Organizational Learning in Innovation Networks: Exploring the Role of Cognitive Distance and Absorptive Capacity

An Agent-Based Model

Model Description

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1 An Agent-Based Model of an Innovation Network

1.1 Model Description: The ODD Protocol

This model description is an extract from Schmid (2015). For any citations please refer to Schmid (2015).
The model description follows the so called ODD protocol (Overview, Design concepts, Details), which developed as a standard for describing social simulations, in particular agent-based models (Grimm et al., 2006; Grimm et al., 2010; Railsback and Grimm, 2012). The model is built by means of the open source agent-based modeling software *NetLogo* (version 5.0.3) (Wilensky, 1999).
In the following, a first overview of the model will be given (1.1.1). Subsequently, the design concepts of the model will be elaborated in detail (1.1.2). Then, this model description will be concluded by a presentation of the model's details (1.1.3).

1.1.1 Overview

The overview of the model starts with its purpose (1.1.1.1). After that, the model's entities, state variables, and scales will be presented (1.1.1.2). Finally, the process schedule of the model is explained briefly (1.1.1.3).

1.1.1.1 Purpose

First of all, the purpose of the model will be shown. Only by knowing the objective of the model and which problems it addresses, it can be evaluated if the model has the appropriate focus (Railsback and Grimm, 2012). This agent-based model represents a stylized inter-organizational innovation network where firms collaborate with each other in order to generate novel organizational knowledge. Innovation networks are therefore understood as places where organizational actors come together in order to *access, share, and create new knowledge* (Cowan and Jonard, 2009; Phelps, 2010). The network constitutes the environment within which interactions between

specific actors might take place.

The focus of this agent-based model lies on the firm's partner choice and the consequent inter-organizational collaboration and learning process to access new knowledge for the purpose of organizational knowledge creation. These processes are largely influenced by the cognitive distance between the firms, their relative absorptive capacity as well as their organizational absorptive capacity. The model addresses the following main research question:

> How does absorptive capacity influence a firm's collaboration partner choice, the subsequent inter-organizational learning process, as well as the organizational learning process and which effect has organizational learning in turn on the development of absorptive capacity?

1.1.1.2 Entities, State Variables, & Scales

In order to get an overview of the model, its *entities* and *state variables* will be introduced. An entity can be understood as an object or actor which interacts with other entities in the model (Grimm et al., 2010). Such entities can be agents, but also the environment in which these actors interact should be understood as such an entity (Railsback and Grimm, 2012). This model's entities are firms, the links between firms (referred to as partnerships or dyads), and the innovation network, which represents the environment in which firms interact with each other.

State variables, on the other hand, differentiate an entity from other entities in the model which are of the same type (Grimm et al., 2010). Agents can be described by their attributes or characteristics and also by their behavioral strategy, both of them can be static or dynamic (Railsback and Grimm, 2012). In general, a state variable cannot be derived directly from another variable (Railsback and Grimm, 2012). In the following, the state variables of the model's entities will be presented.

Firm state variables:

1. *State of having a partner:* Firms can be characterized by having a partner or not. Firms can have multiple partners over their lifetime in the network, but only one partner at the same time.

2. *Partner memory:* Moreover, firms memorize their current and former partners in their partner memory.

3. *Maximum absorptive capacity:* This variable describes a firm's level of prior knowledge, more precisely the breadth of its prior knowledge. Each firm is equipped with an individual maximum absorptive capacity which determines the cognitive scope with which the firm can deal at maximum when interacting with another firm. A firm's maximum absorptive capacity is drawn from a normal distribution (cp. section 1.1.3.1 for detailed information). The variable's value might increase during a simulation run due to learning.

4. *Optimal cognitive distance:* Every firm has an individual optimal cognitive distance. It is the point where the cognitive distance of a firm to another firm is optimal and cannot be further improved. At this point, a firm's absorptive capacity is as high as the novelty value of the partnership ($AC = NV$), i. e., the highest cognitive distance which is possible for this firm without losses in understanding. The value of this variable might change due to learning of a firm. Its mathematical description is as follows:[1]

$$opt_{CD} = \frac{MaxAC}{2}. \tag{1.1}$$

5. *Cognitive distance memory:* By building a link to a collaboration partner, firms can access the cognitive distance which is a state variable of the dyad. They memorize current and former cognitive distance values in their respective memory.

6. *Upper and lower bound of cognitive distance:* Each firm follows an individually adapted *selection strategy* in terms of its partner choice ("cognitive distance search scope"). The cognitive distances of the current partner and the former partners serve as parameters for the determination of the upper or lower bounds in terms of the firm's optimal cognitive distance. By iteratively adapting these limits with each new partner, the firm's search space is heuristically narrowed down towards its optimal cognitive distance.

7. *Novelty value memory:* Through a link to a partner, a firm has also access to the dyad's inherent novelty value. This value is saved in the firm's respective novelty value memory.

[1] The variables cognitive distance, absorptive capacity, novelty value, and maximum absorptive capacity are all measured in the same distance units.

8. *Absorptive capacity:* A firm's *relative absorptive capacity* expresses how well it can cope with the cognitive distance to the partner. It is specific to each firm, but as it depends on the cognitive distance it can take different values for each of a firm's collaboration partners. Additionally, it can only be developed when there is a partner. Absorptive capacity decreases with slope $\alpha = -1$ with increasing cognitive distance and cannot be less than 0. It can be formulated as follows:

$$AC = -CD + MaxAC. \tag{1.2}$$

9. *Satisfaction:* The firm variable satisfaction expresses how satisfied a firm is with its collaboration partner in terms of the dyad's cognitive distance and its own corresponding absorptive capacity. This is the mathematical formula:

$$s = AC - NV. \tag{1.3}$$

10. *State of being satisfied:* If the firm's desired satisfaction level (either network variable "acceptable satisfaction" or firm variable "firm acceptable satisfaction") is reached, the firm wants to collaborate with this partner and sets its own state to "satisfied".

11. *Optimal satisfaction:* A firm's satisfaction with a partner is highest, i. e., at its optimal point, when the difference between the firm's absorptive capacity and the dyad's novelty value is 0. At this point, the firm's absorptive capacity is just high enough to deal with the highest cognitive distance without deficits in understanding. The variable is a constant.

12. *Number of satisfying partners:* Each firm counts how many satisfying partners it had during its participation in the network.

13. *Firm acceptable satisfaction:* This variable describes a firm's individual acceptable satisfaction level. It is a constant which is set once during initialization. The satisfaction level is randomly determined from a uniform distribution. The individual acceptable satisfaction threshold becomes active when the network acceptable satisfaction level is disabled.

14. *Search costs:* Firms increase their search costs when they do not find a partner which fits into their selection strategy. This variable describes the number of unsuccessful contacts.

15. *Organizational absorptive capacity:* The level of a firm's *organizational absorptive capacity* describes how well a firm can explore novel knowledge, assimilate and transform it, and exploit it for its own purposes.

Each of these three characteristics - exploratory learning, transformative learning, and exploitative learning - can be developed differently for each firm. High learning rates in one category do not necessarily imply high levels of learning in the other categories.

a. *Exploratory learning:* A firm's level of exploratory learning expresses how able this firm is to recognize novel knowledge. Firms with a low exploratory learning probability will only grasp little of the novelty, whereas others with a high learning rate will be able to absorb almost the entire inherent novelty value of new knowledge from their partner. The variable might change due to learning of a firm.

b. *Transformative learning:* This is the level of the firm's capability to assimilate and transform the absorbed novel knowledge within the organizational boundaries in order to generate knowledge which is valuable to the firm. Once set, the variable is a constant.

c. *Exploitative learning:* A firm's learning rate of exploitative learning shows how well the firm is able to exploit the assimilated and transformed novel knowledge for its own purposes, such as the development of concrete product or business ideas. Initially set, this firm state variable is a constant.

16. *Dyadic learning probability:* Dependent on the cognitive distance of a dyad and a firm's respective relative absorptive capacity, there is a higher or lower probability of learning, i. e., grasping the novel knowledge. Additionally, there is a temporal effect as over time the dyadic learning probability increases.

17. *Minimum / maximum in dyadic learning probability:* Firms memorize their minimum as well as their maximum value of the variable "dyadic learning probability".

18. *Increase in maximum absorptive capacity:* Moreover, firms keep the increase in their prior knowledge ("maximum absorptive capacity"), which results from learning, in mind.

19. *Knowledge created:* By collaborating with a satisfying partner, firms create knowledge. The novelty level of the newly created knowledge is reported. The higher the value, the higher the novelty level of the knowledge. This variable is collected on a monthly basis and as an accumulated value over the duration of the firm's participation in the network.

20. *Number of collaboration rounds:* Each firm memorizes the number of collaboration rounds it has participated in. It is reported as a total over the lifetime of the firm in the network as well as for each satisfying partnership separately.

21. *Below / above mean:* There is a network variable which calculates each month the median of the knowledge created in the network which is novel. Firms receive this information about the median network performance e. g., through a monthly newsletter from the network. They determine on the basis of this network variable whether they perform better or worse than this value. For the duration of a satisfying partnership, firms count how many times they are above or below the mean.

22. *Category of cognitive distance:* Each firm which is in a satisfying partnership evaluates the perceived cognitive distance to its partner. This perceived "subjective" distance might differ from the actual cognitive distance, because each firm perceives it differently according to the value of its absorptive capacity. Then the firm categorizes the cognitive distance of the partnership from its individual point of view into one of the categories low, medium, or high.

23. *Maximum absorptive capacity difference memory:* Satisfied firms memorize the difference between its own maximum absorptive capacity value and that of its partner.

Dyad state variables:

1. *Cognitive distance:* This is the link length between two firms which form a dyad. As space is two-dimensional, this variable is measured by the Euclidean distance. The two dimensions of the cognitive space have no particular meaning, but allow for enough variability in the model. The cognitive distance value expresses how far or close two firms are to each other in the overall cognitive space of the network.

2. *Novelty value:* The novelty value of a partnership depends on its cognitive distance, thus it rises with slope $\beta = 1$ with increasing cognitive distance. Formally, it can be written as

$$NV = CD. \tag{1.4}$$

3. *Maximum absorptive capacity difference:* For each dyad, the difference between the firm's maximum absorptive capacity values is calculated.

This variable indicates how different the cognitive scope of the partners is.

Network state variables:

1. *Number of network members:* This variable determines how many firms are initially in the network. Once set before a simulation run, it is a constant and represents at the same time the upper limit of network size.

2. *Acceptable satisfaction:* This is the level of satisfaction which at least must be fulfilled for both partners in order to stay together in a partnership. After being set during initialization, it is a constant. Positive values induce exploitative behavior of the firms as their absorptive capacity is higher than the novelty value of the dyad, i. e., they could absorb more novelty than the dyad provides. This is due to a small cognitive distance. Negative values, on the other hand, demand firms to act exploratively, because they look for partnerships with a higher novelty value than they can absorb in terms of their absorptive capacity. These are partnerships with a high cognitive distance.

3. *Number of (satisfied) dyads:* There is a variable which counts the number of partnerships which have been closed throughout the lifetime of the network. The same is done for satisfied dyads.

4. *Leaving firms:* The variable "leaving firms" counts the firms which leave the network each time step. Additionally, there is a variable "leaving firms total" which counts the total number of firms which leave the network.

5. *New entrants:* The variables "leaving firms" and "new entrants" are identical in their values. For each firm leaving the network, a new, randomly positioned firm can enter it.

6. *Search costs threshold:* The search costs threshold sets the number of unsuccessful contacts at which a firm leaves the network. Once set during initialization, it is treated as a constant.

7. *Firm satisfaction:* If this variable is active, the network variable "acceptable satisfaction" is disabled and each firm follows its individual satisfaction threshold.

8. *Variability in optimal cognitive distance:* $var_{opt_{CD}}$ is the allowed deviation from the point of optimal cognitive distance. In this area, firms

can still benefit from the time dependent dyadic learning rate of optimal cognitive distance. This variable remains constant, once set during initialization.

9. *Absorptive capacity increase rate:* This variable describes how fast firms can increase their prior knowledge base (i. e., their maximum absorptive capacity) through organizational learning. It is a constant once set before a simulation run starts.

10. *Network's created knowledge:* This variable displays an accumulation of all the firms' created novel knowledge during one time step. It is also reported as a total.

11. *Median of the network's monthly created knowledge:* Starting from the network's created knowledge during one time step, the median over all network participants is calculated.

12. *Evaluation interval:* This state variable determines how often firms evaluate their success in organizational knowledge creation, and are thus able to learn, i. e., increase their prior knowledge stock. It is set once during initialization and remains constant during a simulation run.

13. *Time intervals:* This list contains the corresponding evaluation time steps determined by the network state variable "evaluation interval".

Temporal and spatial scales:

One time step in the model represents one month in reality. During one time step, firms decide with whom they want to partner and actually collaborate with their partner if it is a satisfying one. The simulation ends when there are either no firms left or when 500 time steps are reached.
The model's space is two-dimensional, whereby the two dimensions have no particular meaning. The overall spatial extensions of the model determine the cognitive space of the model, and thus the calculation of variables such as cognitive distance, novelty value, absorptive capacity, maximum absorptive capacity, or satisfaction. The model's cognitive space is represented by a 20 x 20 grid of patches. These dimensions are set arbitrarily.

1.1.1.3 Process Overview & Scheduling

In one simulated, discrete time step of the model, the following processes take place.

1. If firms have a partner, they decide if they are satisfied with the cognitive distance to their partner or not. If both partners are satisfied, they stay together. If at least one partner is not satisfied with the other partner, the link is cut and the firm variables of these two firms are set to their initial state.

2. Dependent on the cognitive distance between two partners and the time spent in the partnership, satisfied firms determine their dyadic learning probability. They can either belong to the group of low cognitive distance, medium / optimal cognitive distance, or high cognitive distance. It is possible that partners of a dyad do not belong to the same learning group.

3. Satisfied firms try then to create novel organizational knowledge, this is knowledge which is new to a specific firm. First, there are two factors at the dyad level which influence this process: The novelty value of the dyad and the firm's ability to grasp the novelty inherent in the dyad (dyadic learning probability). The resulting value represents the potential novel knowledge which is theoretically available to the firm through the collaboration. Then, an organizational knowledge creation process (organizational absorptive capacity) follows. The potentially available novel knowledge is transformed by the firm's explorative, transformative, and exploitative learning behavior. The value after the firm's learning processes determines the novelty value which the firm is able to realize from the dyadic collaboration.

4. Next, the network calculates the median of the created novel knowledge from all its participants in this time step. On the basis of this value, satisfied firms determine for their current partnership if they perform better or worse than the network's median.

5. Only in time steps which are part of the evaluation interval, the individual knowledge creation success in a dyad is assessed by each firm. As each firm's objective is to increase its novel knowledge, partnerships which are not fulfilling this purpose are cut under consideration of a firm's search costs. Firms which perform better than the network's median are able to learn, i. e., increase their prior knowledge (maximum absorptive capacity).

6. Those firms which are partnerless search for a new partner. They can choose from a pool of firms which are also partnerless. From this pool, each partnerless firm picks one random firm. As firms are constrained in

their resources, they can only approach one firm per time step and they have no prior knowledge about other firms. If these two firms have been unsatisfying partners in the past or if the potential partner does not fit into the cognitive distance selection criteria, the partnership is denied. Thus, it is possible that firms stay partnerless.

7. Firms which have a partner but are not yet satisfied update their values. They memorize their current partner, calculate the difference in the maximum absorptive capacity of themselves and the partner, assess the cognitive distance to their partner and keep the distance in mind either as upper limit or as lower limit for improving their future partner search. Moreover, they assess the corresponding novelty value of the partnership. On this basis, each firm can determine its absorptive capacity with respect to the underlying cognitive distance of the relationship and its corresponding satisfaction with the partnership. Firms which were able to learn during this time step also update their values according to a slightly adapted schedule.

8. Firms which have not found a partner increase their search costs. If they reach the search costs threshold, they leave the network.

9. Last, new firms enter the network if old firms have left and if there are still firms which search for a partner and are below the search costs threshold. The number of new firms is restricted to the number of firms which have left the network. New firms entering the network are randomly positioned in the cognitive space and their characteristics are determined in the same way as those of the other firms during initialization.

1.1.2 Design Concepts

In this part of the model description, the model's design concepts will be elaborated in more detail. First, the basic principles will be discussed shortly (1.1.2.1), this will be followed by presenting the emergent properties of the model (1.1.2.2). Subsequently, the underlying concept of adaptation is explained (1.1.2.3). Moreover, the agents' objectives (1.1.2.4), underlying learning mechanisms (1.1.2.5) and prediction principles are discussed (1.1.2.6). After that, agents' ability of sensing (1.1.2.7) and interaction (1.1.2.8) are presented. Stochasticity plays also an important role in the design concepts (1.1.2.9), as well as collectives (1.1.2.10). Finally, this part is concluded by a consideration of the possibilities to observe the model's behavior (1.1.2.11).

1.1.2.1 Basic Principles

The basic principles of the model refer to a presentation of the underlying concepts, theories, and propositions which were used to build the model (Railsback and Grimm, 2012). This model uses two main concepts, *cognitive distance* and *absorptive capacity*, whereas the latter must be subdivided into *organizational absorptive capacity* and *relative absorptive capacity*. These concepts can be subsumed under the overarching theory of *organizational learning* (Levitt and March, 1988; March, 1991; Levinthal and March, 1993; Nonaka, 1994; Lane and Lubatkin, 1998; Sun and Anderson, 2010). A brief overview will be presented here.

Cognitive distance and relative absorptive capacity:

Cognitive distance describes the trade-off between novelty and understandability (Nooteboom, 1999, p. 140; Nooteboom, 2000, pp. 69). If something is too new for a recipient, it cannot be understood, but if the content is not new enough, there is no or not much novelty value in it, and thus it may be useless (Grant, 1996; Cowan and Jonard, 2009; Mowery et al., 1998).

Recent empirical studies (Mowery et al., 1996 and 1998; Wuyts et al., 2005; Nooteboom et al., 2007; Gilsing et al., 2008; Phelps, 2010; Ahuja and Katila, 2001; Schoenmakers and Duysters, 2006) were able to show that cognitive distance is interrelated with learning, knowledge creation, and innovation. More precisely, they could show that cognitive distance has an inverted-U shaped relationship with exploratory knowledge creation and innovation (Nooteboom et al., 2007; Wuyts et al., 2005; Gilsing et al., 2008).

With increasing cognitive distance, there is an increasing novelty value. This novelty value is the potential needed to be lifted within an innovation collaboration. On the other hand, with increasing cognitive distance a firm's *relative absorptive capacity* decreases. This is the firm's capacity to absorb knowledge from this individual partnership (Lane and Lubatkin, 1998). The relative absorptive capacity is different for each partnership as it depends on the cognitive distance and the firm's prior knowledge base (Eisenhardt and Jeffrey, 2000; Zahra and George, 2002). Moreover, with increasing cognitive distance it might become more difficult for partners to interact with each other and benefit from the high novelty value. This is the challenge of cognitive distance which needs to be met.

Organizational absorptive capacity:

Cohen and Levinthal (1989, 1990) first introduced the concept *absorptive capacity* in their research. They defined it as "[...] the ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commercial ends [...]" (Cohen and Levinthal, 1990, p. 128), whereas the underlying ability is largely due to the firm's level of prior knowledge (Cohen and Levinthal, 1990).

After its introduction, the concept has been heavily used by researchers from various fields. This has resulted in an ambiguity of the construct and its meaning (Zahra and George, 2002). Lane et al. (2006) summarize the most influential absorptive capacity definitions on the basis of an extensive literature review into a comprehensive one. According to them,

> "[a]bsorptive capacity is a firm's ability to utilize externally held knowledge through three sequential processes: (1) recognizing and understanding potentially valuable new knowledge outside the firm through *exploratory learning*, (2) assimilating valuable new knowledge through *transformative learning*, and (3) using the assimilated knowledge to create new knowledge and commercial outputs through *exploitative learning*" (p. 856, accentuations through the author).

This definition is used as basis for the construct *organizational absorptive capacity* in this model. In contrast to relative absorptive capacity, it does not refer to inter-organizational processes, but to an organization's individual capability to explore, assimilate and transform, and exploit novel knowledge.

1.1.2.2 Emergence

In general, emergence occurs when the interactions of agents at one level generate a new object which occurs at a different level, and this new object demands a new category to characterize it (Gilbert and Troitzsch, 2005). In an agent-based model, emergence refers to the results or outputs of the model which arise from behaviors of individuals and these behaviors should not be tightly imposed by behavior rules (Grimm et al., 2010). In this model, there are several emergent results which can be observed.

1. By forming dyads which are satisfying for both partners, firms produce two emergent results:

- First, a frequency distribution of partnerships according to their cognitive distance can be observed. This is of interest as Mowery et al. (1998) and Wuyts et al. (2005) (and former studies of Gulati (1995*a*) and (1995*b*)) showed that the likelihood of alliance formation has an inverse U-shaped relationship with cognitive distance. Firms choose partners from which they expect the highest probability of collaborative success.
- Second, when considering the difference between firm's maximum absorptive capacity values, the proportions of homogeneous versus heterogenous partnerships are emergent and can be observed and analyzed.

2. When being part of a satisfying dyad, firms create novel organizational knowledge, i. e., new to this firm. This emergent property can be analyzed for each firm and for the overall network.

1.1.2.3 Adaptation

Adaptation relates to adaptive traits of agents in the model and their possibilities to make decisions and change their behavior (Grimm et al., 2010). Adaptive traits of agents can be modelled explicitly (*direct objective-seeking*) or implicitly (*indirect objective-seeking*): In the first case, agents determine the option that is most likely to bring them closer to achieving their goal, in the latter case, they just replicate behavior patterns observed from the real world (Railsback and Grimm, 2012). Firms in the model have the following adaptive traits:

1. On the basis of their cognitive distance search scope, firms can decide whether a potential partner will be a promising partner in terms of the cognitive fit or not, and thus decide to stay together and collaborate or to cut the link. This is a form of direct objective-seeking.

2. Moreover, a firm's search costs (i. e., number of unsuccessful contacts with other firms) represent rather an indirect objective-seeking mode. If it does not find a satisfying partner within the network, it will not be able to reach its objective of novel knowledge creation, and thus rather leave the network in order to look somewhere else for a promising option to achieve its objective.

3. Additionally, a firm's desire to create novel knowledge can be understood as direct objective-seeking. Firms choose the most promising partner in order to generate organizational knowledge out of this partnership. If

the novelty of the knowledge is below the firm's expectations, then it decides to cut the link and look for a new partner which might be more promising.

4. Last, after a firm learned, i. e., was able to increase its maximum absorptive capacity, it adapts all its corresponding values (optimal cognitive distance, etc.). Due to this adaptation which is rooted in learning, the firm slightly changes its cognitive scope which affects its future actions in the network as well as its knowledge creation success.

1.1.2.4 Objectives

Agents which engage in action are usually driven by an internal goal which they want to accomplish (Gilbert and Troitzsch, 2005). They need to decide which behavior is most likely to support the accomplishment of their objective (direct objective-seeking) (Gilbert and Troitzsch, 2005). But agents can only evaluate different decision alternatives if there is a measure for their goal (Railsback and Grimm, 2012). Thus, it must be made clear what this objective looks like and how it is measured (Grimm et al., 2010). In this model, firms have the overarching objective of generating novel knowledge. For achieving this goal, they have several subordinate targets:

1. As a basis for a successful collaboration, a partner with a high cognitive fit is needed. Thus, partnerless firms follow first the objective to find a promising partner.

2. Satisfied firms can now work on their superior goal of creating novel knowledge for their organization. In case of performing poorly, they fall back to their subordinate goal of finding a promising partner. They do not stay longer than necessary with a partner from whom they cannot benefit enough. Thus, partnerships which are below expectations are cut.

3. Moreover, firms follow, dependent on the value of the satisfaction level, the objective of exploitation or exploration with varying strictness. This goal is either globally determined ("acceptable satisfaction") or for each firm locally defined ("firm acceptable satisfaction"). This objective manifests itself directly in the partner search and indirectly in the knowledge creation.

1.1.2.5 Learning

Learning is a change of adaptive behavior as an implication of experience (Grimm et al., 2010). Learning can take place at the individual level of the agent as well as at the level of the system (Gilbert, 2008). This model implies several learning processes which take place in four steps. Each of them has a different character.

1. First, firms learn through experience which partner fits cognitively best. As a consequence, they adapt iteratively their search scope.

2. In a second step, firms go through an organizational learning process. By means of the three aspects of their organizational absorptive capacity - explorative learning, transformative learning, and exploitative learning - they absorb external knowledge and put it forth as new organizational knowledge (Lane et al., 2006). This form of learning is not a change of adaptive behavior in the model, but a conceptual learning mechanism which is implemented in the model as it is of interest how this learning process changes the emerging results.

3. Third, inter-organizational learning occurs. Over time, collaborating firms get used to each other and are, as a consequence, able to increase their dyadic learning probability, i. e., over time, they develop the capability to grasp more of the potentially available novelty value inherent in the relationship. The learning curves and the content-related differentiation of firms into groups according to the cognitive distance are based on empirically validated results from Schildt et al. (2012). This learning mechanism is also rather not a change of adaptive traits, but a concept which was introduced into the model, because it is a more realistic approach than a simple adaptation process.
   Further, it must be assumed that such an inter-organizational learning process between two firms is not an asymmetric relationship. As inter-organizational collaborations are embedded to a large extent in a social context, *social capital* eases the access to the dyad's novel knowledge (Nahapiet and Ghoshal, 1998; Tsai and Ghoshal, 1998; Phelps, 2003; Cohen and Levinthal, 1990; Nooteboom, 2000). *Trust* and *reciprocity exchanges* build an important basis for the inter-organizational learning process (Granovetter, 1985; Coleman, 1988; Portes and Sensenbrenner, 1993; Portes, 1998).

4. Last, there is another form of (long-term) organizational learning. Firms might be able to increase their breadth of prior knowledge (maximum

absorptive capacity) over time through the accumulation of novel knowledge. In the literature, it is not yet known exactly how this learning mechanism looks like, thus this part of the model is of explorative nature. It is simply hypothesized that ongoing collaboration and knowledge creation should lead to an increase of the firm's absorptive capacity and that this should have an effect on the cognitive distance between the partners (Cowan and Jonard, 2009; Mowery et al., 1998). The resulting change of a firm's maximum absorptive capacity induces a change of adaptive behavior, because the firm's prior knowledge determines its cognitive scope and a change of it might have consequences on future actions of the firm in the network.

1.1.2.6 Prediction

Prediction is the estimation of future consequences of decisions and it is thereby of particular interest how agents predict these future conditions (e. g., through internal models) (Grimm et al., 2010). Prediction can also take place tacitly by being implied in adaptive traits (Railsback and Grimm, 2012). In the model, prediction happens at four points in time.

1. Firms implicitly predict which partner is going to be the most beneficial by assessing the cognitive distance of a dyad and by evaluating their corresponding satisfaction value.

2. Firms which are in a satisfying partnership, but perform poorly in terms of the network's median, do not end the partnership immediately as they expect to increase their dyadic learning probability in the future.

3. Moreover, firms which leave the network because their search costs reached the search costs threshold, expect that they will not be able to find a satisfying partner in this network in the future.

4. If there are in the network no satisfied partnerships after twelve time steps, possible new entrants predict that it is not promising for them to join the network and will not enter. As a consequence, the network ceases gradually due to an absent demand of new firms to enter.

1.1.2.7 Sensing

Moreover, it is relevant to state whether agents in a model are able to sense certain variables which can influence their decisions and their behavior (Grimm

et al., 2010). Sensing can be implicit, i. e., agents simply know certain variables, or explicit, i. e., there are underlying sensing models, and can have varying degrees of accuracy (Railsback and Grimm, 2012). Firms in this model can sense in various ways:

1. Optimal cognitive distance: Firms know their individual optimal cognitive distance. It serves as a basis for the development of their cognitive distance search scope.

2. Network's median of monthly created novel knowledge: Additionally, firms are informed by the network about the monthly median knowledge created. But they are informed rather imperfectly as they can just assess if they perform better or worse than the median. This seems appropriate as in reality it will also be quite difficult to evaluate HOW novel knowledge actually is. Thus, there remains some form of uncertainty for the firms when they base decisions on this information.

3. When firms perform worse than the network's median in organizational knowledge creation, they need to decide whether they cut the partnership or not. They know, that sometimes it might be better to create knowledge at low levels than to not generate knowledge at all. If they cut the partnership, they face the risk of not finding a partner. Thus, firms weigh their underperformance in knowledge creation with their search costs. There is a range of search costs within which they are willing to stay with a partner despite underperformance, as they feel that the investment they have already made in finding a partner is high enough so that they should now reap at least some of the benefits.

1.1.2.8 Interaction

Interactions, when agents encounter and affect each other, can take place directly or indirectly (Grimm et al., 2010). In this model, firms interact directly as well as indirectly with each other:

1. Direct interactions: In all submodels with direct interactions, one firm is able to update the state of the other either by becoming (satisfied) partners or by cutting the link.
    - Firms interact directly with each other when they determine their satisfaction (submodel 1),
    - in their learning process based on the knowledge creation success (submodel 5), and

- during the partner search (submodel 6).

2. Indirect interactions: In submodels with indirect interactions, firms act upon values (cognitive distance, novelty value) which stem from the partner.
   - Indirect interactions happen when firms determine their dyadic learning probability (submodel 2),
   - during knowledge creation (submodel 3), and
   - when they update their values (submodel 7).

1.1.2.9 Stochasticity

Stochasticity refers to the implementation of random elements in the model (Grimm et al., 2010). Stochastic processes can be used to implement some form of randomness where necessary. Moreover, they can be utilized to rebuild a distribution which can be observed in the real world (Railsback and Grimm, 2012). This model contains several random elements.

1. Most of these stochastic components can be found in the firms' setup process which is described in section 1.1.3.1.
   a. Firms are randomly positioned in the cognitive space according to a uniform distribution. Random numbers are most likely to model the variance of firms' cognitive positions in reality.
   b. A firm's first partner match takes place on a random basis (uniform distribution). As firms do not have any knowledge about each other, there is no basis to make another, probably more informed decision.
   c. A firm's maximum absorptive capacity (prior knowledge) is normally distributed over the model's cognitive space (cp. section 1.1.3.1 for detailed information on the distribution). In reality, most firms will exhibit a moderate level of prior knowledge, whereas only few will deviate from the majority with a very high or low level of prior knowledge.
   d. If the firm variable "firm acceptable satisfaction" is enabled, the variable's value is also drawn from a uniform random distribution. Stochasticity is used in this context to reproduce the variability in firms' different strategies.
   e. Firms' transformative and exploitative learning capabilities are randomly drawn from a uniform distribution. Random numbers should reflect the firms' differences in these capabilities.

2. In submodel 6 (Search for partner), partnerless firms approach another partnerless firm on a random basis and ask it if they want to become partners (if they haven't been partners in the past). Before a firm does not actively interact with another firm it does not know the cognitive distance between them. Thus, there is no other way to find this out than by asking the other firm to become partners.

3. In submodel 9 (New firms enter), new firms which join the network are equipped with the same (random) characteristics as described above.

1.1.2.10 Collectives

An agent-based model can contain collectives (aggregations of agents) which can either emerge from interactions of the agents or which can be defined by the modeler (Grimm et al., 2010). This agent-based model comprises the following collectives which might change each time step:

1. All partnerless firms build the pool of potential partners. Firms without partners search for a new partner within this locally defined collective.

2. Satisfied firms form another collective. They are able to pass other submodels than partnerless and not satisfied firms.

3. Dyads build a collective of links. They emerge as a result of firm interactions.

1.1.2.11 Observation

For a full model description, it is also important to make clear what data are collected from the model in order to analyze and understand it (Grimm et al., 2010). This model utilizes various observation forms.

1. Interface output:

   a. Plots: In total, there are seven plots.

      - Frequency distribution of the current dyads according to their cognitive distance.
      - Histogram of the current dyads according to their difference in maximum absorptive capacity.
      - Number of satisfied dyads over the lifetime of the network.
      - Frequency distribution of firms' maximum absorptive capacities.
      - Histogram of monthly created novel knowledge of satisfied firms.

- Development of the network's total created novel knowledge.
- Histogram of firms which were able to learn, i. e., increase their maximum absorptive capacity value.

b. Text output: The percentage of firms with partner and the percentage of satisfied firms is reported to the interface.

2. File output: The model employs file output in order provide the user the opportunity to make fast analyses of the model's variables and results which are not directly observable from the interface output. Moreover, there are several reporting variables which calculate directly interesting numbers, if applied.

   a. Frustrated firms: Each firm which leaves the network enters the values of its variables into a csv-file.

   b. Satisfied firms: Satisfied firms report their variable values into a csv-file before they cut a partnership.

1.1.3 Details

In the following, the model's initialization values and processes are explained (1.1.3.1). After that, input data is very briefly addressed (1.1.3.2). Lastly, the model's underlying submodels are explained in detail (1.1.3.3).

1.1.3.1 Initialization

A brief description of the model's setup is necessary as these initial conditions may largely influence the later processes and results (Railsback and Grimm, 2012). In the following, the initial values of the network, firm, and dyad state variables will be shortly presented. There are some network state variables which can be changed by the user of the model. This is done once before a simulation run is started. During a running simulation, these values are hold fix. For these variables the possible ranges are laid out. Moreover, the firm setup process will be described.

Network state variables:

Table 1.1 provides an overview of the network's state variables with their initial values.

Firm setup process:

The firms' setup process looks as follows:

Table 1.1: Summary of the network's state variables

	Network state variable	Initial value
1	Number of network members	$[10, 11, \ldots, 200]$
2	Acceptable satisfaction	$[-28.0, -27.9, \ldots, 27.9, 28.0]$
3	*Number of (satisfied) dyads*	
	a. Number of dyads	0
	b. Number of satisfied dyads	0
4	*Leaving firms*	
	a. Each time step	0
	b. Total	0
5	New entrants	0
6	Search costs threshold	$[5, 6, \ldots, 50]$
7	Firm satisfaction	False
8	Variability in optimal cognitive distance	$[0.05, 0.1, 0.15]$
9	Absorptive capacity increase rate	$[0.001, 0.01, 0.05, 0.1, 0.15]$
10	*Network's created novel knowledge*	
	a. Monthly	0
	b. Total	0
11	Median of the network's monthly created knowledge	0
12	Evaluation interval	Quarterly, half-year, yearly, two-year
13	Time intervals	Dependent on "evaluation interval"

1. Number of firms is created according to the network state variable "number of network member".

2. They are endowed with the firm state variables as described in section 1.1.1.2.

3. Each firm gets one random partner.

4. Then all firms update their values according to the submodel "update values".

Firm state variables:

Table 1.2 summarizes the firms' state variables with their corresponding initial values.

Table 1.2: Summary of firms' state variables

	Firm state variable	Initial value
1	State of having a partner	True
2	Partner memory	1 entry
3	Maximum absorptive capacity	$N(14, 5)$
4	Optimal cognitive distance	$\frac{MaxAC}{2}$
5	Cognitive distance memory	1 entry
6	*Cognitive distance search scope*	
	a. Upper bound cognitive distance	MaxAC or CD
	b. Lower bound cognitive distance	0 or CD
7	Novelty value memory	1 entry
8	Absorptive capacity	$-CD + MaxAC$
9	Satisfaction	$AC - NV$
10	State of being satisfied	False
11	Optimal satisfaction	0
12	Number of satisfying partners	0
13	Firm acceptable satisfaction	$[-28.0, -27.9, \ldots, 28.0]$
14	Search costs	0
15	*Organizational Absorptive Capacity*	
	a. Exploratory learning	$\frac{1}{\sqrt{20^2+20^2}} \cdot MaxAC$
	b. Transformative learning	$[0.1, 0.2, \ldots, 1]$
	c. Exploitative learning	$[0.1, 0.2, \ldots, 1]$
16	Dyadic learning probability	0
17	*Min. / Max. in dyadic learning probability*	
	a. Minimum in dyadic learning probability	0
	b. Maximum in dyadic learning probability	0
18	Increase in maximum absorptive capacity	0
19	*Novel knowledge created*	
	a. Knowledge created month	0
	b. Knowledge created total	0
20	*Number of collaboration rounds*	
	a. Number of collaboration rounds total	0
	b. Number of collaboration rounds this dyad	0
21	*Below / Above mean*	
	a. Below mean	0
	b. Above mean	0
22	Category of cognitive distance	NA
23	Maximum absorptive capacity difference memory	

Dyad state variables:

Table 1.3 provides an overview of the dyads' state variables with their initial values.

Table 1.3: Summary of dyads' state variables

	Dyad state variable	Initial value
1	Cognitive distance	Euclidean distance
2	Novelty value	$NV = CD$
3	Maximum absorptive capacity difference	$\|MaxAC_a - MaxAC_b\|$

1.1.3.2 Input Data

This model uses no input data.

1.1.3.3 Submodels

The submodels were already briefly presented in section 1.1.1.3. In the following, there will be a detailed description of each submodel.

Submodel 1: Determine satisfaction

All firms which have a partner but are not yet satisfied need to decide whether they are satisfied with their partnership and stay, or leave the partner.

1. Before this, firms which have collaborated with each other for 48 time steps report their variables to an output file and terminate the partnership. On the basis of research on alliances, it is reasonable to assume that an average collaboration partnership does not last longer than four years (i. e., 48 time steps in the model) (Doz, 1996; Schildt et al., 2012).

2. Then, each firm with a not yet satisfying partner has to determine if it is satisfied with the collaboration.

   a. If optimal satisfaction is reached or if satisfaction lies within the range of (firm) acceptable satisfaction, the firm becomes satisfied.

   b. If satisfaction is below (firm) acceptable satisfaction, the firm cuts the link and can now search again for a new partner with a potentially better cognitive fit. Its former partner must now also search again

for a new partner, independently from its individual satisfaction with the dyad.

3. In dyads in which both partners are satisfied with the partnership, both firms turn green.

Submodel 2: Set dyadic learning probability

Satisfied firms determine their dyadic learning probability p_d in their current partnership. Dependent on a firm's individual match of its relative absorptive capacity with the dyad's novelty value, different learning rates are possible. Additionally, the capability to learn from a collaboration partner develops over time. There are three groups of firms which have each different learning probabilities:

1. Low cognitive distance: Firms which fall into this group have a satisfying partner at low cognitive distance, i. e., the cognitive distance is below the threshold of optimal cognitive distance with included "variance in optimal cognitive distance":

$$CD < opt_{CD} - (opt_{CD} \cdot var_{opt_{CD}}). \tag{1.5}$$

2. Medium / optimal cognitive distance: This group contains firms which have a partner at medium respectively optimal cognitive distance, i. e., the cognitive distance deviates not more than the value of "variability in optimal cognitive distance" from their optimal cognitive distance:

$$opt_{CD} - (opt_{CD} \cdot var_{opt_{CD}}) \geq CD \leq opt_{CD} + (opt_{CD} \cdot var_{opt_{CD}}). \tag{1.6}$$

3. High cognitive distance: These are firms with a partner at high cognitive distance, i. e., higher than their optimal cognitive distance (including the "variance in optimal cognitive distance"):

$$CD > opt_{CD} + (opt_{CD} \cdot var_{opt_{CD}}). \tag{1.7}$$

During this evaluation step, each firm categorizes from its individual point of view the cognitive distance to its partner in one of the corresponding cognitive distance categories low, medium, or high. It is important to note that two firms which build a dyad do not necessarily have to pertain to the same group. Due to varying values of maximum absorptive capacity, it is possible that the same cognitive distance is perceived differently.
Schildt et al. (2012) investigated empirical longitudinal data of inter-firm alliances and identified different learning rates of the three groups. The different

learning rates among the different groups of cognitive distance are in line with the research of Nooteboom et al. (2007) and Wuyts et al. (2005) who found an inverted U-shaped effect of cognitive distance on learning. Moreover, the increasing learning rates over time can be ascribed to some extent to the development of knowledge sharing routines and relational structures which make it easier for a firm to access the partner's knowledge (Inkpen and Dinur, 1998; Dyer and Singh, 1998; Lane and Lubatkin, 1998). Social capital eases this process (Nahapiet and Ghoshal, 1998; Phelps, 2003; Tsai and Ghoshal, 1998). Furthermore, by absorbing knowledge from the partner, the firms' knowledge stocks develop over time some commonalities which support each partner in linking new knowledge from the partner faster to existing organizational knowledge (Cohen and Levinthal, 1990; Cowan and Jonard, 2009).
After having determined their current learning rate, firms check if this value represents a maximum or minimum in their "dyadic learning rate" and memorize it accordingly.

Submodel 3: Create knowledge

Satisfied firms create novel knowledge through an organizational learning process.

1. First, the potential novelty value which is theoretically available to the firm through the collaboration has to be determined. This is done by:

$$NV_{firm} = NV \cdot p_d. \tag{1.8}$$

2. The resulting potential novelty value then enters the firm's organizational learning process. The firm's organizational absorptive capacity influences how much the firm can realize of the potential novelty value. It is transformed by its exploratory, transformative, and exploitative learning characteristics.

3. The resulting value represents the firm's realized potential. The firm memorizes its created novel knowledge on a monthly basis and as an accumulated value over its lifetime in the network.

4. The monthly value is reported to the network.

5. Last, the firm keeps record of the number of collaboration rounds with the current partner and with all satisfying partners.

Submodel 4: Calculate median

Each time step, the median of the network's monthly created novel knowledge over all participants is calculated. The median reports the middle observation, and is thus is not sensitive to outliers such as firms with a significantly higher novelty value in their generated knowledge than the rest of the network.
Firms receive this information about the median network performance, e. g., through a monthly newsletter from the network in which some of the latest novel ideas from network participants are presented. Moreover, with this information firms also consider implicitly the number of partnerless or not satisfied firms in the network which are not able to create novel knowledge at all. Firms assess on the basis of the network's median if they perform better or worse than this value during the current time step. During an ongoing collaboration partnership, firms keep record of their performance for the time they collaborate with this partner.

Submodel 5: Determine success and learn

Firms evaluate their organizational knowledge creation success and are able to learn, i. e., increase their amount of prior knowledge, in the given evaluation interval. Firms pursue the goal to increase their novel knowledge. According to their success in creating organizational knowledge, they decide each time step which belongs to the evaluation interval about the success and continuation of the partnership. There are three possibilities:[2]

1. *Underperformance:* Firms cut partnerships which do not contribute enough to achieve their objective. Additionally, firms take their search costs into account for this decision. If their current search costs lie within the lower 20 % in terms of the search costs threshold, they cut the partnership, because they expect that the chance to find a partner with a better fit in the network is still high. On the other hand, if their search costs lie within the upper 20 % in terms of the search costs threshold, they also cut the partnership, because they perceive the partnership and their activity in the network as sunk costs and expect that the probability to find a partner with a better cognitive fit is higher outside the network. If the knowledge creation success from the partnership is below the firm's expectations, but search costs are within the middle 60 %

[2] Firms count for the duration of a satisfying partnership how many times they perform better (*above mean*) or worse (*below mean*) than the network's median value. Underperformance: *below mean* > *above mean*, average performance: *below mean* = *above mean*, above-average performance: *below mean* < *above mean*.

with respect to the search cost threshold, firms stay because they invested already a lot in finding a partner and want now to reap at least some benefits from their engagement in the network. If they hadn't a partner at all, they would also not create novel knowledge at all.

2. *Average performance:* Partnerships which contribute at least partially to the firm's objective of organizational knowledge creation are continued.

3. *Above-average performance:* Firms which perform more often better than the network's median than not, are able to learn. The accumulated novel knowledge increases their prior knowledge base (i. e., their maximum absorptive capacity). A firm's maximum absorptive capacity is increased by the percentage value of the network state variable "absorptive capacity increase rate". This represents an exponential learning rate which is assumed to persist as the wider the knowledge base of a firm is, the better it can link new knowledge to it (Cohen and Levinthal, 1990). This implies higher learning rates for firms with higher levels of prior knowledge. The current and the absolute increase in the "maximum absorptive capacity"-value are memorized.

Submodel 6: Search for partner

Only firms without a partner search for a new partner. All partnerless firms within the network constitute the pool of potential partners. Every partnerless firm can approach one firm from the pool of potential partners. As firms are constrained in their resources, among others time, they can only ask one firm per time step. Moreover, they have no prior knowledge about other firms which whom they have not yet been partners.

1. First, the asking firm needs to check whether this firm has been a partner in the past. It can happen that two firms randomly come together a second time when there was not enough variation in the pool of potential partners. If yes, the firm stops the process here and cannot ask any other firm during this time step. As search is a costly process, firms do not have the capacity to approach more than one firm per month. However, this firm can be asked again by another firm and find a partner this way.

2. If the other firm has not been a partner in the past, it checks whether the cognitive distance of the potential partner lies within its search range of cognitive distance. If yes, and only if the asking firms also lies within the search scope of the potential partner, these two firms become collaboration partners and build a link.

Submodel 7: Update values

All firms which have a partner but are not yet satisfied, update their values.

1. They memorize the current partner in their partner memory.
2. The difference between the maximum absorptive capacity values is calculated.
3. Then, they memorize the cognitive distance of the partnership. If this cognitive distance value is smaller than their optimal cognitive distance, it is used as lower bound in determining the cognitive distance range within which they will accept a potential new partner. If this value is larger than their optimal cognitive distance, it serves as upper bound. If the current cognitive distance meets exactly the firm's optimal cognitive distance, it is set as upper and as lower bound.
4. Afterwards, the novelty value, which is inherent in the relationship, is assessed and memorized.
5. On this basis, every firm calculates its absorptive capacity specific to this partnership. If the novelty value exceeds the firm's cognitive scope (i. e., larger than its maximum absorptive capacity), absorptive capacity is set to 0.
6. Then the firm's satisfaction with the partnership is calculated. If the novelty value is larger than the firm's maximum absorptive capacity (cp. above), satisfaction is directly set to the symbolic value of -100 as the firm will not be able to interact with this partner. The value -100 is used to symbolize that a firm has either no partner or that the current partner is not satisfying.

The same holds true for firms which were able to learn in the current time step. As their value of maximum absorptive capacity changed, they need to update several values. However, they follow a slightly adapted schedule:

1. Maximum absorptive capacity difference is renewed.
2. The upper bound of their cognitive distance search scope is raised to the amount of learning.
3. Absorptive capacity is calculated anew.
4. Satisfaction needs to be updated as well.
5. Firms which learned need also to adapt their optimal cognitive distance.

6. Last, their exploratory learning capability must also be newly evaluated.

It is possible that a firm's satisfaction value exceeds the allowed satisfaction threshold (acceptable satisfaction or firm satisfaction). This irregularity is accepted as the firm is at the moment in a beneficial learning environment which is contributing to achieving its goals. However, in the next partnership, this firm will only accept partners which are within the range of acceptable satisfaction respectively firm satisfaction.

Submodel 8: Be frustrated and exit

Firms which have not found a partner increase their search costs. With each time step in which they have not found a partner, their search costs increase by value 1 (i. e., number of unsuccessful contacts). With $sc = sc_t - 2$, they turn yellow, red at $sc = sc_t - 1$. If the search costs threshold sc_t is reached, they leave the network. The partner search is a costly process and firms are constrained in their time budget as well as in their human resources which are needed to be a part of the network. Due to their experience, they assume that they will not be able to find a satisfying partner in this network in the future and take advantage of outside options. Before they finally leave the network, they report their variable values to an output-file.

Submodel 9: New firms enter

For those firms which have left the network, new firms can enter. New firms can enter only if there is at least one dyad with satisfied partners in the network after twelve time steps, and if there are still firms in the network which search for a new partner and have not so high search costs that they are about to leave the network in the next time step ($sc < sc_t - 1$). New firms are endowed with firm characteristics in the same way as already described. Moreover, they are randomly positioned in the cognitive space.

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