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Governance interactions of spatial data infrastructures: an agent-based modelling approach

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ABSTRACT

In order to facilitate and coordinate spatial data sharing and exchange, many organisations have developed spatial data infrastructures (SDIs). SDI governance plays a pivotal role in the development and evolution of an SDI, but as SDIs are complex adaptive systems, governing is a challenge. This research therefore proposes a complexity perspective to SDI governance by exploring the use of agent-based modelling to simulate and examine SDI governance interactions. In this agent-based simulation, we examine interactions between SDI stakeholders, data availability and the effects of different governance styles (hierarchical, network and laissez-faire governance) and budget policies. The simulation shows that it is possible to mimic SDI governance dynamics through agent-based modelling. By running different scenarios, it appears that a network approach is more successful compared to a hierarchical or laissez-faire approach. Expert validation shows that overall the results of the simulation are credible and insightful, although improvements can be made to make the model more realistic. With agent-based modelling, SDI governance becomes more tangible and visible, which facilitates discussion and understanding. Agent-based modelling therefore appears to be a helpful new approach in a better understanding of the complexities and dynamics of SDI governance.

1. Introduction

In the past decades, many organisations developed spatial data infrastructures (SDIs) to facilitate and coordinate spatial data sharing and exchange (Crompvoets et al. 2004). Although originally, SDIs were established to enable spatial data sharing between – mainly – public organisations, nowadays many organisations have decided to open up their spatial data to anyone, resulting in open spatial data infrastructures (Vancauwenberghe and van Loenen 2018).

With growing SDI use, also the group of SDI stakeholders is growing. This generates more benefits, but also tensions. SDI stakeholders can have conflicting needs and interests. What facilitates achieving the objectives of one group of SDI stakeholders, can be counterproductive in achieving objectives of others (Hendriks, Dessers, and van Hootegem 2012). To maintain the delicate

balance between all stakeholder interests, setting up an SDI governance framework is crucial, but also a challenge (Coetzee et al. 2020).

SDI governance is a complex and dynamic process. SDIs are acknowledged to behave like complex adaptive systems where 'features and behaviours such as openness, level of self-organization, adaptability and existence of feedback loop mechanisms, play an important role in the efficient and effective functioning of SDI (Grus, Crompvoets, and Bregt 2010, 457).' Governing complex adaptive systems is challenging, as surprises, threshold and cascading effects occur (Duit and Galaz 2008). In governance, solutions to problems can lead to new problems (Verhoest, Bouckaert, and Guy Peters 2007) or undesired effects (Kooiman 2003). Case studies on SDI governance (Sjoukema, Bregt, and Crompvoets 2017, 2020) show that 'tipping points' or 'crucial decisions' in SDI governance also definitely occur, which can influence the development and evolution of the SDI considerably.

Complexity of a system emerges from local interactions among individual entities (Manson, Sun, and Bonsal 2012). As both governance and SDIs exist of many local interactions between involved stakeholders, it is not surprising that both governance and SDIs are seen as complex subjects. Despite this fact, in general, research on SDIs and SDI governance tend to focus on SDI components (e.g. Hendriks, Dessers, and van Hootegem 2012; Vandenbroucke et al. 2009) or SDI governance instruments and structures (e.g. Vancauwenberghe and van Loenen 2017; Crompvoets et al. 2018; Sjoukema, Bregt, and Crompvoets 2017). This is not surprising, as these are the more tangible appearances of SDIs and SDI governance. Social network analyses (such as the studies of Vandenbroucke et al. 2009; Coetzee et al. 2019, 2020) help to give insights in the broad range of interacting SDI actors, but it is difficult to identify from these analyses the dynamics and emergent phenomena. SDIs are emergent phenomena, as their properties are wider than the sum of their parts (components) (Bonabeau 2002; De Man 2006).

A method which is suitable to reproduce emergent phenomena by programming local interactions is agent-based modelling. With agent-based modelling complex macro level behaviour can be mimicked by simulating micro level interactions (Manson, Sun, and Bonsal 2012). 'Even a simple agent-based model can exhibit complex behaviour patterns and provide valuable information about the dynamics of the real-world system that it emulates (Bonabeau 2002, 7280).' It is therefore a promising method for understanding SDI governance as 'the stronger any interaction effects are, then the more important it will be to consider agent-based or other disaggregated approaches (O'Sullivan et al. 2012, 119).' Other advantages of agent-based modelling are that it is flexible, provides a natural way to describe systems and makes complex systems more tangible (Bonabeau 2002).

Although agent-based modelling is often applied in the field of geo-information science, it has not been used in SDI research until recently: Lubida et al. (2020) show in their study on the Tanzanian NSDI that agent-based modelling can be an useful method to better understand the process of SDI development.

Craglia et al. (2012) argue that SDIs lack in general multi-disciplinary models for forecasting change, thresholds and tipping points, that they do not include scenarios of possible policy responses and lack participatory frameworks to engage decision-makers. We think that this does not only apply to the services SDIs provide but also to the way SDI governance is performed and understood. Agent-based modelling can help to overcome these challenges.

A possible reason why agent-based modelling is hardly used for SDI governance, is the fact that SDIs exist of many interrelated components and are always unique, which makes it hard to distinguish all influential local governance interactions and mechanisms. As a model is always a simplification of reality, developing an agent-based model asks for the right balance of complexity: 'If the level of abstraction is too simple, one may miss the key variables. Too much detail, and the model will have too many constraints and become overly complicated (Crooks and Heppenstall 2012, 98).' In general there seems a tendency to favour simple agent-based models over complex models as complex models will be equally difficult to understand as the real world phenomena. The aim of an agent-based model should be to represent the key features in a particular context

of a system in order to enable us to improve our understanding of how that system works (O'Sullivan et al. 2012).

The objective of this research is to simulate and examine SDI governance dynamics using agent-based modelling. We do this by developing a generic agent-based model which simulates local SDI governance interactions. These local governance interactions should be adjustable in order to apply different governance styles and policies. The model should provide insights to SDI stakeholders in which governance strategies are the most effective. By discussing the simulated model and its results with SDI experts, the added value of an agent-based modelling approach to the field of SDI governance can be determined.

The first step in agent-based modelling is to develop a conceptual model. The following section therefore will operationalise these interactions further and summarise it into a conceptual model. In the third section the method for model development is explained. Section four explains the model simulation results. Section five discusses the use of agent-based modelling for SDI governance, its limitations and the possibilities for future research. The last section concludes this research.

2. SDI governance concepts

Governance is the process of governing in which multiple actors (both public and private) participate to influence this process through interactions. Interactions are a key element in governance, which does not only apply to interactions between actors, but also between actors and the structures they are bound to. Actors, structures and interactions are therefore considered as the basic aspects of governance (Figure 1) (Kooiman 2003; Sjoukema, Bregt, and Crompvoets 2020).

The governance process works as follow: Actors define and shape problems they want to solve based on their perception or 'image.' In order to solve problems, they are interdependent of other actors, who need to, for example, change their behaviour or help the governing actor. To steer another actor into the desired actions, governing instruments are used. A wide variety of instruments can be used, ranging from 'soft' instruments such as information sharing towards 'hard' instruments such as laws and punishments. These instruments are applied into action which will affect the other actors. These actors will respond by giving either indirect or direct feedback, which can be both positive and negative. This interactive day-by-day process is also what we can call the 'actor level' of governance (Kooiman 2003).

Structures, such as institutions, cultures and resources, enable and constrain these actors and interactions. These structures are stable in the short term, but can be changed in the long term (Giddens 1984). Through interactions, actors communicate with other actors or try to change the structures they are bound to (Kooiman 2003).

We apply this framework onto SDIs and try to simulate how the actors and the state of the SDI influence each other. To limit the complexity of the model, we chose to simulate the following SDI governance interactions, to see how they influence the course of an SDI:
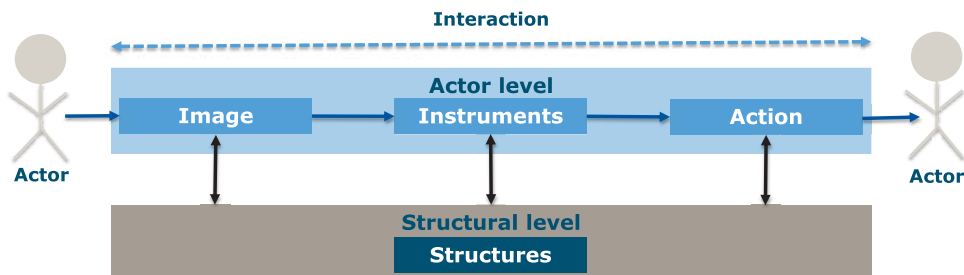

Figure 1. Actors, interactions and structures (Retrieved from: Sjoukema, Bregt, and Crompvoets 2020).

- Interactions between SDI actors themselves, depending on various governance styles (hierarchical, network and laissez-faire);
- Interactions between SDI actors and the SDI;
- Interactions between SDI actors, the SDI and their structures (resources).

The following section describes the actors, interactions, structures and the SDI which together shape the conceptual model used for simulating SDI governance. To gain a full understanding of the complete agent-based model, an ODD (Overview, Design concepts and Details) is added as supplemental material (Grimm et al. 2010).

2.1. Actors

Most SDIs have a large diversity of actors or stakeholders. And with open SDIs, these actors can be virtually everyone. Several SDI scholars have tried to define SDI actors and their roles (e.g. Hjelmager et al. 2008; Richter, Miscione, and Georgiadou 2010; Coetzee et al. 2020). In this research we use a 'geographic data flow' perspective on the SDI (Richter, Miscione, and Georgiadou 2010), which connects well to the network perspective described by Vandenbroucke et al. (2009). In this network perspective, actors act as nodes on a network. Producers and users of spatial data are nodes in this network, as well as coordinating bodies and stakeholders who process and facilitate the spatial data infrastructure (Vandenbroucke et al. 2009). In total we identified four important SDI actor roles:

(1) *SDI executive:* This actor role represents the executive branch of government that has authority and responsibility for the SDI. In many cases, the SDI executive has the role of 'policy maker' or coordinator, and determines the mission and vision of the SDI. The SDI executive is in many cases the most influential actor in SDI governance (see e.g. Coetzee et al. 2019, 2020).
(2) *SDI data provider*: This actor role represents the organisation(s) who delivers spatial data to the SDI. It can also be seen as data producer.
(3) *SDI platform provider*: This actor role represents the organisation(s) who maintains and updates the infrastructure and plays a central role in bridging data from SDI data providers to SDI users. It can have the role of provider or broker.
(4) *SDI user*: This actor role represents the organisations(s) who uses the spatial data from the SDI. SDI users use spatial data as end-user or as value added re-seller.

In the model, the four actor roles should be seen as aggregations of the total group they represent as in practice, an SDI never exists of four actors. In general this applies foremost to the SDI data provider and user, but also the role of SDI executive or platform provider can be shared by multiple actors in practice. Also, an organisation can take multiple roles, for example as data provider and as user. However, to better understand the dynamics and interactions of the agent-based model, we deliberately choose to limit the number of agents to four actor roles.

The actor's image is an important starting point in governance. A positive image of the SDI will lead to a more used and trusted SDI, while a negative image will lead to the opposite effect. A negative image can also influence the SDI negatively as Coetzee et al. (2020) note that: 'it is highly unlikely that providers of local data will bring up the energy and resources to implement something that has only indirect or longer-term benefits for them (Coetzee et al. 2020, 17).' Within an SDI, images of actors do not have to be aligned with each other. In the model, all actors own the attribute 'satisfaction.' This represents their overall satisfaction with the SDI and its governance in a broad sense.

2.2. Interactions

One of the core principles of governance is that every involved actor can influence the governance process. However, it depends heavily on the governing position of the actor and her/his resources

what kind of governing instrument it can choose (Kooiman 2003). For example, in many cases it is the SDI executive who can make legally binding policies around an SDI. An SDI user can also influence the course of the SDI, by giving feedback, taking part in user committees or providing information on how the data is used. However, a user will not have the power to use any 'hard' instruments.

In the model we therefore make a distinction between three types of instruments:

- Hierarchy messages, representing the use of hierarchical instruments.
- Network messages, representing the use of network instruments.
- No messages, representing a laissez-faire approach: no instruments are used.

In our model, only the SDI executive has the power to use hierarchy messages which resemble the 'hard' instruments. In practice this can translate to decisions on standards, policies, laws and allocation of tasks and responsibilities (Vancauwenberghe and van Loenen 2017). In the model, every actor has the ability to send network messages representing the 'soft' instruments. A no message resembles the act of doing nothing, as choosing to do nothing can also influence the governing process.

Feedback loops are an essential part of complex adaptive systems (Grus, Crompvoets, and Bregt 2010). In the model, the actor who receives the message will respond with feedback. Whether this feedback is positive or negative, depends on the history of sent messages to an actor. Actors in the model prefer a mix of messages as Edelenbos et al. (2015) notices that 'continuously steering towards interaction, participation and consultation tends to produce inertia; over-emphasis on hierarchical top-down control has the disadvantage of driving parties to dig in their heels, leading to resistance, delays and postponements of implementation' (Edelenbos et al. 2015). Mixing governance styles seems also a prerequisite for adaptive governance (Dietz, Ostrom, and Stern 2003). Therefore, in the model, when an actor gets too many similar messages in a row, the satisfaction of this actor decreases and the actor responds with negative feedback.

2.3. Structures

Structures, such as policies, laws and resources enable and constrain the governance process. Standards, technology and policies are not only key components of an SDI (Rajabifard, Feeney, and Williamson 2002) but also examples of SDI structures. Resources, such as monetary, but also knowledge, time, social and political capital are also essential structures as they influence the choice for instruments (Sjoukema, Bregt, and Crompvoets 2020).

As resources are also necessary to produce and maintain spatial data and the SDI itself, we limit the structural level in the model to budgetary resources and resource allocation policies. This does not mean that other types of structures are not important to SDI governance, but resources add an extra dynamic dimension to the interactions where for example standards, laws and policies are more static in the short term.

Producing spatial data and maintaining an SDI are costly endeavours. The data providers and SDI platform provider are in many cases the actors who are making these costs. SDI users will benefit from the data and services the SDI delivers. There are multiple funding models for SDIs and their data (see e.g. Welle Donker and Van Loenen 2016). In the model we will simulate three: piecemeal funding, continuous funding and pay-per-use funding.

- *Piecemeal funding:* With piecemeal funding, budget is provided without a coherent long term vision or strategy, for example by projects. Literature on early SDIs shows that many SDIs are funded by a piecemeal approach (Crompvoets et al. 2004).
- *Continuous funding:* With continuous funding, there is a stable flow of budget covering the main costs of the SDI. According to Crompvoets et al. (2004): 'It seems that the stability of funding has a positive impact on people's use and management and of the quantity of the data (Crompvoets et al. 2004, 682).'

- *Pay-per-use funding*: In the previous two financing model, resources were gained and allocated through the central governing actor, the SDI executive. In this model, not the SDI executive but the SDI users will recover the costs of the SDI data provider and SDI provider by paying for the data if the quality is good enough.

2.4. Conceptual model

Figure 2 summarises the conceptual model which is used for the agent-based model. It shows the four actors (SDI executive, SDI data provider, SDI user and SDI platform provider) and the way they interact. All actors can send each other messages and respond to the received messages with feedback.

The SDI is represented by a data flow, streaming from the SDI data provider through the SDI platform provider to the SDI user. One of the main objectives of the first two actors is to keep the quality of data good enough in order to satisfy the SDI user. In order to provide a good data flow, the SDI data providers and SDI platform provider have to spend resources and should be satisfied. Depending on the budget policy either the SDI executive (continuous and piecemeal funding) or the SDI user (pay-per-use funding) recover these costs.

3. Method

This section describes the model development, its workings, the process of verification and validation and the formation of scenarios for applying the model. For a full model description following the ODD (Overview, Design concepts and Details) protocol (Grimm et al. 2010), we refer to the supplemental materials of this paper.

3.1. Model development, setup and working

The agent-based model was iteratively developed based on the described theoretical concepts, with the help of the agent-based modelling software NetLogo version 6 (Wilensky 1999). By starting
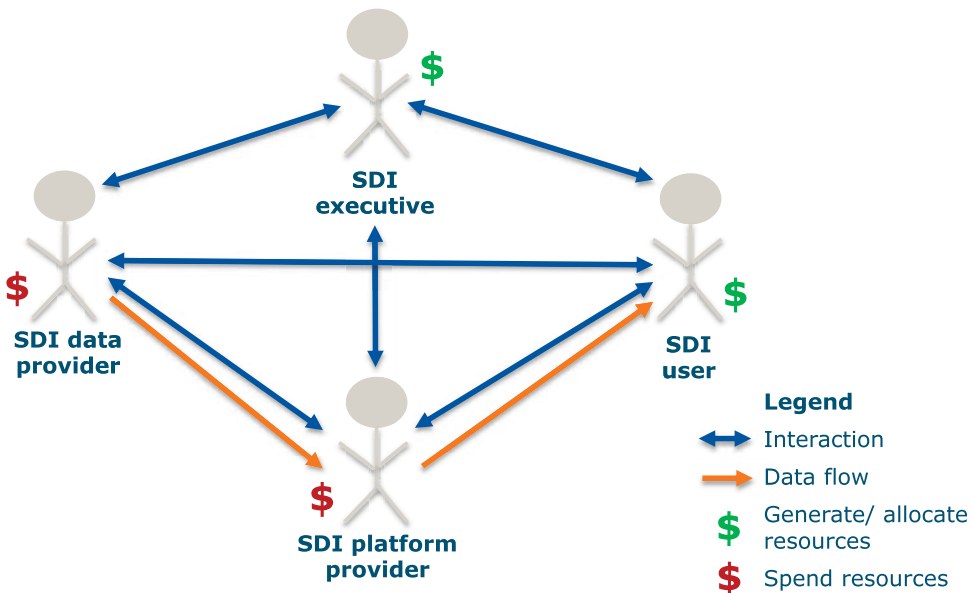

Figure 2. Conceptual model showing the interactions in the SDI Governance model.

small and iteratively extending the model, the working of the code could directly be tested. As the model developers and the authors of this research are the same, miscommunication risks were prevented.

Before initialising the agent-based model, the user can influence five inputs. The first three are the probability on a certain type of message (hierarchy, network or no messages) on a 0–100% scale. As in the model there is an equal chance for each message type to be selected, setting them all to the same percentage will result in a 1/3 chance of a certain message. However, by setting each input to a different ratio, it is possible to make a certain message type more dominant.

Another input is the susceptibility to feedback of actors. In reality, not every actor will either send explicit feedback or listen to received feedback. Therefore, we added in the model an input called susceptibility to feedback on a 0–100% scale. By changing this ratio, the influence of feedback in the model can be altered.

The last input which can be influenced by the user is the budget policy, which can be set to continuous, piecemeal or pay-per-use financing. With the continuous budget policy, funding is provided and allocated from the SDI executive to the SDI data and platform provider every time step. With the budget policy set to piecemeal, every 5 time steps budget is provided to the SDI executive, while this actor keeps the role of allocating resources at every time step. In the pay-per-use budget policy, the SDI user pays the SDI data and platform provider if the data quality is good enough.

When running the model, first a message type and an actor are selected. Then this actor chooses randomly another actor to send her/his message to. The receiver compares this message with previously received messages and changes her/his satisfaction. Basic principle is that the satisfaction of the receiver decreases when she/he gets three times in a row a network or no message or two times in a row a hierarchy message. However, a single hierarchy message boosts the satisfaction more than a single network message. A single no message has no positive or negative effect. Based on the receiver's change in satisfaction and her/his current satisfaction, feedback is sent. Depending on the susceptibility to feedback settings, this feedback affects the satisfaction of the original sender.

Budget is allocated to the SDI data provider and SDI platform provider. They need to be satisfied and spend resources to maintain the quality of the data flow. When the quality is good enough, the SDI user will increase her/his satisfaction and gain resources. When the quality is poor, the SDI user will give negative feedback to the SDI data provider and SDI platform provider. They will then spend extra resources to improve the quality.

The model runs until the average satisfaction of all involved actors is below 1 on 0–10 scale: the SDI and its governance interactions have then failed to satisfy its stakeholders.

3.2. Verification, calibration & validation

Verification, the process of comparing the agent-based model to the conceptual model and its behaviours, is important for any agent-based model (Rand and Rust 2011). We took several steps to verify the model. At each iteration of the model development process, the model was manually tested in order to see if the dynamics behaved according to the theoretical conceptions. From the first developments onwards, the model was continuously verified and documented in both the code and the ODD protocol.

We used relative value testing and sensitivity analysis to test the model (Rand and Rust 2011; Ngo and See 2012). With relative value testing, we tested if the chances of message types (hierarchy, network, no message) which can be influenced during model initiation, corresponded with the distribution of messages as output. During sensitivity analysis, the model was run 1000 times while chances on a certain message type were increased step by step with 5%. All other message inputs and the susceptibility to feedback were held stable at 50%. In this way, it was assessed if there was any unexpected behaviour. When necessary, the model was altered and the tests were run again. We ran the model 1000 times in order to gain robust results. Section 4 discusses the final results from the sensitivity analysis.

At the final stage, the model was validated through expert judgement (Bonabeau 2002). First, the conceptual model, the agent-based model and its underlying concepts were shown and assessed individually by SDI governance experts to validate the micro-level behaviour of the agents and its interactions (micro-face validation). Thereafter, the outcomes and the emergent macro-level dynamics were shown and individually assessed by these experts (macro-face validation (Rand and Rust 2011)). Empirical validation was not used, as the model should be seen as a generic exploration of SDI governance dynamics instead of a model which resembles any particular reality with an SDI governance case.

Four online expert sessions were organised in 2020 where first the face-validation was done individually and thereafter a panel discussion was held to discuss the model, the outcomes and its usefulness. The consulted experts have different backgrounds, either in practice with experience in at least one SDI role (executive, data provider, platform provider or user) or as an SDI governance researcher. In the first session among Dutch experts, it was argued that the validation would become stronger if also experts from a different cultural and institutional background participated. Therefore, also Dutch speaking experts from Belgium were invited, as they bring a different background while the questions could remain the same, which prevents possible misinterpretation due to translations. In total 18 SDI governance experts, 5 from Belgium and 13 from the Netherlands, were consulted. In the appendix the questions and results are shown.

3.3. Scenarios

As we want to examine the effect of different governance interaction styles on the performance and sustainability of SDI governance, three scenarios were drafted. In each scenario a different message type is dominant:

(1) Hierarchy scenario: A scenario with a relative high chance of hierarchy messages (70%), while setting the network and no message types relatively low (30%).
(2) Network scenario: A scenario with a relative high chance of network messages (70%), while setting the hierarchy and no message types relatively low (30%).
(3) Laissez-faire scenario: A scenario with a relative high chance of no messages (70%), while setting the hierarchy and network message types relatively low (30%).

The reason to choose for a 70/30/30 setting for each scenario, is the fact that we want to compare the performance and sustainability of each scenario. When we use less extreme settings, the results become less distinct. Because of chances and random factors in the model, chances rise that another message types than the message type with the highest setting becomes dominant. However, when we choose a more extreme setting, the scenarios become too much determinant by one message type and therefore less realistic.

From the sensitivity analysis (see paragraph 4.1) it appeared that setting the susceptibility to feedback to 100% gave the best performance, while 0% gave the worst. During simulation of the scenarios we fixed this setting to 75% as 100% did not feel realistic, while a lower setting could influence the dynamics emerging from sending the messages too much.

The governance style scenarios were run with the budget policy set to continuous financing as this policy proved to give the most stability to the simulation. Thereafter, we ran the other two budget policy scenarios (piecemeal and pay-per-use) to analyse if these budget policies affect the interaction and course of the SDI positively or negatively.

Like almost all agent-based models, also this SDI governance model shows stochastic behaviour (Rand and Rust 2011). This manifests itself in the fact that ultimately the SDI governance failed in all simulations, although the duration of the simulation varied heavily. Even in the best performing scenario it could happen that the SDI governance failed quickly. This is not wrong as in reality there does not seem to be a golden recipe for SDI governance and with bad decision making, all SDIs can

fail. Also in practice, it seems natural that SDI governance renews itself after 10–20 years (Sjoukema, Bregt, and Crompvoets 2017, 2020).

To get reliable trends from the scenarios despite the stochastic behaviour, we ran each scenario 1000 times. As the average SDI life span still could be skewed because of the fact that some runs took a very long time, while others failed quickly, we also ran the scenarios with a fixed amount of time steps set to 70. Then we looked at their success/fail ratio: how many runs per scenario hit the fixed time period and how many runs failed earlier? In this way we can determine the chance for a successful run in a certain setting.

4. Results

This section describes and discusses the simulation results. First it discusses the sensitivity of the model to the various inputs. Thereafter, the outputs from the different governance and budget scenarios are described.

4.1. Sensitivity analysis of the SDI governance model

In order to get a feeling of the emergent behaviour of the model, a sensitivity analysis is done. By varying one input setting with incremental steps of 5%, while holding the other inputs stable, the effects of that particular input can be determined in relation to the average number of time steps it took, before the model run failed.

Figure 3 shows the average duration in time steps of the SDI governance model, while increasing the susceptibility to feedback with a 5% step from 0 to 100%. This indicates that with an increase in actor's susceptibility to feedback, SDI governance will last longer. 100 percent, meaning all feedback is always considered, leads to the longest SDI governance life span. In practice, it is not realistic that feedback is always directly given or properly addressed, but the positive effect of feedback loops is a clear outcome of this model.

An incremental increase of 5% of the chance of a certain message type also affects the outcome of the model as is shown in Figures 4–6. Hierarchy messages help the SDI governance model to increase its sustainability. However, only in small amounts as after the 30% the average performance decreases as is shown in Figure 4. Figure 5 shows that the life span increases when the chance of network messages becomes higher. However, this result also shows that governance existing of only network messages would not be preferable, as the life span peaks around the 70% chance. Thereafter, an increase of network messages does not seem to have much effect anymore and the average duration even slightly decreases. An increase of the chance of no messages brings a less clear trend to the SDI governance performance (Figure 6). It is clear that above 35% it brings a positive effect, but the course is more capricious. This is not surprising as the no message indicates an absence of governance instruments and thus the SDI governance is still dependent on how the network and hierarchy messages evolve themselves.
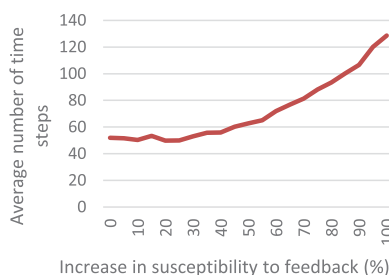

Figure 3. Relation between an increase in the susceptibility to feedback and the average life span of the SDI.
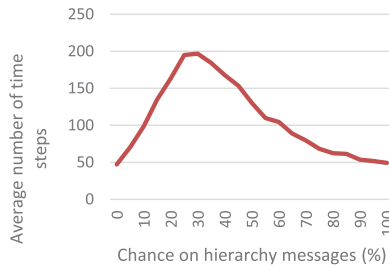
Figure 4. Relation between an increase in the chance of hierarchy messages and the average life span of the SDI.
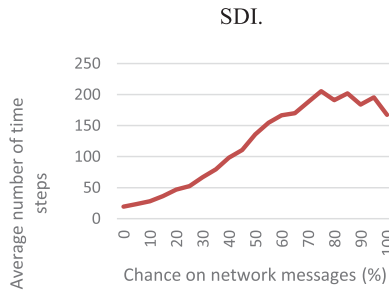
SDI.

Figure 5. Relation between an increase in the chance of network messages and the average life span of the SDI.
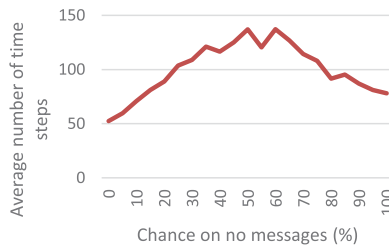
Figure 6. Relation between an increase in the chance of no messages and the average life span of the SDI.

4.2. SDI governance scenarios

The results from running the three predefined governance style scenarios (hierarchy, network and laissez-faire) are presented in Figures 7 and 8. Figure 7 shows that with an average life span of 100, the network scenario performs the best. With an average of 38 time steps, the hierarchy scenario

Figure 7. Average lifespan of SDI per different type of SDI governance scenario.

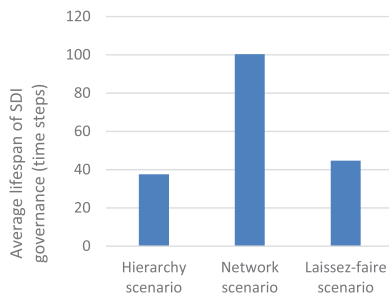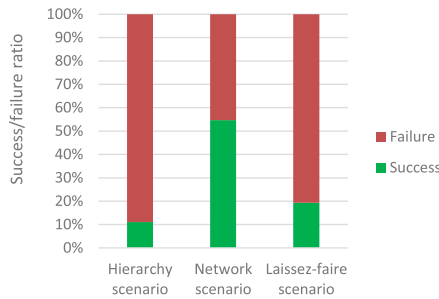**Figure 8.** Success and failure ratio per different type of SDI governance scenario. Success is defined as running for 70 time steps or more.

performs the worst. The laissez-faire scenario performs slightly better and has an average of 45 time steps.

This does not mean that the laissez-faire and hierarchy scenario always result in a failure. Figure 8 shows the percentage of runs per scenario who hit the 70 time steps. It shows that 11% of the hierarchy scenario simulations and 19% of the laissez-faire approach hit this milestone. Also slightly more than half (55%) of all network scenario simulations run longer than 70, indicating that also the network scenario still has a high share of fairly short runs (45%).

4.3. Influence of budget policies

We simulated three types of budget policies: continuous, piecemeal and pay-per-use. Figure 9 shows how the budget policies affect the average life span per SDI governance scenario. The graph shows that both the continuous and pay-per-use financing are quite successful. From Figure 10 it appears that the continuous financing has a slightly higher success rate for the network and laissez-faire scenario. It indicates that the pay-per-use policy can be very sustainable, although the stability of the continuous budget policy generates a more stable success. In all scenarios, the piecemeal budget policy is the worst performing scenario.

In general we can conclude that, in this model, the lifespan of the SDI is more affected by the interaction mix than by the budget policies. This can be explained by the fact that the differences in the budget policies are perhaps less extreme compared to the differences between the three governance style scenarios.
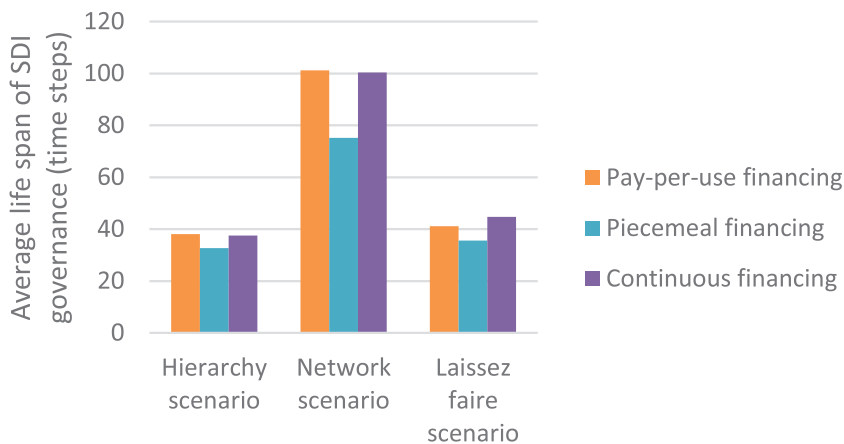

Figure 9. Average life span of SDI governance per budget policy scenario.
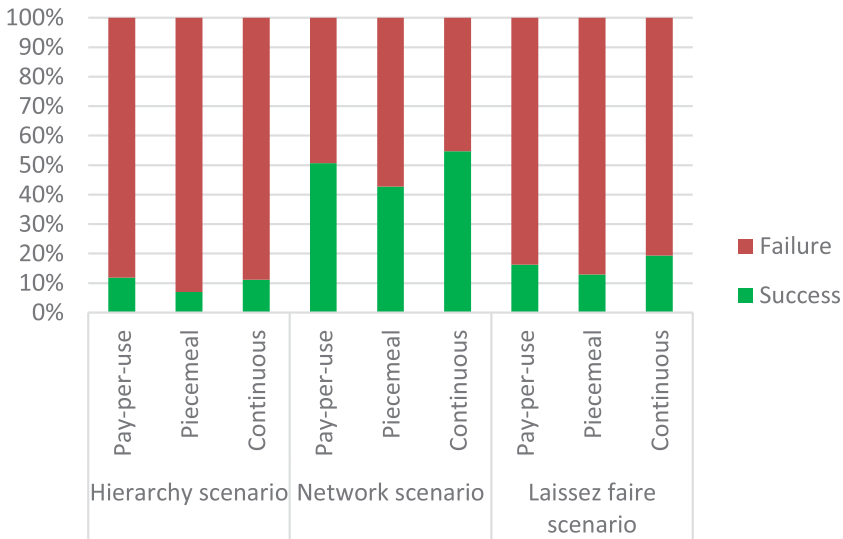
Figure 10. Success and failure ratio in different types of SDI governance per budget.
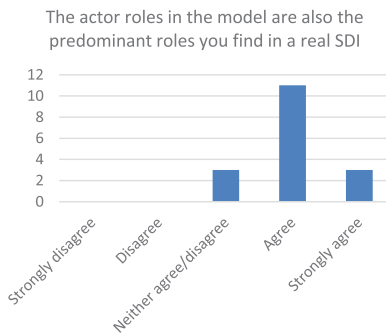

Figure 11. Expert responses (*N* = 17) to statement: 'The actor roles in the model are also the predominant roles you find in a real SDI.'

4.4. Expert judgement

The inputs, interactions, results and also the model were shown to 18 SDI experts for micro and macro-face validation. Figures 11–14 show the outcomes of four main questions. All questions and results are given in the appendix. The experts agreed that the actor roles in the model are also the predominant roles that can be found in a real SDI (Figure 11). Especially the behaviour and interactions of the SDI platform provider was positively reviewed. The behaviour and interactions of the SDI executive gave the most mixed results although 10 experts found it realistic. Experts were the least outspoken on the behaviour of the SDI user as 10 found it not realistic/unrealistic.

From the various types of interactions (interactions between actors, interactions between actors and budget and interactions between actors and the SDI), the interactions between actors and budget were the least positively reviewed. Experts explained that the SDI data provider does in many cases not get directly budget from the SDI executive. In fact, the SDI data provider has to pay the SDI platform provider in many cases the costs for hosting their data. Also experts explained that in reality, several mixes of budget policies exist (e.g. part is covered by the central government, part is covered by pay-per-use policy).
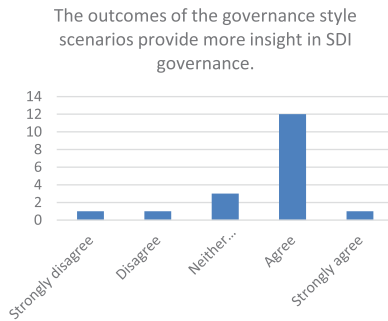
Figure 12. Expert responses (*N* = 18) to statement: 'The outcomes of the governance style scenarios provide more insight in SDI governance.'

When looking at the results from the three governance style scenarios, 13 experts agreed that they were credible and provided more insights in SDI governance (Figure 12). Again, the budget scenarios (Figure 13) scored less compared to the governance style scenarios, although also 10 experts agreed that these outcomes were credible and 12 agreed that they provided more insight in SDI governance. Considering all aspects, 13 of the 18 experts found the model useful for gaining more insights in SDI governance (Figure 14). However, during discussion also some key remarks came from the experts. The next section will discuss these and identify next steps for an agent-based model on SDI governance.

5. Discussion

With the agent-based model, experts found that SDI governance became much more vibrant and visible compared to an average policy document. Multiple SDI experts also stated that it directly makes you think about SDI governance in a different perspective and that it provokes discussion. They saw that potential application areas of the model are in exploring and discussing SDI governance for SDIs on crucial decision moments. When discussions arise about which direction to take, the model can be used to explore possible futures and their dynamics. Therefore, it can be seen as an important 'discussion support tool.'

Many experts found the results on budget policies especially interesting. Currently, both in Belgium and the Netherlands, open data has become successful, but the increased costs also put
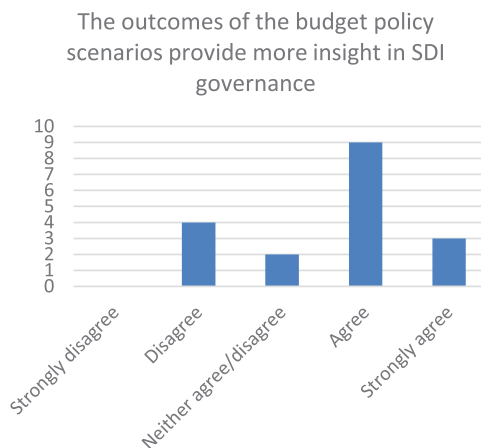

Figure 13. Expert responses (*N* = 18) to statement: 'The outcomes of the budget policy scenarios provide more insight in SDI governance.'
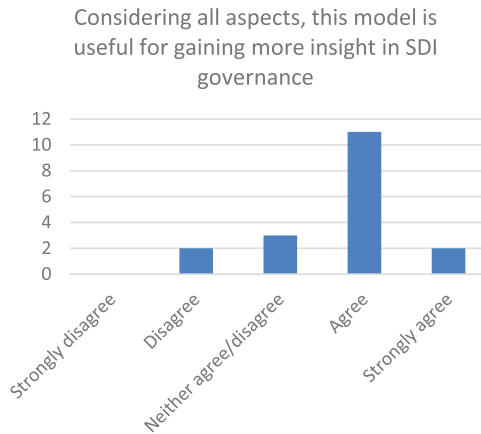
Figure 14. Expert responses (*N* = 18) to statement: 'Considering all aspects, this model is useful for gaining more insight in SDI governance.'

pressure on the way it is financed. The fact that the piecemeal scenario performed the worst did not surprise the experts. However, it was surprising that the pay-per-use budget scenario performed almost equal to the continuous budget scenario, as the pay-per-use scenario depends heavily on a proper data quality. This can be interpreted as an argument against open data, but as the model does not give insights in the outreach and benefits of the data this cannot be concluded. However, it does indicate that a pay-per-use budget policy can generate a sustainable flow of resources, supporting the SDI. Sustainable business models on open data tend to incorporate aspects where a part of the users have to pay (Welle Donker and Van Loenen 2016). By adding more and hybrid business models to the agent-based model, it can become a useful tool for exploring sustainable funding models for SDIs and open data.

From the governance style scenario results, the network scenario with continuous financing performs the best. Experts agreed that network governance is probably the best governance mode, but questioned if this result is culturally biased as the model is developed and validated in a mainly Dutch context, where traditionally a lot of consensus building and network governance is dominant (Meuleman 2010). For this reason, also Belgian experts were included in the analysis who bring a different cultural and contextual perspective. However, their valuation of the model did not differ. In general, there has been a shift noted in governance literature towards the current focus on network governance, which makes this also a more popular style than for example an hierarchical approach (Pollitt and Bouckaert 2011; Rhodes 1996). Of course, the only way to determine the value of the model in other governance contexts, is by evaluating it in a more diverse expert group with different cultural backgrounds.

One of the key remarks on the outcomes of the model is that SDI governance seems not very successful as every run always fails after a while. This is indeed not realistic as in reality actors will adapt to the decreased situation and change the SDI governing strategies and system (Sjoukema, Bregt, and Crompvoets 2017, 2020). This adaptive behaviour is indeed absent in the current model as we chose to focus on the effect of governance interaction styles on the SDI governance. By developing a more adaptive future agent-based model where actors themselves choose the type of message, it should be possible to replicate the complex adaptive dynamics of SDI governance.

Another extension to the model could be the addition of more agents. Agent-based modelling is very suitable for larger number of actors with various behaviours. From SDI stakeholder analyses (Coetzee et al. 2019, 2020) it appears that in many cases the influential power of an actor can vary heavily. Also the influence of a centralised versus a decentralised network can be examined, as findings from Dessers et al. (2015) indicate that unfragmented processes and centralised

coordination lead to a better spatial data performance (Dessers et al. 2015). By incorporating aspects from stakeholder analysis, such as power, proximity and urgency (Coetzee et al. 2019), a more realistic network of SDI actors can be developed. Social network analysis and agent-based models can form a powerful combination (Alam and Geller 2012).

6. Conclusion

This research brings together agent-based modelling and SDI governance interactions for the first time. It is thereby a bold and innovative approach, as the complexity of SDI governance emerges from the countless interactions among SDI stakeholders that are difficult to model. However, by simplifying these interactions and developing a generic model, it seemed to be possible to simulate SDI governance in an agent-based model which is valued by experts.

As the model allows to influence the local interactions, it becomes possible to play with various governance interaction forms and examine the trade-offs between a hierarchical, network or laissez-faire approach to governance. From the model simulations, it appeared that a network approach was the most effective mode of governance compared to the hierarchical and laissez-faire approach. A continuous budget policy was the most sustainable form, although the pay-per-use budget policy was almost equally successful. The piecemeal budget policy had the worst performance.

Expert validation revealed that overall the results of the simulation are credible and insightful. The model and its results helped to offer the experts a different perspective to SDI governance as the agent-based model makes SDI governance more tangible and visible. They expressed the need for models like this when discussing new policies, especially currently on the theme of SDI financing. Agent-based models could therefore become an important tool for SDI governors to experiment, learn and discuss how SDI governance interactions evolve and which strategies are effective.

The model in this paper is not the ultimate SDI governance model, but a first stepping stone to develop more advanced agent-based models. By extending this model and developing others, like Lubida et al. (2020) did, SDI governance dynamics can be further examined. Although challenges lie in the validation of the model as it is difficult to empirically validate a governance model, use of agent-based modelling for studying governance proved to be an promising method and a helpful tool for SDI governors for learning and discussion.

Further experimentation and innovation with agent-based modelling in the field of governance is certainly encouraged. By adding more actors, budget policies and social network concepts such as power, distance and trust, the model could gain more depth. And by making the actors behave more adaptive, the model could truly show the dynamics of SDI governance as a complex adaptive system.

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Data availability statement

The Netlogo model and an overview, design concepts and details (ODD) document are provided as supplemental material. Questions and answers of the expert validation are shown in the appendix.

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Appendix

Results and questions expert validation

Questions 1, 4, 5 and 6 used a Likert scale answers as follow: 1 = Strongly Disagree, 2 = Disagree, 3 = Neither agree/disagree, 4 = Agree, 5 = Strongly agree. Questions 2 and 3 used the following Likert scale answers: 1 = Very unrealistic, 2 = Unrealistic, 3 = Not realistic/unrealistic, 4 = Realistic, 5 = Very realistic. Questions and answers are translated from Dutch.

		1	2	3	4	5	Avg.	N=
1.	The actor roles in the model are also the predominant roles you find in a real SDI	0	0	3	11	3	**4.00**	17
	Do you think the behaviour of the following actor roles corresponds with reality?							
2a.	SDI Executive	2	3	3	8	2	**3.28**	18
2b.	SDI Data Provider	1	0	9	5	3	**3.50**	18
2c.	SDI Platform Provider	1	0	6	9	2	**3.61**	18
2d.	SDI User	1	1	10	3	3	**3.33**	18
	Do you think that interactions in the model correspond with interactions in reality?							
3a.	Interactions between actors in the model (sending messages and feedback)	1	2	7	7	1	**3.28**	18
3b.	Interactions between actors and budget (allocating and spending budget)	1	5	8	4	0	**2.83**	18
3c.	Interactions between actors and the SDI (costs/benefits of SDI)	1	3	8	5	1	**3.11**	18
	Evaluation on results of the governance style scenarios							
4a.	The outcomes of the governance style scenarios are credible	1	1	3	11	2	**3.67**	18
4b.	The outcomes of the governance style scenarios provide more insight in SDI governance.	1	1	3	12	1	**3.61**	18
	Evaluation on the results of the budget policy scenarios							
5a.	The outcomes of the budget policy scenarios are credible	0	5	3	7	3	**3.44**	18
5b.	The outcomes of the budget policy scenarios provide more insight in SDI governance	0	4	2	9	3	**3.61**	18
6.	Considering all aspects, this model is useful for gaining more insight in SDI governance	0	2	3	11	2	**3.72**	18