A permanent website, which is more comprehensive and provides the final template, procedures such as peer review, and a repository, will be released in spring 2024; rbb4abm.com will then link to this new website.

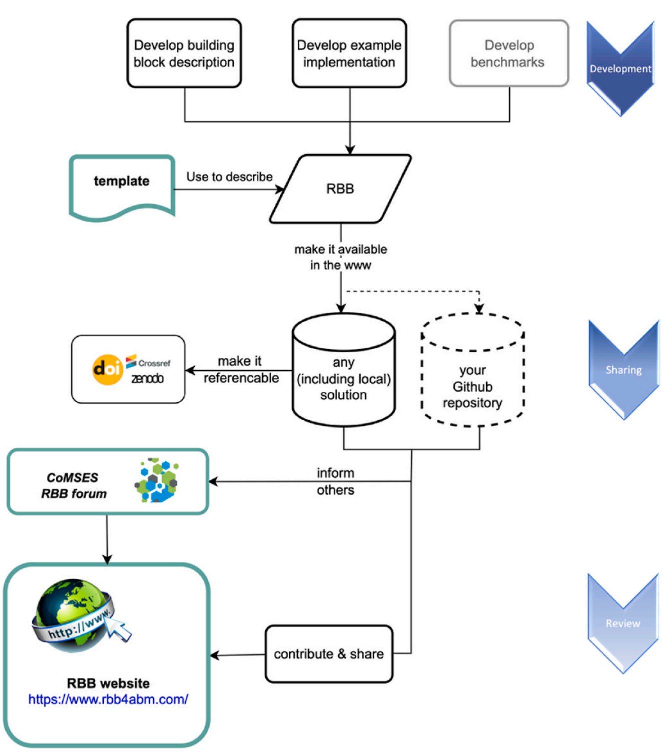

Fig. 4. The workflow to publish, document, approve and receive a doi for a reusable building block as suggested in this paper. The boxes marked with green shape lines are provided by our initiative.

Naturally, a critical mass is needed, which will require efforts beyond this article and the provisioning of a website. We plan to devote considerable man power in providing online and in person events such as conference sessions, short training courses and videos, etc., to spread the word, build capacity and build a community. We will also align and integrate our efforts with those of the Open Modeling Foundation (OMF; Barton et al., 2022a,b), which is "is an alliance of modelling organisations that coordinates and administers a common, community developed body of standards and best practices among diverse communities of modelling scientists"[2]. Some of the authors are active members of OMF working groups.

8. A template for RBBs and examples for its use

Our initial template is a documentation of the RBB available at the RBB website https://www.rbb4abm.com/for download. It was developed in the spirit of the ODD protocol for describing ABMs (Grimm et al., 2020) - refined through broad discussions as part of the Volkswagen Foundation's symposium series "From Cases to General Principles - Theory Development Through Agent-based Modelling" (Hannover – Germany –2018, 2019 and 2020); from workshop participants at IEMSS 2022 in Brussels, the Social Simulation Conference in Milan (2022); Complex Systems Society 2022 meeting in Santa Fe. ODD's main purpose is to make model descriptions complete, easy to read and easy to write. Readers are presented an overview first before being asked to go into details, which facilitates understanding and navigation in the model description. Writers know exactly what readers expect, by using a given structure and terminology. Our RBB template tries to achieve the same.

One challenge was that RBBs can require a considerable amount of additional information beyond the model description itself, so that the first templates we developed and tested, which included all these elements, might have deterred too many potential RBB developers. We therefore went for a tiered approach: our template has two components (i) minimum required information (marked by [*]) and (ii) optional information. The minimum required information should be sufficient to understand what the RBB is doing and how. The complete description should enable users to re-implement the RBB themselves, to understand its assumptions, and to evaluate its functioning. The ultimate intent is to have a rigorous, tested contribution that can be archived in the repository with a *doi*, similarly to a journal submission (Box 1).

For this initiative, we prepared a few examples with the template presented above (all of them are work in progress) to demonstrate how the entries of the template should be understood (https://www.rbb4abm.com/).

9. Discussion and outlook

To address the challenges of our rapidly changing world, we need to better understand how ecological, social, and political systems may respond to external interventions, trends, and shocks. The dynamics of these systems are driven by the adaptive behaviour and complex interactions of agents (e.g., organisms, humans, and organisations), motivating the use of agent-based models (ABM) to capture these dynamics. Since not all systems and scenarios can be described by a new model, ABMs should be used as virtual laboratories for developing predictive theory at both the agent and system levels and, most importantly, simultaneously at both levels. Presently, though, this development is isolated within disciplines and often focuses on individual cases. To boost agent-based modelling to the next level, we need to establish an iterative process of theory development via testing, collective learning,

[2] https://www.openmodelingfoundation.org/.

Box 1
A template to document RBBs, which can be downloaded from .[31] It distinguishes between minimum required (marked with [*]) and optional information in order to lower the initial barrier to submission, so that good ideas can be shared and developed quickly.

1. The name of the RBB [*]
This name should be self-explanatory and short. Ideally, it will indicate the types of entity it is applicable to, the processes described and any theory it is based on, e.g.:
- Theory of Planned Behaviour (TPB) to represent human intention-driven decision-making.
- Perfectly-rational optimizer (PRO): to represent human non intention-driven decision-making.
- The Zone-Of-Influence (ZOI): a phenomenological description of competition among sessile agents (e.g., neighbouring plants).
- The Field-of-Neighbourhood (FON): a phenomenological description of facilitation among sessile agents (e.g., neighbouring plants).
- Correlated Random Walk (CRW) to describe agent's (e.g., animals or humans) movement in homogeneous landscapes.

2. The author(s) names [*] & affiliation(s)
All authors should be mentioned here - the one(s) who originally submitted the RBB to the repository, and the ones who contributed to its subsequent development ***[*]***. Additional details such as email addresses and ORCID IDs are considered optional.

3. Keywords *[*]*
Additional terms that suggest what the topic of the RBB is about. They may also include words and phrases that are closely related to your topic and help interested modellers find your RBB easily. For example, if the RBB is about random walk, use phrases like animal movement, animal behaviour, food search, etc.

4. The purpose of the RBB [*]
A narrative description of what mechanism or process the RBB is representing and in what environments or systems. What kind of questions has the RBB already been used to address and what other questions could it be relevant to? Preferably include references to relevant publications.

5. *Concepts*
A description of the theoretical concepts the RBB is building on, e.g., a specific standard description of a certain behaviour such as symmetric competition or the informed user. This helps to classify the building block and to find a link to others that could be grouped in one category.

6. An overview of the RBB and its use [*]
This section follows the rationale of the *Overview* part of the ODD protocol (see supplement S1 of Grimm et al., 2020). RBBs are typically relatively short procedures that describe a certain process affecting a certain entity, e.g., an agent. For example, a plant uses water, or competes with other plants, a buyer buys something, or a farmer is affecting the way other farmers use their land. Note that the calling and affecting agents can be the same. The following information should thus be provided:

- **Entity *[*]*:**
  - What entity, or entities, are running the submodel or are involved (e.g., by providing information)? What state variables does the entity need to have to run this RBB?
  - Which variables describe the entities?
- **Context, model parameters & patterns:**
  - What global variables (e.g., parameters characterising the environment) or data structures (e.g., a gridded spatial environment) does the use of the RBB require?
  - Does the RBB directly affect global variables or data structures?
  - What parameters does the RBB use? Preferably a table including parameter name, meaning, default value, range, and unit (if applicable).
- **Patterns and data to determine parameters and/or to claim that the RBB is realistic enough for its purpose:**
  - Which of the variables (or parameters) can be set independent of the model/RBB, using direct measurement, other models (e.g. regression), etc.?
  - Which variables or parameters can only be estimated within the context of the model or require calibration?
  - Which data or patterns can be used for calibration?
  - Are pre-existing datasets available to users already exist (references)?
- ***Interface - A list of all inputs and outputs of the RBB [*]***

A table which specifies:

- **Scales *[*]*:**
  - Which input variables that the RBB requires from an external, calling entity and in which units?
  - What specific outputs does it produce and how does this update the state variables of the calling entity?

On which spatio-temporal scales is the RBB valid, i.e. what are the possible range of resolutions and extents of the spatial and temporal scale?

7. Pseudocode, a Flowchart or other type of graphical representation [*]
We consider this as semi-optional information since the suitability of each tool strongly depends on the complexity of the RBB. The author should ensure, however, that a reader understands what the RBB code is doing and in which sequence.

8. The program code [*]
- A well commented code. ***[*]***
- Information on the programming language, operating system, development environments incl. any required software package or library, version etc. ***[*]***.
- If possible, the code should be provided for different programming languages. If an author contributes their RBB in one programming language only, it could be an option that other authors provide a new implementation in a different programming language or environment. Thus, this list could be broadened over time.

9. Example analyses of a simulation output, test cases and benchmarks *[*]*
Results obtained with the example implementation providing insights into how - under different settings - the RBB performs, including extreme scenarios.

(*continued on next page*)

(*continued*)

For a linear output at least two test cases should be provided, for a curved one as many as required to capture the behaviour of the RBB over the full range of input values.
Benchmarks should provide outputs for standardised scenarios. They are the base for evaluating re-implementations.

10. Version control [*]

A version control is already included if GitHub is used. If the RBB is provided via a different platform, an individual version control would help to document the history. At least it should be provided:

- Publish Date
- Last Updated

11. Status info

- Peer Review: yes/no. In case of a double open reviewing process, the name(s) of the reviewer(s) could be provided. This would increase the transparency of the process and acknowledge the effort of the reviewer for the ABM community.
- Licence (if relevant): For example GNU Lesser General Public Licence, General Public License (GPL) etc.

12. Citation of the RBB

Any information on how the RBB should be referenced when reused. If the RBB is already tested and received a *DOI*, this is the place to find it.

13. Example implementation of the RBB to demonstrate its use

It should be a demonstration program specifically written for the purpose of demonstrating the RBB in action with minimal superfluous content (like the code examples provided in the NetLogo library). It must be in a format that is readable by compilers or development environments commonly used by agent-based modellers (like NetLogo, GAMA etc.). Complex model structures should be avoided to reduce the risk of obsolescence over time and to prevent the actual mechanics of the RBB being obscured by unimportant model details.
The following information should be provided:

- An executable demonstration program (including its code) that demonstrates how the RBB is working and allows users to play with its inputs and parameters.

14. Use history

What is the history of the RBB? Is it entirely new or based on earlier submodels, or an implementation of an existing submodel? Has the RBB, or its predecessors, been used in literature? Reference list of publications where the RBB was successfully used.

15. *A manual and/or tutorial, in particular for more complex RBBs.*

Optional because of the effort, but it would be worthwhile particularly if the RBB is complex.

16. Relationship to other RBBs

Sometimes an RBB belongs to a family of others. For example:

- The *Field-Of*-Neighbourhood (FON), which describes competition or facilitation among neighbouring plants, is an extension of the *Zone-of-Influence* (ZOI).
- The perfectly-*rational optimizer* (PRO) serves as a NULL model for the *Theory of Planned Behaviour* (TPB).

17. References

Any external reference (not included in bullet point 11) if required.

and improvement.

RBBs can support and accelerate this process in different ways: (1) the standardised documentation, sharing and collective testing of RBBs improves the transparency of ABMs. (2) A collective effort can promote the regular development of RBBs and their use as good scientific practice. (3) By compiling a critical mass of RBBs in an open-access, searchable website, the ABM community can begin to converge around certain approaches and strengthen the power of theory development for social-ecological systems (SES).

The development of repositories containing both domain and cross-domain specific RBBs will make agent-based modelling more accessible to scientists who are beginners in modelling. Considering that even experienced ABM modellers are usually not computer scientists, but experts in their own domains and autodidacts in software development, the proposed initiative could strengthen the whole community.

Our literature survey (Supplement) showed that RBBs do not yet play an important role in ABM and theory development for SES. Existing reuse of submodels and code snippets are limited to occasions where authors explicitly share their code and readers, usually in the same domain, find them. Even so, a recent review found that only 18% of ABM applications made their code available in 2018 (Janssen et al., 2020). There are a few locations where RBB code examples can be found (e.g., some Code Examples included in the NetLogo library or the Toy Models library in GAMA) which could serve as de facto RBBs; and there are also a few RBBs already available, e.g., the Siplab R-package provided by (García 2014 and following updates of the R-package). But searching for reusable code snippets in distributed platforms, ABM platforms like CoMSES.net, or within the mass of scientific publications is time consuming.

Repositories like Zenodo[4] already provide a *DOI* if a modeller uploads their RBB code. But finding such contributions among the mass of all other model types and data sets remains a challenge. Also, a simple upload of the RBB to Zenodo does not guarantee the suitability, and that the correctness and documentation is approved by other users. This is, on one hand, an advantage because it lowers the bar to contribute RBBs to the community; but on the other hand, it undermines quality assurance and might delay or mislead inferences about the functioning of SES.

This paper emphasises the necessity of a concerted action to develop and disseminate RBBs, and aims to stimulate participation by members of the ABM community. We introduced a first, still simple, workflow and a first template which both need to be discussed and further developed. It hopefully stimulates discussion on "atomic" RBBs and links modellers to others with similar interests and contexts to help each other in testing and revising the programming code, including the translation of the RBB from one programming language (e.g., NetLogo) into other ones (e.g., R or Python). We encourage contributions to use this pilot infrastructure to expand the RBB offering and to help us assess efficacy of the approach.

Advertising an RBB in the CoMSES pilot forum and announcing it at the envisioned RBB website (see 'How to' in Supplementary material) is not a must to contribute to our initiative. Other repositories can be used and linked to the forum or other forums can be established. However, using the pilot infrastructure proposed here will bundle community

[4] https://zenodo.org/.

efforts, helping to improve it as understanding of best practice evolves.

We established a RBB website where the template can be found and downloaded. More importantly, the website provides a collection of initial examples and the respective links to the developers' repos where they can be downloaded. Assuming that numerous modellers contribute their own RBBs, other solutions such as a joint RBB repository might be more efficient for ABM modellers to search and find RBBs useful to them, similar to the archive of numerical recipes provided for programming languages such as C++ or Python (e.g., Press et al., 2007). We, the authors of this paper, will offer both minimal and substantial review upon request. A minimal review will be done of the uploaded files verifying that all of the requirements (template) are adequately met. If this is the case, the RBB contribution will be published on the website for all readers to see. A more substantial review would involve testing the provided code under the range of the benchmarks (if this information is provided by the author(s) of the RBB). After passing the substantial review process, the status "reviewed" will be announced for the particular RBB at the RBB website.

Documentation and evaluation are both key to making RBBs useful and to avoid the risk that they become "reusable black boxes". Still, a peer review process of a RBB in the context provided by an RBB author does not give a green light to an uncritical re-use of the RBBs. The ultimate responsibility for appropriate use of an RBB in a new context remains with the re-user, e.g., if some part of the original implementation turns out to be inappropriate in the new context. Similar concerns are emerging with the recent proliferation of large language models (LLMs; e.g., Chat GPT), which can rapidly generate segments of code that can also be used as building blocks for ABMs. We believe that our proposed peer review process can provide a level of verification beyond that possible through LLMs, though how LLMs could enhance RBB generation or the peer review process is a question for future research.

Finally, the term reusable building block (RBB) suggests interoperability, and our paper discussed the usefulness of such a concept. But is it also viable? There are indeed some domains where RBBs exist that can directly talk to one another without much custom coding. Examples include the ZOI and FON approaches implemented in NetLogo or Python and used in plant ecology to describe above-ground or below-ground competition and facilitation among neighbouring plants in the several combinations needed for a particular specific context (see e.g., May et al., 2009, Lin et al., 2012, 2013; Peters et al., 2020; Bathmann et al., 2023). However, to enable such interoperability, RBB implementations would need to come up with a common low-level grammar and a set of data structures. To achieve this generally and across disciplines and contexts would be difficult at this stage that aims at introducing RBBs to the ABM community. This is not the intention of our initiative, which is to support and motivate the exchange of RBBs and not to hinder it by technical hurdles. We thus consider RBBs less as being like plug and play Lego bricks but rather like building blocks that must be carefully combined with mortar.

We see the RBB initiative in the light of previous initiatives like ODD (Grimm et al., 2006, 2010, 2020), ODD + D (Müller et al., 2013), or TRACE (Grimm et al., 2014) which helped to increase the transparency of ABM studies and increased the acceptance of the ABM approach in the scientific community. These initiatives were successful because an increasing number of scientists have been participating in the last decade. We hope that we can convince readers about the necessity and potential of compiling a joint RBB repository and hope to have motivated you to participate.

CRediT authorship contribution statement

Uta Berger: Conceptualization, Project administration, Writing – original draft, Writing – review & editing, Software. **Andrew Bell:** Writing – review & editing, Conceptualization. **C. Michael Barton:** Writing – review & editing. **Emile Chappin:** Writing – review & editing. **Gunnar Dreßler:** Software, Writing – review & editing. **Tatiana Filatova:** Writing – review & editing. **Thibault Fronville:** Software. **Allen Lee:** Conceptualization, Software, Writing – review & editing. **Emiel van Loon:** Writing – review & editing. **Iris Lorscheid:** Conceptualization, Software, Writing – review & editing. **Matthias Meyer:** Conceptualization, Software, Writing – review & editing. **Birgit Müller:** Writing – review & editing. **Cyril Piou:** Software, Writing – review & editing. **Viktoriia Radchuk:** Software, Writing – review & editing. **Nicholas Roxburgh:** Writing – review & editing. **Lennart Schüler:** Writing – review & editing. **Christian Troost:** Writing – review & editing. **Nanda Wijermans:** Writing – review & editing. **Tim G. Williams:** Writing – review & editing. **Marie-Christin Wimmler:** Conceptualization, Software, Writing – review & editing. **Volker Grimm:** Software, Writing – original draft, Writing – review & editing.

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.

Data availability

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2024.106003.

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