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Adaptive network modeling of the influence of leadership and communication on learning within an organization

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ABSTRACT

This research addresses the influence of leadership and communication on learning within an organisation by direct mutual interactions in dyads. This is done in combination with multilevel organizational learning as an alternative route, which includes feed forward and feedback learning. The results show that effective communication (triggered by the active team leader, and/or by natural, informal communication), leads to a faster learning process within an organization compared to the longer route via feed forward and feedback formal organisational learning. However, this more direct form of bilateral learning in general may take more of the employee's time, as a quadratic number of dyadic interactions in general is less efficient than a linear number of interactions needed for feed forward and feedback organisational learning.

1. Introduction

The concept of multilevel organizational learning (Crossan, Lane, & White, 1999; Wiewiora, Smidt, & Chang, 2019) is not new, however, combining it with artificial intelligence to obtain possibilities for computer simulation has emerged only in recent years, e.g., (Canbaloğlu, Treur, & Roelofsma, 2021; Canbaloğlu, Treur, & Wiewiora, 2023b; Canbaloğlu, Treur, & Wiewiora, 2023a). Organisational learning is a shared knowledge development process involving individuals, groups and the organisation. It occurs through (1) the exchange and formation of shared mental models between team or projects members and (2) institutionalisation of these shared mental models on the organizational level for future use. This process is referred to feed-forward learning. Learning also occurs in the feedback direction when the institutionalised learning and the shared mental models are being transferred and used by teams and individuals. Computer simulations can be used to determine the best possible way to learn, so that an organization can share their knowledge as quick and efficient as possible. This research explores the link between leadership, communication and learning within an organisation. This is done by simulating four scenarios, based on an active or inactive team leader, as well as high or low extent of natural communication.

This paper consists of nine sections. In the second section background information about (shared) mental models, organizational learning and different types of leadership styles are introduced. In the section thereafter, the self-modelling network modelling approach used is briefly introduced. Next, a real-life situation, addressed in this paper will be discussed. In Section 5, the designed model is described in more detail. Example simulation results can be found in Sections 6 and 7. Section 8 is a discussion. Finally, Section 9 is a section that discusses limitations as well as possible further research.

2. Background knowledge

2.1. (Shared) mental models

Kenneth Craik (1943) suggested that the human brain constructs 'small-scale models' of reality; this phenomenon was later referred to as mental models. Mental models can represent events and processes, spatial relations, and the operations of complex systems (Glasgow & Ram, 1994; Hegarty, 1992; Moray & Gopher, 1999; Treur & Van Ments, 2022; Van Ments & Treur, 2021). They are working models of situations or processes from the world, and include information we know, as well as our beliefs (Glasgow & Ram, 1994; Johnson-Laird, 2001; Paoletti, Reyes, & Salas, 2019). Through a person's mental manipulation or internal simulation, mental models are capable of understanding and

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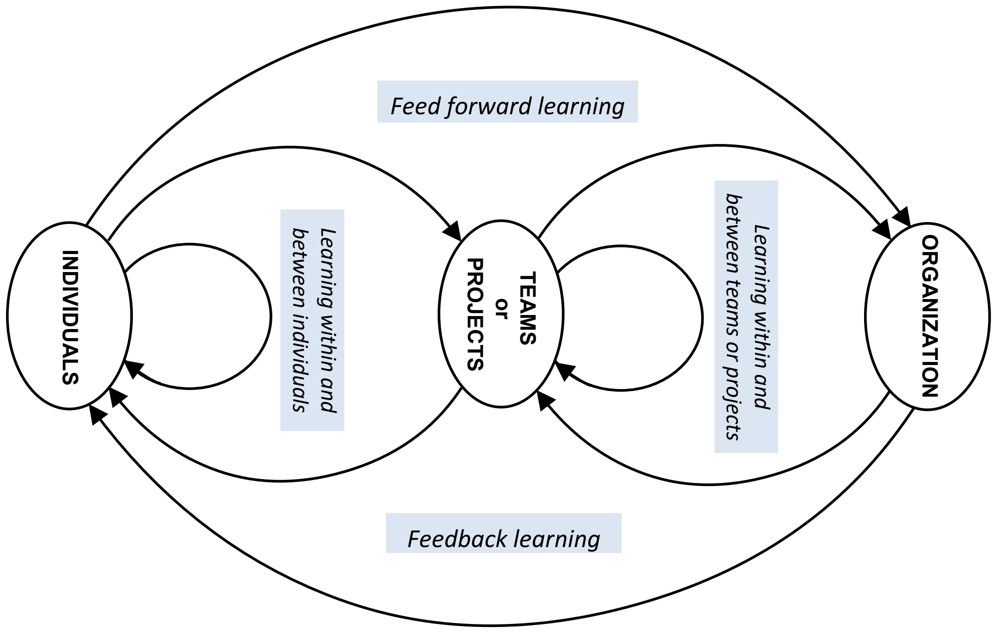

Fig. 1. Multilevel organizational learning (Canbaloğlu et al., 2023a).

explaining phenomena, and thus react appropriately (Greca & Moreira, 2000). Mental models are also termed analogical representations of reality (Greca & Moreira, 2000). The theory of mental models for human reasoning lies on three assumptions: (1) each mental model represents a possibility, (2) the principle of truth: mental models represent what is true according to the premises, but by default not what is false, and (3) deductive reasoning depends on mental models (Johnson-Laird, 2001).

When working in teams, every individual person has their own mental model. Teams learn by sharing individual mental models with each other, and then forming a shared mental model. These shared mental models, in combination with common beliefs that are institutional are very important in organizational learning (Kim, 1993; Canbaloğlu et al., 2021; Canbaloğlu et al, 2023a).

2.2. Organizational learning

Humans have the ability to act in groups and through joint action. In such joint action, the group creates a set of intersubjective meanings that are expressed in their communication, either verbal or nonverbal, or through acts, or even objects. Communication includes metaphors, myths, etc. These are shared within the group. New members will initially have little to no idea of the communication within that group, but with time they learn (Cook & Yanow, 2011). Groups and organizations also can trigger learning to other levels (Crossan et al., 1999). According to Levitt and March (1988), organizational learning looks at how people learn from other people and their experience; in parallel individuals simultaneously adapt their behaviour based on organizational routines and processes (Levitt & March, 1988). According to Levitt and March (1988), there are three observations that form organizational learning, these are (1) organizational behaviour is based on routines, (2) actions made by organizations are often history-dependent, and lastly (3) organizations are oriented to targets. In this scenario routines include “forms, rules, procedures, conventions, strategies, and technologies” (Levitt & March, 1988) constructed in organizations.

Organizational learning is considered a multilevel phenomenon that involves individuals, teams and organizations and the connections between those (Crossan et al., 1999; Fiol & Lyles, 1985). This learning process works in feed forward and feedback directions. Feed forward learning means that organizations can learn from individuals and teams. Feedback learning refers to the utilization of already existing and institutionalized knowledge and sharing this with individuals and teams (Crossan et al., 1999; Wiewiora et al., 2019). Features of individual memories have an influence on the organizational learning. The formation of shared mental models is usually part of (feed forward) organizational learning. Multilevel organizational learning can be depicted as shown in Fig. 1.

2.3. Leadership

There is an established link between leadership and organizational learning (Senge, 1990, 1994; Tushman & Nadler, 1986). In 1939 psychologist Kurt Lewin and his group identified different styles of leadership. They identified three different styles; since then, more styles have been added (Lewin, 1951). In Lewin’s study, children were divided into three groups with a different leadership style: (1) authoritarian, (2) participative, and (3) delegative. Later, transformational and transactional leaderships were added to this list.

For authoritarian leadership, the leader provides clear instructions of what is needed and expected. This leadership style assumes a strong leader and people who (willingly) follow this. In this style, there is a strong distinction between the leader and the rest of the group. The leaders make the decisions with little to no input from the rest. This style of leadership is often negatively presented, because it can be seen as controlling, or close-minded, and in Lewin’s research it was also found as the group where the creativity was the lowest. However, in situations where a lot of decisions need to be made quickly, or where the group needs a lot of direction, it could be beneficial. Another benefit is that this style maintains a sense of order well; see also (What Are Prominent Leadership Styles and Frameworks You Should Know, 2022).

A participative leadership style involves a leader who is very involved with the group and involves other members in the decision making as well as providing guidance when needed. Lewin’s study concluded that this was the most effective leadership. The children in Lewin’s participative study group were not as productive as the children in the authoritarian group, but the inputs provided were of higher quality. While the rest of the group is involved in the decision making in this style, the leader does have the last say.

The third and last style Lewin and his group came up with was the delegative leadership style. According to the scientists, this was the least productive group. There were more demands made on the leader, and

Table 1
The combination functions used in the introduced self-modeling network model.

	Notation	Formula	Parameters
Advanced logistic sum	**alogistic** $_{\sigma,\tau}$ (V_1, …,V_k)	$\left[\frac{1}{1+e^{-\sigma(V_1+\cdots+V_k-\tau)}} - \frac{1}{1+e^{\sigma\tau}}\right](1+e^{-\sigma\tau})$	Steepness $\sigma > 0$ Excitability threshold τ
Steponce	**steponce**$_{\alpha,\beta}$ (..)	1 if time t is between α and β, else 0	Start time α End time β

the children showed little cooperation, while also not being able to work independently. While this style can work with qualified experts, it often leads roles which are not well-defined as well as a lack of motivation. According to Lewin, children in this group often lacked direction, blamed others for mistakes thus not accepting responsibilities, as well as making less progress and producing less work.

A relatively newly distinguished leadership style is transformational leadership; in these groups, leaders inspire their followers. These leaders help both fulfil the goals of the organization, as well as helping members reach their potential. According to research, the transformational leadership style has a positive effect on organizational learning (Noruzy, Dalfard, Azhdari, Nazari-Shirkouhi, & Rezazadeh, 2012; Radzi, Huang, Jenatabadi, Kasim, & Son, 2013).

The last, also relatively newly identified leadership style is the transactional one. This is often seen in work environments with an employer and an employee. The employee has a role of follower, in exchange for a compensation, often money. This type of leadership creates clear roles and provides supervision and direction when needed. This style of leadership can have a negative effect on creativity.

These leadership styles will be addressed and compared in the different scenarios, to analyse how they affect the learning within the organization.

3. Real-world scenario

For a case study used to evaluate the model, the case described by Edmondson (2002) was used. This paper looks at the role of learning within teams. This is done by observing several teams, and the collective learning process is investigated by looking at the team's reflection, and action.

The paper describes an organization with 12 different teams, according to 5 different team types: top management team (TMT), middle management team (MMT), product development team (PDT), internal services team (IS), and production team (PT). These teams were divided into three different groups: (1) reflection and action, (2) reflection without action, and (3) neither action nor reflection.

In Edmondson (2002)'s explanation of group division, different types of leadership can be recognized, and in the current paper it is explored how organizational learning was influenced by this. To make the comparison as fair as possible, the different groups should be of the same team type. The team type of product development was chosen. This team occurs in two different ways (1 and 2) and these team types (PDT) were discussed in-depth in Edmondson's paper. This enabled us to grasp what was going on in the team, and thus model it more realistically.

In this way, the following situation was assumed: There is a team, whose job it is to promote a new product. The relevant team members in this situation are the team leader (TL), the marketing consultant (M), the designer (D), and the financial representative (F). The marketing consultant suggests billboards to advertise a new product, while the designer suggests social media. For both ideas there is money needed from the financial representative. The team leader suggests that both team members talk to the financial representative. In next sections, O represents the organization and how this learns, and is represented to show the connections between the people, and organization.

4. The Self-Modeling network modeling approach used

In this section, the network-oriented modeling approach used is briefly introduced. A (temporal-causal) network model is characterized as follows; here X and Y denote nodes of the network, also called states (Treur, 2020a, 2020b):

- *Connectivity characteristics*
- Connections from a state X to a state Y and their weights $\boldsymbol{\omega}_{X,Y}$
- *Aggregation characteristics*

For any state Y, some combination function $\mathbf{c}_Y(..)$ defines the aggregation that is applied to the impacts $\boldsymbol{\omega}_{X_i,Y}X_i(t)$ on Y from its incoming

Table 2
Base states.

	Nr	State	Explanation
Individual mental model states from the team leader	X_1	a_TL	Starting meeting for the team leader
	X_2	b_TL	Getting more money from the FD for the team leader
	X_3	c_TL	Starting social media strategy for the team leader
	X_4	d_TL	Starting billboard strategy for the team leader
	X_5	e_TL	Having improved marketing strategy for the team leader
Individual states from the designer	X_6	a_D	Starting meeting for the designer
	X_7	b_D	Getting more money from the FD for the designer
	X_8	c_D	Starting social media strategy for the designer
	X_9	d_D	Starting billboard strategy for the designer
	X_{10}	e_D	Having improved marketing strategy for the designer
Individual states from the marketeer	X_{11}	a_M	Starting meeting for the marketeer
	X_{12}	b_M	Getting more money from the financial department for the marketeer
	X_{13}	c_M	Starting social media strategy for the marketeer
	X_{14}	d_M	Starting billboard strategy for the team leader
	X_{15}	e_M	Having improved marketing strategy for the marketeer
Shared states from the organization	X_{16}	a_O	Shared mental model for the start of the meeting
	X_{17}	b_O	Shared mental model for getting more money from the financial department
	X_{18}	c_O	Shared mental model for starting social media strategy
	X_{19}	d_O	Shared mental model for starting billboard strategy
	X_{20}	e_O	Shared mental model for having improved marketing strategy
States from the financial deparment	X_{21}	a_F	Starting meeting for the financial department
	X_{22}	b_F	Giving more money to the other departments from the financial department

connections from states X_i.

- *Timing characteristics*
- Each state Y has a speed factor η_Y defining how fast it changes for given causal impact.

The following canonical difference (or related differential) equations are used for simulation purposes; they incorporate these network characteristics $\omega_{X,Y}$, $c_Y(..)$, η_Y in a standard numerical format:

$$Y(t+\Delta t) = Y(t) + \eta_Y\left[c_Y\left(\omega_{X_1,Y}X_1(t), \cdots, \omega_{X_k,Y}X_k(t)\right) - Y(t)\right]\Delta t \quad (1)$$

for any state Y and where X_1 to X_k are the states from which Y gets its incoming connections. The available dedicated software environment described in (Treur, 2020a, Ch. 9), includes a combination function library with currently around 50 useful basic combination functions. The above concepts enable us to design network models and their dynamics in a declarative manner, based on mathematically defined functions and relations. The examples of combination functions that are applied in the model introduced here can be found in Table 1.

Combination functions as shown in Table 1 and available in the combination function library are called *basic combination functions*. For any network model some number m of them can be selected; they are represented in a standard format as $\text{bcf}_1(..)$, $\text{bcf}_2(..)$, …, $\text{bcf}_m(..)$. In principle, they use parameters $\pi_{1,i,Y}, \pi_{2,i,Y}$ such as the α, β, σ, and τ in Table 1. Including these parameters, the standard format used for basic combination functions is (with V_1, …, V_k the single causal impacts): $\text{bcf}_i(\pi_{1,i,Y}, \pi_{2,i,Y}, V_1, \cdots, V_k)$.

For each state Y just one basic combination function can be selected, but also a number of them can be selected by weights $\gamma_{i,Y}$; this will be interpreted as a weighted average of them. A function $c_Y(..)$ can then be specified by these weight factors $\gamma_{i,Y}$ and the parameters $\pi_{i,j,Y}$.

Realistic network models are usually adaptive: often not only their states but also some of their network characteristics change over time. By using a *self-modeling network* (also called a *reified* network), a similar network-oriented conceptualization can also be applied to *adaptive* networks to obtain a declarative description using mathematically defined functions and relations for them as well; see (Treur, 2020a, 2020b). This works through the addition of new states to the network (called *self-model states*) which represent (adaptive) network characteristics. In the graphical 3D-format as shown in Section 5, such additional states are depicted at a next level (called *self-model level* or *reification level*), where the original network is at the *base level*.

As an example, the weight $\omega_{X,Y}$ of a connection from state X to state Y can be represented (at a next self-model level) by a self-model state named $\mathbf{W}_{X,Y}$. Such first-order $\mathbf{W}$-states will be used in the model introduced here to model learning within an organization. Similarly, all other

Table 3
First-order self-model states.

	Nr	State	Explanation
Self-model states for the team leader's shared mental model	X_{23}	$\mathbf{W}_{a\_TL, b\_TL}$	First-order self-model for the weight of the connection from a to b within the shared mental model of the team leader
	X_{24}	$\mathbf{W}_{b\_TL, c\_TL}$	First-order self-model for the weight of the connection from b to c within the shared mental model of the team leader
	X_{25}	$\mathbf{W}_{b\_TL, d\_TL}$	First-order self-model for the weight of the connection from b to d within the shared mental model of the team leader
	X_{26}	$\mathbf{W}_{c\_TL, e\_TL}$	First-order self-model for the weight of the connection from c to e within the shared mental model of the team leader
	X_{27}	$\mathbf{W}_{d\_TL, e\_TL}$	First-order self-model for the weight of the connection from d to e within the shared mental model of the team leader
Self-model states for the designer's shared mental model	X_{28}	$\mathbf{W}_{a\_D,b\_D}$	First-order self-model for the weight of the connection from a to b within the shared mental model of the designer
	X_{29}	$\mathbf{W}_{b\_D,c\_D}$	First-order self-model for the weight of the connection from b to c within the shared mental model of the designer
	X_{30}	$\mathbf{W}_{b\_D,d\_D}$	First-order self-model for the weight of the connection from b to d within the shared mental model of the designer
	X_{31}	$\mathbf{W}_{c\_D,e\_D}$	First-order self-model for the weight of the connection from c to e within the shared mental model of the designer
	X_{32}	$\mathbf{W}_{d\_D,e\_D}$	First-order self-model for the weight of the connection from d to e within the shared mental model of the designer
Self-model states for the marketeer's shared mental model	X_{33}	$\mathbf{W}_{a\_M,b\_M}$	First-order self-model for the weight of the connection from a to b within the shared mental model of the marketeer
	X_{34}	$\mathbf{W}_{b\_M,c\_M}$	First-order self-model for the weight of the connection from b to c within the shared mental model of the marketeer
	X_{35}	$\mathbf{W}_{b\_M,d\_M}$	First-order self-model for the weight of the connection from b to d within the shared mental model of the marketeer
	X_{36}	$\mathbf{W}_{c\_M,e\_M}$	First-order self-model for the weight of the connection from c to e within the shared mental model of the marketeer
	X_{37}	$\mathbf{W}_{d\_M,e\_M}$	First-order self-model for the weight of the connection from d to e within the shared mental model of the marketeer
Self-model states for organization O's shared mental model	X_{38}	$\mathbf{W}_{a\_O,b\_O}$	First-order self-model for the weight of the connection from a to b within the shared mental model of organisation O
	X_{39}	$\mathbf{W}_{b\_O,c\_O}$	First-order self-model for the weight of the connection from b to c within the shared mental model of organisation O
	X_{40}	$\mathbf{W}_{b\_O,d\_O}$	First-order self-model for the weight of the connection from b to d within the shared mental model of organisation O
	X_{41}	$\mathbf{W}_{c\_O,e\_O}$	First-order self-model for the weight of the connection from c to e within the shared mental model of organisation O
	X_{42}	$\mathbf{W}_{d\_O,e\_O}$	First-order self-model for the weight of the connection from d to e within the shared mental model of organisation O
Self-model states for the FD's shared mental model	X_{43}	$\mathbf{W}_{a\_F,b\_F}$	First-order self-model for the weight of the connection from a to b within the shared mental model of the financial department
	X_{44}	F1	Phase 1: Learning through communication
Phases	X_{45}	F2	Phase 2: Shared mental model is formed
	X_{46}	F3	Phase 3: Feedback
Context states	X_{47}	CS	Context states
	X_{48}	TLS	Team leader states

Table 4
Second-order self-model states.

	Nr	State	Explanation
Second-order self-model states to the organizational model	X_{49}	$\mathbf{W}_{\mathbf{W}_{TL},\mathbf{W}_O}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the team leader to the first-order self-model states of the shared organizational model.
	X_{50}	$\mathbf{W}_{\mathbf{W}_{D},\mathbf{W}_O}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of designer to the first-order self-model states of the shared organizational model.
	X_{51}	$\mathbf{W}_{\mathbf{W}_{M},\mathbf{W}_O}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the marketeer to the first-order self-model states of the shared organizational model.
	X_{52}	$\mathbf{W}_{\mathbf{W}_{F},\mathbf{W}_O}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the financial department to the first-order self-model states of the shared organizational model.
Second-order self-model states from the organization	X_{53}	$\mathbf{W}_{\mathbf{W}_{O},\mathbf{W}_{TL}}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the organization to the first-order self-model states of the team leader.
	X_{54}	$\mathbf{W}_{\mathbf{W}_{O},\mathbf{W}_{D}}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the organization to the first-order self-model states of the designer.
	X_{55}	$\mathbf{W}_{\mathbf{W}_{O},\mathbf{W}_{M}}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the organization to the first-order self-model states of the marketeer.
Second-order self-model states from one person to another	X_{56}	$\mathbf{W}_{\mathbf{W}_{TL},\mathbf{W}_{D}}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the team leader to the first-order self-model states of the designer as well as second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the designer to the first-order self-model states of the team leader.
	X_{57}	$\mathbf{W}_{\mathbf{W}_{TL},\mathbf{W}_{M}}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the team leader to the first-order self-model states of the marketeer as well as second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the team leader to the first-order self-model states of the marketeer.
	X_{58}	$\mathbf{W}_{\mathbf{W}_{TL},\mathbf{W}_{F}}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the team leader to the first-order self-model states of the financial department as well as second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the team leader to the first-order self-model states of the financial department.
Second-order self-model states from one person to another	X_{59}	$\mathbf{W}_{\mathbf{W}_{D},\mathbf{W}_{M}}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the designer to the first-order self-model states of the marketeer as well as second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the designer to the first-order self-model states of the marketeer.
	X_{60}	$\mathbf{W}_{\mathbf{W}_{D},\mathbf{W}_{F}}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the designer to the first-order self-model states of the financial department as well as second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the designer to the first-order self-model states of the financial department.
Second-order self-model states from one person to another	X_{61}	$\mathbf{W}_{\mathbf{W}_{M},\mathbf{W}_{F}}$	Second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the marketeer to the first-order self-model states of the financial department as well as second-order self-model state for the weights of the connections from the first-order self-model states of the shared mental model of the marketeer to the first-order self-model states of the financial department.

network characteristics from $\boldsymbol{\omega}_{X,Y}$, $\mathbf{c}_Y(..)$, $\boldsymbol{\eta}_Y$ could be made adaptive by including self-model states for them. This self-modeling network construction can easily be applied iteratively to obtain multiple orders of self-models at multiple (first-order, second-order, …) self-model levels. For example, a second-order self-model may include a second-order self-model state $\mathbf{W}_{\mathbf{W}_{V,W},\mathbf{W}_{X,Y}}$ representing the weight of the connection from first-order self-model state $\mathbf{W}_{V,W}$ to first-order self-model state $\mathbf{W}_{X,Y}$. Such higher-order $\mathbf{W}_{\mathbf{W}\mathbf{W}}$-states can be used to control the learning processes that are modeled by the **W**-states; they will be used as well in the model introduced here.

5. The second-order adaptive network model

The introduced second-order adaptive network model addresses the effect of communication and leadership on learning within an organisation. Communication can occur by either natural communication or communication organized by the team leader. In this paper, natural communication is described as communication that happens naturally, without extra encouragement from the team leader, within a team. Examples of natural communication are team members who talk with each other within or outside meetings. This includes talking to each other about a project without prompting from their team leader. The team leader can also influence communication, by for example, regulating meetings or encouraging team members to communicate among themselves. In this model, certain assumptions are made:

- Natural communication is a spectrum from completely off (low) to completely on (high), and this natural communication can be adjusted for every dyad.
- The level of encouragement from the team leader to communicate is also a spectrum. Communication within team members (in dyads) as well as the relations between team members can be adjusted by the team leader.
- There is also a spectrum from feedback and feed forward learning.
- If the team leader states that something will happen, it will happen. This means nobody overrules the team leader.
- The simulation by the model follows three phases; these phases do not overlap:

o First, the natural communication and the team leader interaction (time 20–60)

Employees are learning by mutual interaction in dyads.

o Feedforward learning (time 60–120) A shared mental model is formed (O)

o Feedback learning (time 140–180)

So, the model shows three different types of learning processes within an organization. The benefit of this model is that the relationships between members can be adjusted separately. This ensures that the model can be made as realistic as possible and can show many different scenarios. In the scenarios addressed, for the sake of simplicity we assumed that all relationships between people are either completely off or completely on. Four different scenarios will be presented. Details were added to make the model more realistic and fitting for a specific scenario.

- **Scenario 1** is the base scenario. In this scenario we will assume that there is neither an active team leader nor a high extent of natural

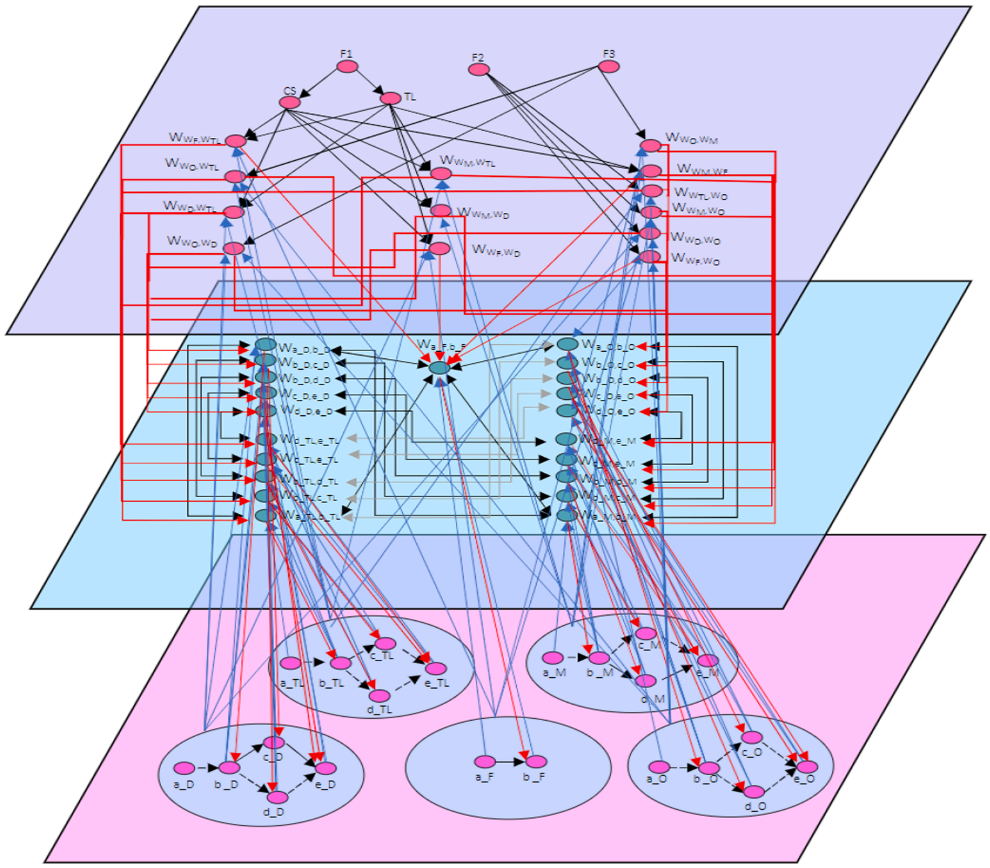

Fig. 2. Connectivity of the second-order adaptive network model.

communication. In this scenario people do not learn from each other in Phase 1, only from feedback learning in Phase 3 (after feed forward learning in Phase 2). An example case in which this happens is when individuals work in a temporary team which has been recently assembled. We assume that they have not worked with each other. This can happen when the team members come from different departments, organisations, or when the team is virtual and thus does not have many opportunities to communicate with each other. The team leader can also influence the team's communication in several ways that have a negative effect. For example, (1) the team leader might not be very comfortable with taking the lead due to having a new position, (2) the team leader might be busy with other responsibilities, or (3) the team leader exercises their position of power by limiting learning opportunities. When the team members have a hard time communicating with each other, and the team leader does not encourage communication, we have this first scenario.

- **Scenario 2** describes that of an inactive team leader, but a high extent of natural communication within the team. This is like a delegative leadership style. This is because the leader only delegates their tasks. It is up to the team members to ensure the quality they deliver. There are several reasons why a team may come to this scenario. It might be that the team leader feels like the team is capable to handle things on their own, and thus not feel the need for regular meetings. They assume that the members will come to them if they have any problems. The team leader might expect this because the team members have worked together in the past and feel comfortable reaching out to each other when they need help from another member. When the team members have worked together in the past, but the team leader is new, they might have a difficult time taking instructions from the leader. However, it is also possible that the team leader has a lot of other responsibilities, and therefore does not take an active role in leading the team.
- In **Scenario 3**, we describe an active team leader and a low natural communication, this type of leadership is consistent with transactional or authoritarian leadership. Here, every team member gets a specific task, reducing the need for team members to talk with each other. Instances where this scenario is realistic, is a new team with an experienced team leader who knows exactly what needs to be done or a team in which the leader purposefully limits communication opportunities because he/she wants to retain position of power and control the extend of the teamwork. The team leader is comfortable taking the lead and organizes regular meetings in which the whole team gets updates, however team members are not encouraged to propose or share new ideas. Because of this, communication mainly goes through the team leader. The team leader could also use this position of power to control team members and tell them what to do, to maintain their powerful position.
- In **Scenario 4**, we assume an active team leader and high natural communication. This scenario fits with a participative or transformational leadership style. In both these leadership styles the team leader plays an active role in the team, both as a worker and as an inspirer. This scenario could happen when the team members, including the team leader, are familiar with each other and the team leader is comfortable with taking the lead. The team leader organizes regular meetings in which they provide updates about the project, initiative and work and motivates the team members to provide input, participate in the discussions and share ideas. The team members feel comfortable reaching out to other members when they need help. This is encouraged by the team leader who supports their team members in sharing knowledge and provides opportunities for exchanging ideas and communication.

For the detailed design of the network model, Tables 2–4 explain every state, and the influence of states on each other can be seen in the graphical connectivity representation in Fig. 2. All states use the combination function **alogistic** from Table 1, except the three states X_{44} to X_{46} for the control of Phase 1 to Phase 3 that use the function **steponce** from Table 1 to control the time intervals for these phases.

In Fig. 2, as well as in Table 2, at the base level (lower plane) it is shown how the internal simulation of a mental model by the different individuals is modelled: the team leader (TL), the marketing consultant (M), the designer (D), and the financial representative (F). Every individual has their own mental model of the same situation. In this model, a_*X*, where *X* can be swapped out for any team member, stands for the mental model state (at the base level: the lower plane in Fig. 2) for starting of the meeting, b_*X* for getting more money from the financial representative; c_*X* and d_*X* stand for, respectively, mental model states for starting a social media strategy and starting a billboard strategy. Finally, e_*X* stands for mental model states for having an improved marketing strategy.

As can be seen in Table 2 and Fig. 2, the financial representative only has mental model states for a and b. This is because they, outside of granting more funds for the marketing strategy, are not directly involved further in the process. The solid arrows represent things that the team member is already sure off; the financial representative is sure that there is money available, making a_F to b_F a solid arrow. The dashed arrows indicate relations that are initially not (completely) known yet; the team leader only knows this after either (1) communication with the financial representative, or (2) feedback learning. In this graphical representation, the O stands for the organization.

The first-order self-model level includes self-model states $\mathbf{W}_{X,Y}$ where *X* and *Y* are two subsequent base level mental model states; for example, $\mathbf{W}_{\text{a\_TL,b\_TL}}$, see Table 3 and the middle plane in Fig. 1. The upward connections are depicted by blue arrows, and the downward arrow shows how the value from $\mathbf{W}_{X,Y}$ is used in the activation of base state *Y*. Changes in values for these **W**-states represent learning. To this end, the $\mathbf{W}_{X,Y}$ states from all dyads of different team members are linked by black or grey arrows, these model their mutual communication; they only differ in colour to keep the graphical representation as clear as possible. This means that they can learn from each other. How much they learn from each other is determined by the second-order self-model level.

The second-order self-model level models the control for how the team members learn from each other; see Table 4 and the upper plane in Fig. 2. This directly relates to how learning is represented in the first-order self-model level. These $\mathbf{W}_{\text{WW}}$-states represent the weights of the (communication) channels between the **W**-states for different mental models. At this level, they are grouped per team member instead of a

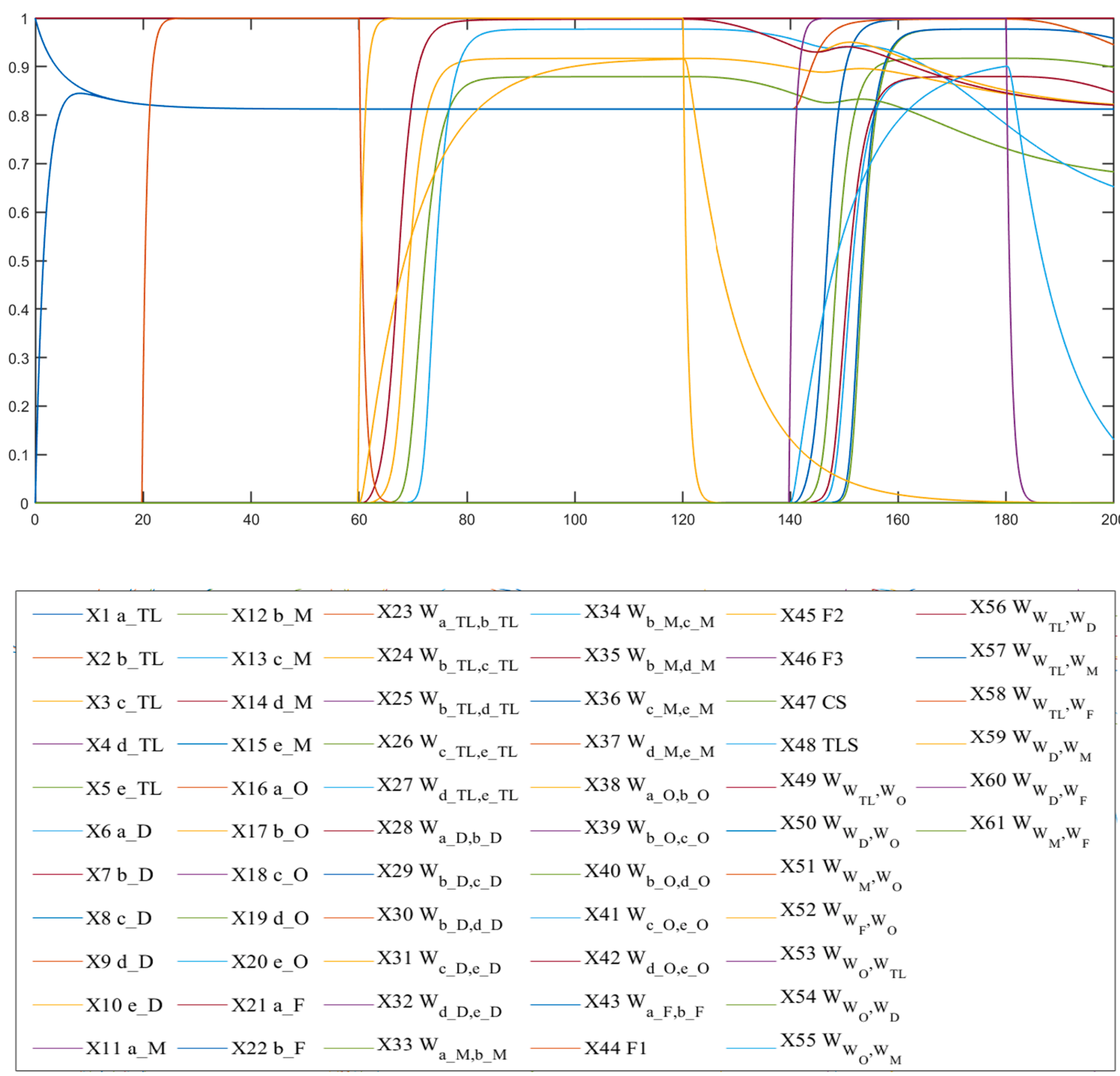

Fig. 3. Simulation results for Scenario 1.

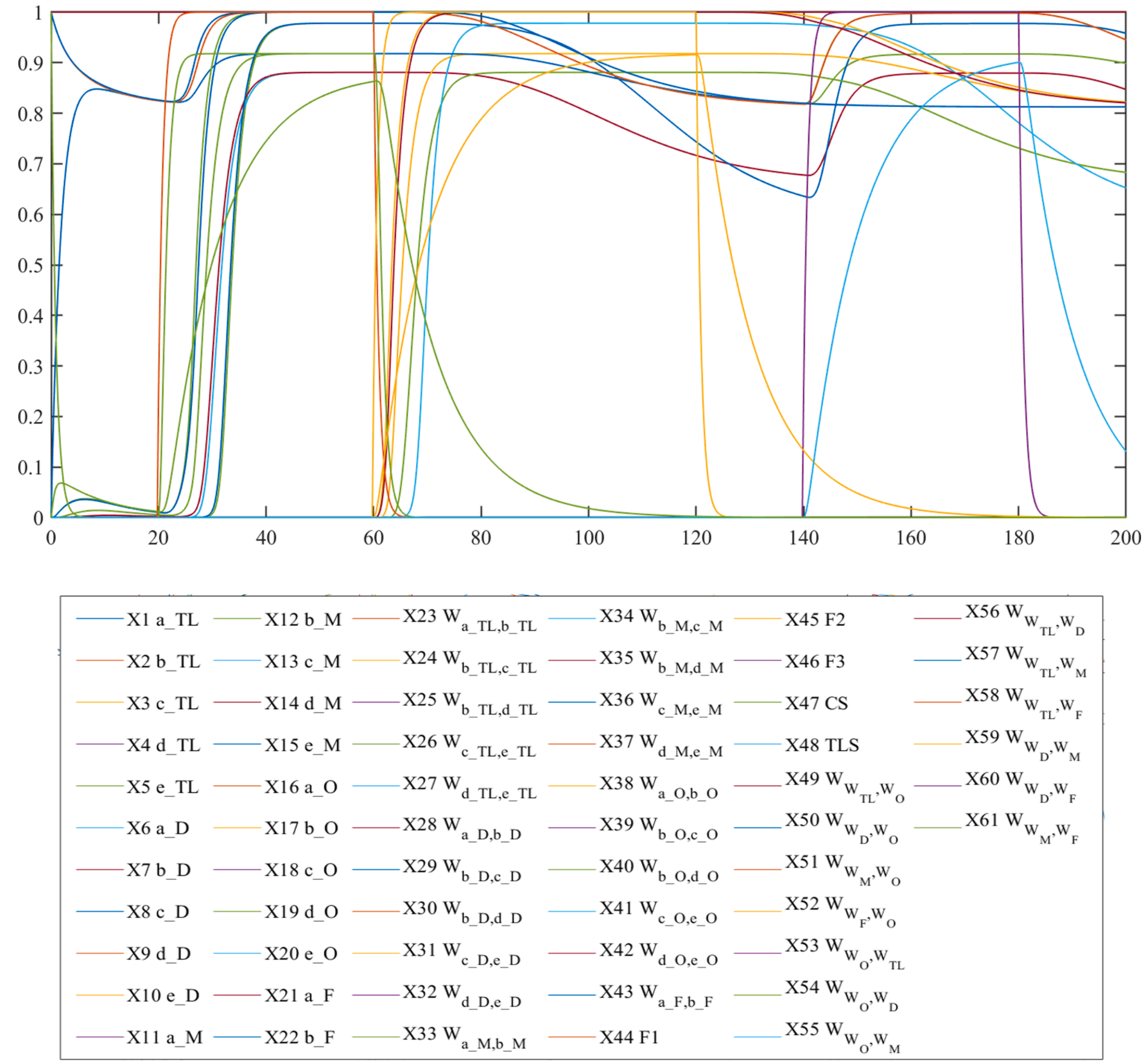

Fig. 4. Simulation results for Scenario 2.

different state for every task. This is done to keep the representation as clear as possible. Every $\mathbf{W}_{WW}$-state has incoming arrows that provide the context information that is relevant for the processes it controls, and a downward (control effectuating) arrow to the first-order self-model level to determine how it influences the processes for the respective **W**.states. These **W**-states have (horizontal) black incoming arrows, these represent the (potential) communication, and the feedback and feed-forward learning channels.

The first phase has influences on the communication state and the team leader state, which in their turn influence all team member states from the first-order level, thus excluding O. Phase 2 models the feed forward learning, so from team members to O. Lastly, Phase 3 models the feedback learning, from O to the team members. The fact that all these states, and their effect on other states can be adapted individually, ensures that this network model is highly adaptive.

In the Appendix section the full specification of the model by role matrices is shown.

6. Simulation results

The available dedicated software environment in MATLAB was used to run a few simulations, in particular for Scenario 1 to 4 as described in Section 5; see Figs. 3–6.

Because communication is influenced by both the team leader states TLS and the context states CS (for natural communication), and by both feedback and feedforward learning, we decided to focus on these states. Both feedforward and feedback learning have an influence on the knowledge of each person. When the feedforward is (partially) missing, the individual may learn this process through feedback learning (from the organization).

In the base Scenario 1, there is no natural communication for dyads, nor dyad communication initiated by the team leader; therefore, the individuals only learn after the feedback learning, which takes longer.

In all other scenarios, there is at least one state which leads to dyad learning. This leads to (partial or complete) dyad learning and completing this with feed forward and feedback organizational learning. For an overview, see Table 5.

6.1. Scenario 1: Inactive team leader and low natural communication

As mentioned before, this scenario has no communication during Phase 1 (time 20–60). Neither through natural communication nor through an active team leader. It can indeed be seen that there is no learning during Phase 1, the learning only starts in Phase 2 (time 60–120). This learning is only feed forward organizational learning. Thus, the organization is learning, but team members are not yet. The team members only start learning in the feedback learning phase, Phase 3 (time 140–180).

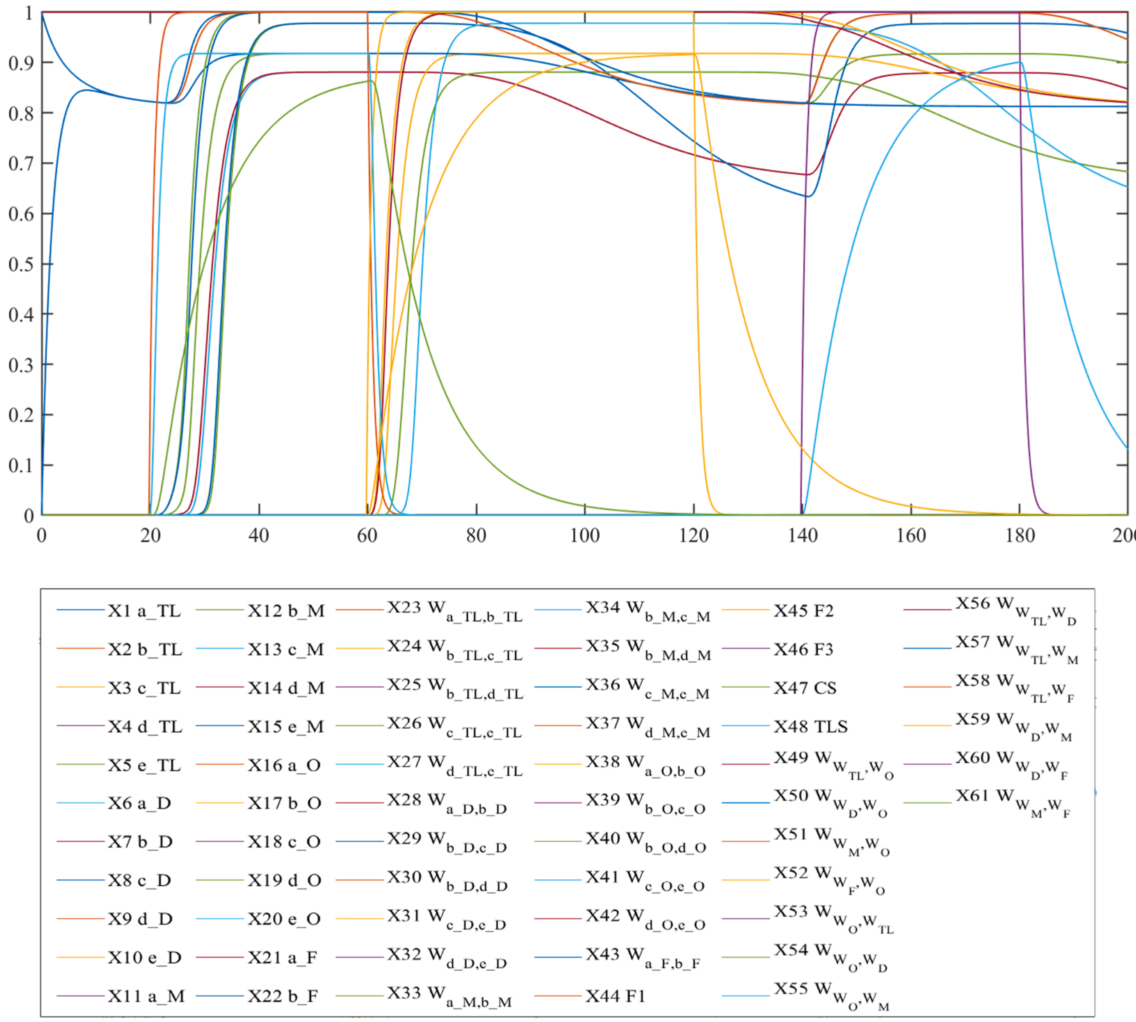

Fig. 5. Simulation results for Scenario 3.

6.2. *Scenario 2: Inactive team leader and high natural communication*

This Scenario 2 has an inactive team leader, but a high natural communication. Because of this, the team members are already learning during Phase 1. In addition, organizational learning happens in Phase 2, like in Scenario 1. However, since the team members have a good communication, the knowledge is already shared.

6.3. *Scenario 3: An active team leader and a low natural communication*

Like in Scenario 2, the team members are already learning in the first phase. This is because the team leader makes sure there is communication within the team. Because of this, the team members are already learning in Phase 1, and in addition the information is learned by the organization through feed forward learning in Phase 2.

6.4. *Scenario 4: An active team leader and a high natural communication*

Comparable to the previous two scenarios, in this scenario the learning is too happening in Phase 1. In this case the communication can happen naturally, or through the team leader. This ensures that there is enough communication between the team members to establish a shared learning process in Phase 1. In Phase 2 this knowledge is shared with the organization, during the feed forward learning. Finally in Phase 3, the feedback learning is updating the individual mental models, as far as needed.

7. Addressing variations in imperfect communication

In this section it is discussed and illustrated how the proposed computational model can also address imperfect communication and variations in the strength of communication between individuals. Two new scenarios are illustrating this: Scenario 5 and Scenario 6.

7.1. *Scenarios 5 and 6*

- Scenario 5 describes a scenario in which some colleagues know each other better than other colleagues. In this scenario, the financial representative has a higher natural communication with the designer than with marketing director. Apart from this, the team leader is inactive. This could happen, for example, when the financial representative and the designer have been colleagues before. It has some similarity to Scenario 2, where there is a delegative team leader style, however with the marketing director being a new addition, the natural communication might be weaker than with the financials' representative other colleagues.
- In Scenario 6, we, again, describe a situation where some colleagues have stronger natural communication than other colleagues. In this scenario, there is also an active team leader. This could happen in a participative, or transformational leadership, where two colleagues in the team get along less than the other colleagues. This may happen for all sorts of reasons; it is natural to have different friendliness levels with different colleagues.

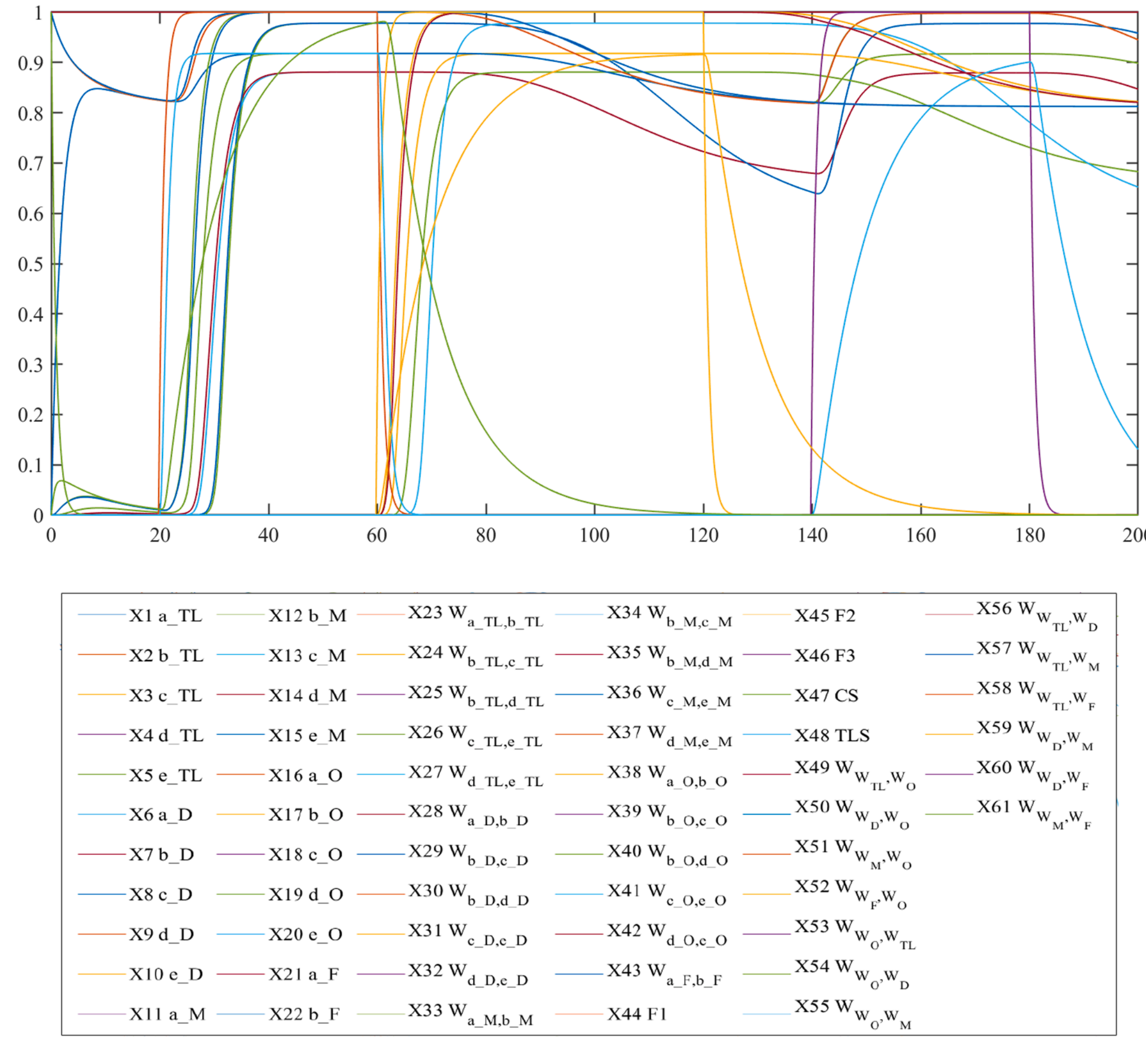

Fig. 6. Simulation results for Scenario 4.

7.2. Simulation results for scenarios 5 and 6

In Fig. 7 the outcomes for Scenario 5 are shown: there are certain colleagues who know each other better than other colleagues, due to an inactive team leader, there is quite some difference in the different phases. Because there is natural communication between some colleagues, and not between others, there are some lines which start earlier than others, or do not rise all the way to one, meaning they do not learn everything in Phase 1, but still completed their knowledge in Phase 3 with feedback learning.

In Fig. 8 the results for Scenario 6 are shown. In this case there are also colleagues who have different levels of knowledge from each other, but in this scenario, there is a more active team leader. You can see that the outcomes of this scenario are like those of Scenario 2, 3, and 4. However, there are some small differences. There are some lines that do not reach quite as high, this is due to the lower communication between colleagues. Because the team leader is active, the colleagues who are lesser known still get to share almost all of the knowledge, and this will be completed in Phase 3.

8. Discussion

This research addressed the influence of leadership and communication on learning within an organisation by direct mutual dyadic interactions. This is done in combination with multilevel organizational learning as an alternative route, including feed forward and feedback learning. The results show that when good communication is present (either due to the team leader, or due to the natural communication, or both), this can lead to a faster learning process within an organization than the longer route via feed forward and feedback learning. However, this more direct form of learning in general may take more of the employee's time, as a quadratic number of dyadic interactions in general requires more invested time than a linear number of interactions needed for feed forward and feedback learning.

Table 5
Overview of scenarios 1 to 4.

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Natural communication		–	+	–	+
Team-leader-initiated communication		–	–	+	+
CS	Context states	0	1	0	1
TLS	Team leader states	0	0	1	1

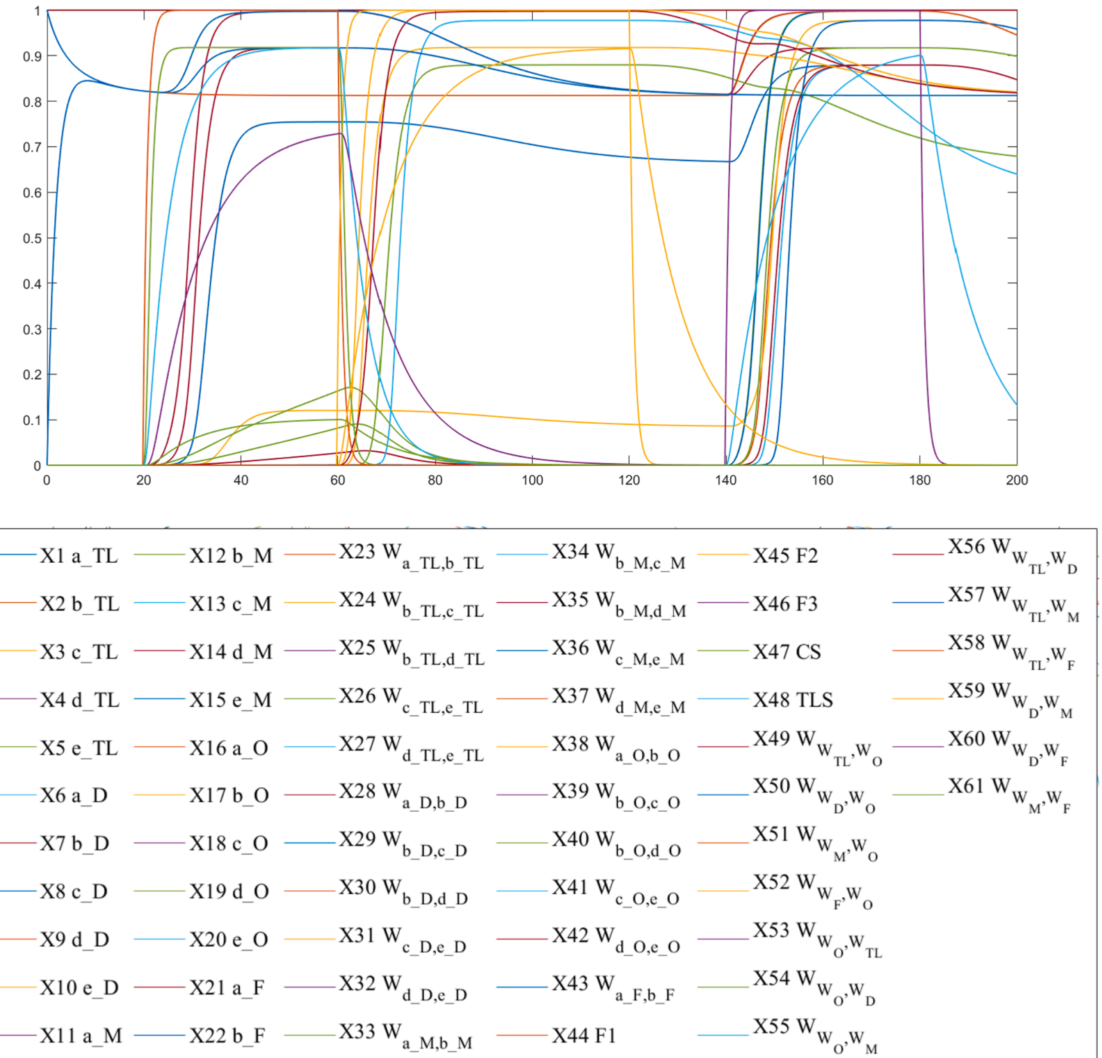

Fig. 7. Simulation results for Scenario 5.

As can be seen in the graphs in Sections 6 and 7, learning between team members takes place when there is at least one basis for communication. In this case, Scenario 1 lacks such a basis but for Scenario 2 to 4 this basis was there: either an active team leader, a high level of natural communication, or both. Therefore, the outcomes for latter three scenarios are quite similar. More differences were shown in Scenario 5 and 6 where variations in strengths of communications were addressed. Due to this, different levels of imperfectness of knowledge occurred which only were resolved after feedforward and feedback (organisational) learning.

When there is only an active team leader, this person is often seen as the boss, and treated as such. This team leader is very important, because they make sure that everything that needs to get done, will be done. However, this can lead to the 'hierarchical mum effect', which is defined as "individuals' reluctance to provide negative feedback to another for fear of being associated with the message, …". This means that people are less likely to say something to their superior, even if this is at the expense of task accomplishments, because they want to maintain a positive relationship. This can be seen specifically in work relationships. Another factor is that team members are more likely to expect negative feedback from their team leader than the team leader expects negative feedback from them. This may negatively influence team members to expressing their feedback (Bisel, Messersmith, & Kelley, 2012).

Other research has shown that when there is a two-way symmetrical communication system, which also includes internal team peer communication, the likelihood of employees' job satisfaction increases as well as their participation and commitment. Internal communication helps team leaders connect with their members, and so help the organization with bettering its' environment (García-Morales, Matías-Reche, & Verdú-Jover, 2011). So, the presence of an active team leader as well as natural communication leads to a more satisfactory work experience.

When there is only a high level of natural communication, team members may learn a lot from each other, but things could still be missing. Like mentioned before, a team leader is important because they ensure that everything that needs to be done, will be done (Bisel et al., 2012). When this responsible person is missing, it could be that some things are missed or stay undecided.

Thus, even though three scenarios had, to an extent, the same outcome, there could be differences that are not shown in the graphs.

In summary, it has been explored how learning within an organisation can make use of different mechanisms: natural interactions between individuals, leader-initiated interactions between individuals, feed forward organisational learning, and feedback organisational learning. It is shown how learning flows within an organisation may differ depending on which of these mechanisms are actually functional within the organisation.

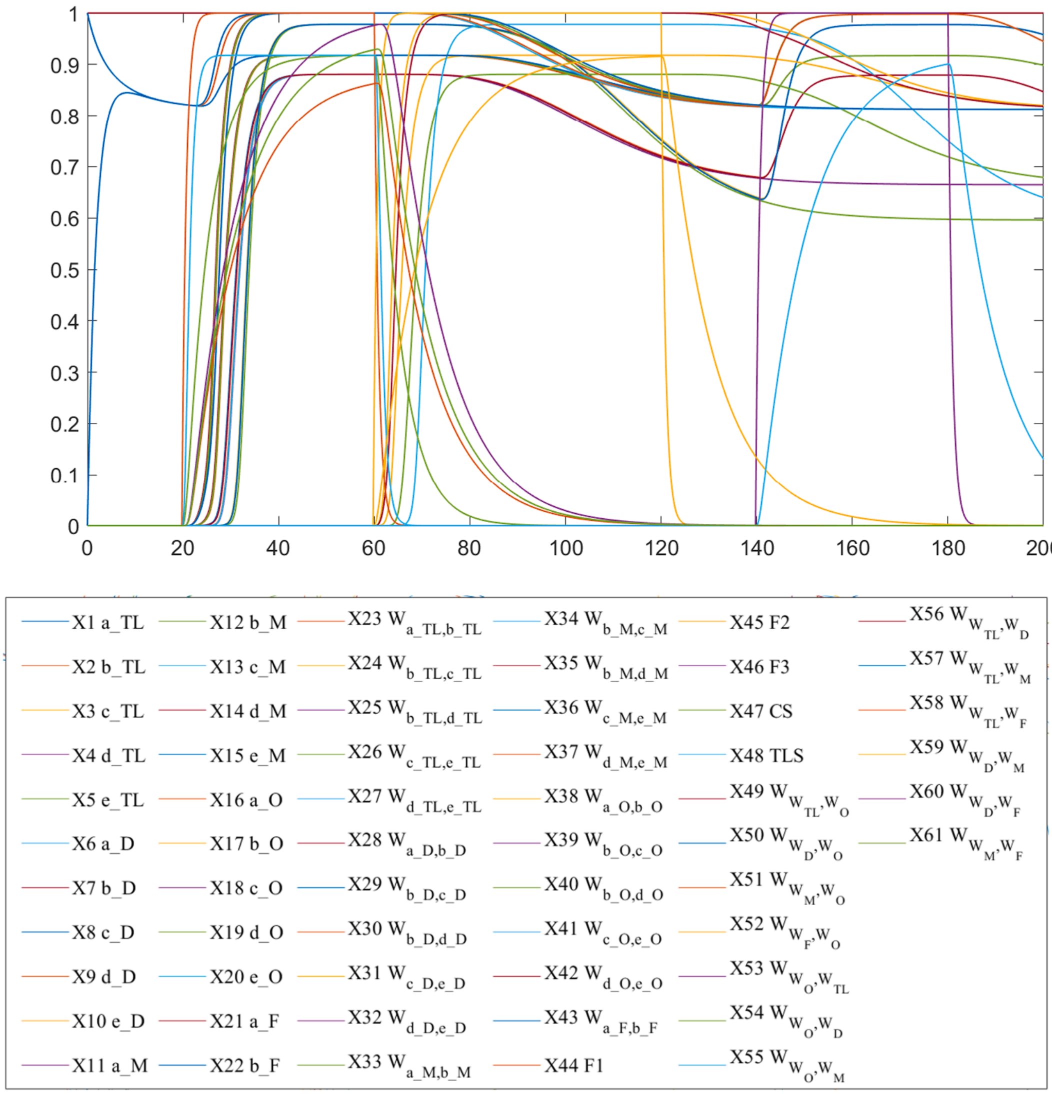

Fig. 8. Simulation results for Scenario 6.

9. Limitations and further research

A few factors that influence an organization and the learning processes have been left out of consideration, such as the amount of people in an organization, the relationship for each individual dyad, type of project they are working on, or individual personality traits. Although a model is not representative fully and may not be generalizable to all types of organisations, it provides a useful and relatively simple way to predict general learning pattens. Real life experiments are not suitable for the type of research addressed here, because analysing the differences between different leadership styles in the same situation cannot be done easily by such experiments in reality. Since scenarios, for example, without an active team leader and high level of natural communication could lead to a hostile work environment, real life experiments certainly would not be suited for such research.

For further research, differentiations within a scenario could be made. For example, two co-workers have a high level of natural communication between them, but not with another co-worker; for the sake of simplicity, this was not addressed yet. Further research could also look at larger teams, or more layers within a team. Except the research reported here, there is little research linking a leadership style and learning within an organisation. That is something that could be improved upon by further research. Furthermore, further work is planned on mathematical analysis of the model concerning stationary points and equilibria, according to the approach described in (Canbaloğlu & Treur, 2022).

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgement

None.

Appendix A. Role matrices

In Figs. 9–13, the different role matrices are shown that provide a full specification of the network characteristics defining the adaptive network model in a standardized table format. Here in each role matrix, each state has its row where it is listed which are the impacts on it from that role.

mb		1	2	3	4	5
X_{1}	a_TL	X_{1}				
X_{2}	b_TL	X_{1}				
X_{3}	c_TL	X_{2}				
X_{4}	d_TL	X_{2}				
X_{5}	e_TL	X_{3}	X_{4}			
X_{6}	a_D	X_{6}				
X_{7}	b_D	X_{6}				
X_{8}	c_D	X_{7}				
X_{9}	d_D	X_{7}				
X_{10}	e_D	X_{8}	X_{9}			
X_{11}	a_M	X_{11}				
X_{12}	b_M	X_{11}				
X_{13}	c_M	X_{12}				
X_{14}	d_M	X_{12}				
X_{15}	e_M	X_{13}	X_{14}			
X_{16}	a_O	X_{16}				
X_{17}	b_O	X_{16}				
X_{18}	c_O	X_{17}				
X_{19}	d_O	X_{17}				
X_{20}	e_O	X_{18}	X_{19}			
X_{21}	a_F	X_{21}				
X_{22}	b_F	X_{21}				
X_{23}	$\mathbf{W}_{a\_TL,b\_TL}$	X_{23}	X_{28}	X_{33}	X_{38}	X_{43}
X_{24}	$\mathbf{W}_{b\_TL,c\_TL}$	X_{24}	X_{29}	X_{34}	X_{39}	
X_{25}	$\mathbf{W}_{b\_TL,d\_TL}$	X_{25}	X_{30}	X_{35}	X_{40}	
X_{26}	$\mathbf{W}_{c\_TL,e\_TL}$	X_{26}	X_{31}	X_{36}	X_{41}	
X_{27}	$\mathbf{W}_{d\_TL,e\_TL}$	X_{27}	X_{32}	X_{37}	X_{42}	
X_{28}	$\mathbf{W}_{a\_D,b\_D}$	X_{23}	X_{28}	X_{33}	X_{38}	X_{43}
X_{29}	$\mathbf{W}_{b\_D,c\_D}$	X_{24}	X_{29}	X_{34}	X_{39}	
X_{30}	$\mathbf{W}_{b\_D,d\_D}$	X_{25}	X_{30}	X_{35}	X_{40}	
X_{31}	$\mathbf{W}_{c\_D,e\_D}$	X_{26}	X_{31}	X_{36}	X_{41}	
X_{32}	$\mathbf{W}_{d\_D,e\_D}$	X_{27}	X_{32}	X_{37}	X_{42}	
X_{33}	$\mathbf{W}_{a\_M,b\_M}$	X_{23}	X_{28}	X_{33}	X_{38}	X_{43}
X_{34}	$\mathbf{W}_{b\_M,c\_M}$	X_{24}	X_{29}	X_{34}	X_{39}	
X_{35}	$\mathbf{W}_{b\_M,d\_M}$	X_{25}	X_{30}	X_{35}	X_{40}	
X_{36}	$\mathbf{W}_{c\_M,e\_M}$	X_{26}	X_{31}	X_{36}	X_{41}	
X_{37}	$\mathbf{W}_{d\_M,e\_M}$	X_{27}	X_{32}	X_{37}	X_{42}	
X_{38}	$\mathbf{W}_{a\_O,b\_O}$	X_{23}	X_{28}	X_{33}	X_{38}	
X_{39}	$\mathbf{W}_{b\_O,c\_O}$	X_{24}	X_{29}	X_{34}	X_{39}	
X_{40}	$\mathbf{W}_{b\_O,d\_O}$	X_{25}	X_{30}	X_{35}	X_{40}	
X_{41}	$\mathbf{W}_{c\_O,e\_O}$	X_{26}	X_{31}	X_{36}	X_{41}	
X_{42}	$\mathbf{W}_{d\_O,e\_O}$	X_{27}	X_{32}	X_{37}	X_{42}	
X_{43}	$\mathbf{W}_{a\_F,b\_F}$	X_{23}	X_{28}	X_{33}	X_{38}	X_{43}
X_{44}	F1	X_{44}				
X_{45}	F2	X_{45}				
X_{46}	F3	X_{46}				
X_{47}	CS	X_{47}	X_{44}			
X_{48}	TLS	X_{48}	X_{44}			
X_{49}	$\mathbf{W}_{W_{TL},W_{O}}$	X_{49}	X_{45}			
X_{50}	$\mathbf{W}_{W_{D},W_{O}}$	X_{50}	X_{45}			
X_{51}	$\mathbf{W}_{W_{M},W_{O}}$	X_{51}	X_{45}			
X_{52}	$\mathbf{W}_{W_{F},W_{O}}$	X_{52}	X_{45}			
X_{53}	$\mathbf{W}_{W_{O},W_{TL}}$	X_{53}	X_{46}			
X_{54}	$\mathbf{W}_{W_{O},W_{D}}$	X_{54}	X_{46}			
X_{55}	$\mathbf{W}_{W_{O},W_{M}}$	X_{55}	X_{46}			
X_{56}	$\mathbf{W}_{W_{TL},W_{D}}$	X_{56}	X_{47}	X_{48}		
X_{57}	$\mathbf{W}_{W_{TL},W_{M}}$	X_{57}	X_{47}	X_{48}		
X_{58}	$\mathbf{W}_{W_{TL},W_{F}}$	X_{58}	X_{47}	X_{48}		
X_{59}	$\mathbf{W}_{W_{D},W_{M}}$	X_{59}	X_{47}	X_{48}		
X_{60}	$\mathbf{W}_{W_{D},W_{F}}$	X_{60}	X_{47}	X_{48}		
X_{61}	$\mathbf{W}_{W_{M},W_{F}}$	X_{61}	X_{47}	X_{48}		

Fig. 9. Role matrix mb for base connectivity.

mcw	Connection weights $\boldsymbol{\omega}$	1	2	3	4	5
X_{1}	a_TL	1				
X_{2}	b_TL	X_{23}				
X_{3}	c_TL	X_{24}				
X_{4}	d_TL	X_{25}				
X_{5}	e_TL	X_{26}	X_{27}			
X_{6}	a_D	1				
X_{7}	b_D	X_{28}				
X_{8}	c_D	X_{29}				
X_{9}	d_D	X_{30}				
X_{10}	e_D	X_{31}	X_{32}			
X_{11}	a_M	1				
X_{12}	b_M	X_{33}				
X_{13}	c_M	X_{34}				
X_{14}	d_M	X_{35}				
X_{15}	e_M	X_{36}	X_{37}			
X_{16}	a_O	1				
X_{17}	b_O	X_{38}				
X_{18}	c_O	X_{39}				
X_{19}	d_O	X_{40}				
X_{20}	e_O	X_{41}	X_{42}			
X_{21}	a_F	1				
X_{22}	b_F	X_{43}				
X_{23}	$\mathbf{W}_{a\_TL,b\_TL}$	1	X_{57}	X_{56}	X_{53}	X_{58}
X_{24}	$\mathbf{W}_{b\_TL,c\_TL}$	1	X_{57}	X_{56}	X_{53}	X_{58}
X_{25}	$\mathbf{W}_{b\_TL,d\_TL}$	1	X_{57}	X_{56}	X_{53}	X_{58}
X_{26}	$\mathbf{W}_{c\_TL,e\_TL}$	1	X_{57}	X_{56}	X_{53}	X_{58}
X_{27}	$\mathbf{W}_{d\_TL,e\_TL}$	1	X_{57}	X_{56}	X_{53}	X_{58}
X_{28}	$\mathbf{W}_{a\_D,b\_D}$	X_{59}	1	X_{56}	X_{54}	X_{60}
X_{29}	$\mathbf{W}_{b\_D,c\_D}$	X_{59}	1	X_{56}	X_{54}	X_{60}
X_{30}	$\mathbf{W}_{b\_D,d\_D}$	X_{59}	1	X_{56}	X_{54}	X_{60}
X_{31}	$\mathbf{W}_{c\_D,e\_D}$	X_{59}	1	X_{56}	X_{54}	X_{60}
X_{32}	$\mathbf{W}_{d\_D,e\_D}$	X_{59}	1	X_{56}	X_{54}	X_{60}
X_{33}	$\mathbf{W}_{a\_M,b\_M}$	X_{59}	X_{57}	1	X_{55}	X_{61}
X_{34}	$\mathbf{W}_{b\_M,c\_M}$	X_{59}	X_{57}	1	X_{55}	X_{61}
X_{35}	$\mathbf{W}_{b\_M,d\_M}$	X_{59}	X_{57}	1	X_{55}	X_{61}
X_{36}	$\mathbf{W}_{c\_M,e\_M}$	X_{59}	X_{57}	1	X_{55}	X_{61}
X_{37}	$\mathbf{W}_{d\_M,e\_M}$	X_{59}	X_{57}	1	X_{55}	X_{61}
X_{38}	$\mathbf{W}_{a\_O,b\_O}$	X_{49}	X_{50}	X_{51}	1	X_{52}
X_{39}	$\mathbf{W}_{b\_O,c\_O}$	X_{49}	X_{50}	X_{51}	1	X_{52}
X_{40}	$\mathbf{W}_{b\_O,d\_O}$	X_{49}	X_{50}	X_{51}	1	X_{52}
X_{41}	$\mathbf{W}_{c\_O,e\_O}$	X_{49}	X_{50}	X_{51}	1	X_{52}
X_{42}	$\mathbf{W}_{d\_O,e\_O}$	X_{49}	X_{50}	X_{51}	1	X_{52}
X_{43}	$\mathbf{W}_{a\_F,b\_F}$	X_{58}	X_{60}	X_{61}	1	X_{52}
X_{44}	F1	1				
X_{45}	F2	1				
X_{46}	F3	1				
X_{47}	CS	1				
X_{48}	TLS	1				
X_{49}	$\mathbf{W}_{W_{TL},W_{O}}$	1				
X_{50}	$\mathbf{W}_{W_{D},W_{O}}$	1				
X_{51}	$\mathbf{W}_{W_{M},W_{O}}$	1				
X_{52}	$\mathbf{W}_{W_{F},W_{O}}$	1				
X_{53}	$\mathbf{W}_{W_{O},W_{TL}}$	1				
X_{54}	$\mathbf{W}_{W_{O},W_{D}}$	1				
X_{55}	$\mathbf{W}_{W_{O},W_{M}}$	1				
X_{56}	$\mathbf{W}_{W_{TL},W_{D}}$	1	1			
X_{57}	$\mathbf{W}_{W_{TL},W_{M}}$	1	1			
X_{58}	$\mathbf{W}_{W_{TL},W_{F}}$	1	1			
X_{59}	$\mathbf{W}_{W_{D},W_{M}}$	1	1			
X_{60}	$\mathbf{W}_{W_{D},W_{F}}$	1	1			
X_{61}	$\mathbf{W}_{W_{M},W_{F}}$	1	1			

Fig. 10. Role matrix mcw for connection weights.

msv		Speed factors η	**Initial Value**
X_1	a_TL	0.5	1
X_2	b_TL	0.5	0
X_3	c_TL	0.5	0
X_4	d_TL	0.5	0
X_5	e_TL	0.5	0
X_6	a_D	0.5	1
X_7	b_D	0.5	0
X_8	c_D	0.5	0
X_9	d_D	0.5	0
X_{10}	e_D	0.5	0
X_{11}	a_M	0.5	1
X_{12}	b_M	0.5	0
X_{13}	c_M	0.5	0
X_{14}	d_M	0.5	0
X_{15}	e_M	0.5	0
X_{16}	a_O	0.5	1
X_{17}	b_O	0.5	0
X_{18}	c_O	0.5	0
X_{19}	d_O	0.5	0
X_{20}	e_O	0.5	0
X_{21}	a_F	0.5	1
X_{22}	b_F	0.5	0
X_{23}	$\mathbf{W}_{a\_TL,b\_TL}$	0.5	0
X_{24}	$\mathbf{W}_{b\_TL,c\_TL}$	0.5	0
X_{25}	$\mathbf{W}_{b\_TL,d\_TL}$	0.5	0
X_{26}	$\mathbf{W}_{c\_TL,e\_TL}$	0.5	0
X_{27}	$\mathbf{W}_{d\_TL,e\_TL}$	0.5	0
X_{28}	$\mathbf{W}_{a\_D,b\_D}$	0.5	0
X_{29}	$\mathbf{W}_{b\_D,c\_D}$	0.5	1
X_{30}	$\mathbf{W}_{b\_D,d\_D}$	0.5	0
X_{31}	$\mathbf{W}_{c\_D,e\_D}$	0.5	1
X_{32}	$\mathbf{W}_{d\_D,e\_D}$	0.5	0
X_{33}	$\mathbf{W}_{a\_M,b\_M}$	0.5	0
X_{34}	$\mathbf{W}_{b\_M,c\_M}$	0.5	0
X_{35}	$\mathbf{W}_{b\_M,d\_M}$	0.5	1
X_{36}	$\mathbf{W}_{c\_M,e\_M}$	0.5	0
X_{37}	$\mathbf{W}_{d\_M,e\_M}$	0.5	1
X_{38}	$\mathbf{W}_{a\_O,b\_O}$	0.5	0
X_{39}	$\mathbf{W}_{b\_O,c\_O}$	0.5	0
X_{40}	$\mathbf{W}_{b\_O,d\_O}$	0.5	0
X_{41}	$\mathbf{W}_{c\_O,e\_O}$	0.5	0
X_{42}	$\mathbf{W}_{d\_O,e\_O}$	0.5	0
X_{43}	$\mathbf{W}_{a\_F,b\_F}$	0.5	1
X_{44}	F1	1	1
X_{45}	F2	1	0
X_{46}	F3	1	0
X_{47}	CS	0/2	0
X_{48}	TLS	2/0	0
X_{49}	$\mathbf{W}_{\mathbf{W}_{TL},\mathbf{W}_{O}}$	0.1	0
X_{50}	$\mathbf{W}_{\mathbf{W}_{D},\mathbf{W}_{O}}$	0.1	0
X_{51}	$\mathbf{W}_{\mathbf{W}_{M},\mathbf{W}_{O}}$	0.1	0
X_{52}	$\mathbf{W}_{\mathbf{W}_{F},\mathbf{W}_{O}}$	0.1	0
X_{53}	$\mathbf{W}_{\mathbf{W}_{O},\mathbf{W}_{TL}}$	0.1	0
X_{54}	$\mathbf{W}_{\mathbf{W}_{O},\mathbf{W}_{D}}$	0.1	0
X_{55}	$\mathbf{W}_{\mathbf{W}_{O},\mathbf{W}_{M}}$	0.1	0
X_{56}	$\mathbf{W}_{\mathbf{W}_{TL},\mathbf{W}_{D}}$	0.1	0
X_{57}	$\mathbf{W}_{\mathbf{W}_{TL},\mathbf{W}_{M}}$	0.1	0
X_{58}	$\mathbf{W}_{\mathbf{W}_{TL},\mathbf{W}_{F}}$	0.1	0
X_{59}	$\mathbf{W}_{\mathbf{W}_{D},\mathbf{W}_{M}}$	0.1	0
X_{60}	$\mathbf{W}_{\mathbf{W}_{D},\mathbf{W}_{F}}$	0.1	0
X_{61}	$\mathbf{W}_{\mathbf{W}_{M},\mathbf{W}_{F}}$	0.1	0

Fig. 11. Role matrix ms for speed factors and initial values iv.

mcfw	Combination function weights γ	**alogistic**	**steponce**
X_1	a_TL	1	
X_2	b_TL	1	
X_3	c_TL	1	
X_4	d_TL	1	
X_5	e_TL	1	
X_6	a_D	1	
X_7	b_D	1	
X_8	c_D	1	
X_9	d_D	1	
X_{10}	e_D	1	
X_{11}	a_M	1	
X_{12}	b_M	1	
X_{13}	c_M	1	
X_{14}	d_M	1	
X_{15}	e_M	1	
X_{16}	a_O	1	
X_{17}	b_O	1	
X_{18}	c_O	1	
X_{19}	d_O	1	
X_{20}	e_O	1	
X_{21}	a_F	1	
X_{22}	b_F	1	
X_{23}	$\mathbf{W}_{a\_TL,b\_TL}$	1	
X_{24}	$\mathbf{W}_{b\_TL,c\_TL}$	1	
X_{25}	$\mathbf{W}_{b\_TL,d\_TL}$	1	
X_{26}	$\mathbf{W}_{c\_TL,e\_TL}$	1	
X_{27}	$\mathbf{W}_{d\_TL,e\_TL}$	1	
X_{28}	$\mathbf{W}_{a\_D,b\_D}$	1	
X_{29}	$\mathbf{W}_{b\_D,c\_D}$	1	
X_{30}	$\mathbf{W}_{b\_D,d\_D}$	1	
X_{31}	$\mathbf{W}_{c\_D,e\_D}$	1	
X_{32}	$\mathbf{W}_{d\_D,e\_D}$	1	
X_{33}	$\mathbf{W}_{a\_M,b\_M}$	1	
X_{34}	$\mathbf{W}_{b\_M,c\_M}$	1	
X_{35}	$\mathbf{W}_{b\_M,d\_M}$	1	
X_{36}	$\mathbf{W}_{c\_M,e\_M}$	1	
X_{37}	$\mathbf{W}_{d\_M,e\_M}$	1	
X_{38}	$\mathbf{W}_{a\_O,b\_O}$	1	
X_{39}	$\mathbf{W}_{b\_O,c\_O}$	1	
X_{40}	$\mathbf{W}_{b\_O,d\_O}$	1	
X_{41}	$\mathbf{W}_{c\_O,e\_O}$	1	
X_{42}	$\mathbf{W}_{d\_O,e\_O}$	1	
X_{43}	$\mathbf{W}_{a\_F,b\_F}$	1	
X_{44}	F1	1	
X_{45}	F2	1	
X_{46}	F3	1	
X_{47}	CS		1
X_{48}	TLS		1
X_{49}	$\mathbf{W}_{\mathbf{W}_{TL},\mathbf{W}_{O}}$	1	
X_{50}	$\mathbf{W}_{\mathbf{W}_{D},\mathbf{W}_{O}}$	1	
X_{51}	$\mathbf{W}_{\mathbf{W}_{M},\mathbf{W}_{O}}$	1	
X_{52}	$\mathbf{W}_{\mathbf{W}_{F},\mathbf{W}_{O}}$	1	
X_{53}	$\mathbf{W}_{\mathbf{W}_{O},\mathbf{W}_{TL}}$	1	
X_{54}	$\mathbf{W}_{\mathbf{W}_{O},\mathbf{W}_{D}}$	1	
X_{55}	$\mathbf{W}_{\mathbf{W}_{O},\mathbf{W}_{M}}$	1	
X_{56}	$\mathbf{W}_{\mathbf{W}_{TL},\mathbf{W}_{D}}$	1	
X_{57}	$\mathbf{W}_{\mathbf{W}_{TL},\mathbf{W}_{M}}$	1	
X_{58}	$\mathbf{W}_{\mathbf{W}_{TL},\mathbf{W}_{F}}$	1	
X_{59}	$\mathbf{W}_{\mathbf{W}_{D},\mathbf{W}_{M}}$	1	
X_{60}	$\mathbf{W}_{\mathbf{W}_{D},\mathbf{W}_{F}}$	1	
X_{61}	$\mathbf{W}_{\mathbf{W}_{M},\mathbf{W}_{F}}$	1	

Fig. 12. Role matrix mcfw for combination function weights.

mcfw	Combination function parameters π	alogistic steepness σ	alogistic threshold τ	steponce α	steponce β
X_1	a_TL	5	0.5		
X_2	b_TL	5	0.5		
X_3	c_TL	5	0.5		
X_4	d_TL	5	0.5		
X_5	e_TL	5	1		
X_6	a_D	5	0.5		
X_7	b_D	5	0.5		
X_8	c_D	5	0.5		
X_9	d_D	5	0.5		
X_{10}	e_D	5	1		
X_{11}	a_M	5	0.5		
X_{12}	b_M	5	0.5		
X_{13}	c_M	5	0.5		
X_{14}	d_M	5	0.5		
X_{15}	e_M	5	1		
X_{16}	a_O	5	0.5		
X_{17}	b_O	5	0.5		
X_{18}	c_O	5	0.5		
X_{19}	d_O	5	0.5		
X_{20}	e_O	5	1		
X_{21}	a_F	5	0.5		
X_{22}	b_F	5	0.5		
X_{23}	$\mathbf{W}_{a\_TL,b\_TL}$	5	1		
X_{24}	$\mathbf{W}_{b\_TL,c\_TL}$	5	1		
X_{25}	$\mathbf{W}_{b\_TL,d\_TL}$	5	1		
X_{26}	$\mathbf{W}_{c\_TL,e\_TL}$	5	1		
X_{27}	$\mathbf{W}_{d\_TL,e\_TL}$	5	1		
X_{28}	$\mathbf{W}_{a\_D,b\_D}$	5	1		
X_{29}	$\mathbf{W}_{b\_D,c\_D}$	5	1		
X_{30}	$\mathbf{W}_{b\_D,d\_D}$	5	1		
X_{31}	$\mathbf{W}_{c\_D,e\_D}$	5	1		
X_{32}	$\mathbf{W}_{d\_D,e\_D}$	5	1		
X_{33}	$\mathbf{W}_{a\_M,b\_M}$	5	1		
X_{34}	$\mathbf{W}_{b\_M,c\_M}$	5	1		
X_{35}	$\mathbf{W}_{b\_M,d\_M}$	5	1		
X_{36}	$\mathbf{W}_{c\_M,e\_M}$	5	1		
X_{37}	$\mathbf{W}_{d\_M,e\_M}$	5	1		
X_{38}	$\mathbf{W}_{a\_O,b\_O}$	5	1.5		
X_{39}	$\mathbf{W}_{b\_O,c\_O}$	5	1.5		
X_{40}	$\mathbf{W}_{b\_O,d\_O}$	5	1.5		
X_{41}	$\mathbf{W}_{c\_O,e\_O}$	5	1.5		
X_{42}	$\mathbf{W}_{d\_O,e\_O}$	5	1.5		
X_{43}	$\mathbf{W}_{a\_F,b\_F}$	5	0.5		
X_{44}	F1	5	0.5		
X_{45}	F2	5	0.5		
X_{46}	F3	5	0.5		
X_{47}	CS			20	80
X_{48}	TLS			120	180
X_{49}	$\mathbf{W}_{\mathbf{w}_{TL},\mathbf{w}_O}$	5	0.5		
X_{50}	$\mathbf{W}_{\mathbf{w}_D,\mathbf{w}_O}$	5	0.5		
X_{51}	$\mathbf{W}_{\mathbf{w}_M,\mathbf{w}_O}$	5	0.5		
X_{52}	$\mathbf{W}_{\mathbf{w}_F,\mathbf{w}_O}$	5	0.5		
X_{53}	$\mathbf{W}_{\mathbf{w}_O,\mathbf{w}_{TL}}$	5	0.5		
X_{54}	$\mathbf{W}_{\mathbf{w}_O,\mathbf{w}_D}$	5	0.5		
X_{55}	$\mathbf{W}_{\mathbf{w}_O,\mathbf{w}_M}$	5	0.5		
X_{56}	$\mathbf{W}_{\mathbf{w}_{TL},\mathbf{w}_D}$	5	0.5		
X_{57}	$\mathbf{W}_{\mathbf{w}_{TL},\mathbf{w}_M}$	5	0.5		
X_{58}	$\mathbf{W}_{\mathbf{w}_{TL},\mathbf{w}_F}$	5	0.5		
X_{59}	$\mathbf{W}_{\mathbf{w}_D,\mathbf{w}_M}$	5	0.5		
X_{60}	$\mathbf{W}_{\mathbf{w}_D,\mathbf{w}_F}$	5	0.5		
X_{61}	$\mathbf{W}_{\mathbf{w}_M,\mathbf{w}_F}$	5	0.5		

Fig. 13. Role matrix mcfp for combination function parameters.

A.1. Role matrices for connectivity characteristics

The connectivity characteristics are specified by role matrices **mb** and **mcw** shown in Fig. 9 and Fig. 10. Role matrix **mb** lists the other states (at the same or lower level) from which the state gets its incoming connections, whereas in role matrix **mcw** the connection weights are listed for these connections.

Nonadaptive connection weights are indicated in **mcw** (in Fig. 10) by a number (in a green shaded cell), but adaptive connection weights are indicated by a reference to the (self-model) state representing the adaptive value (in a peach-red shaded cell). This can be seen for base states X_2 to X_5 (with self-model states X_{23} to X_{27}), states X_7 to X_{10} (with self-model states X_{28} to X_{32}), X_{12} to X_{15} (with self-model states X_{33} to X_{37}), X_{17} to X_{20} (with self-model states X_{38} to X_{42}), and X_{22} (with self-model state X_{43}). Moreover, from state X_{38} to X_{43} on second-order self-model states X_{49} to X_{61} are indicated.

A.2. Role matrices for timing characteristics

In Fig. 11, the role matrix **ms** for speed factors is shown, which lists all speed factors. Next to it, the list of initial values can be found.

A.3. Role matrices for aggregation characteristics

The network characteristics for aggregation are defined by the selection of combination functions from the library and values for their parameters. In role matrix **mcfw** it is specified by weights which state uses which combination function; see Fig. 12.

In role matrix **mcfp** (see Fig. 13) it is indicated what the parameter values are for the chosen combination functions.

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