Modeling higher-order adaptive evolutionary processes by reified adaptive network models

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Chapter 7
Modeling Higher-Order Adaptive Evolutionary Processes by Reified Adaptive Network Models

Abstract In this chapter, a fourth-order reified network model is introduced to describe different orders of adaptivity found in a case study on evolutionary processes. The network model describes how the causal pathways for newly developed features in this case study affect the causal pathways of already existing features, which makes the pathways of these new features one order of adaptivity higher than the existing ones, as they adapt a previous adaptation. The network reification approach is shown to be an adequate means to model this transparently.

7.1 Introduction

In the literature, many examples can be found relating to first-order adaptive networks, in different (e.g., cognitive, mental, social) domains. For second-order adaptive networks there is at least a substantial amount of Cognitive Neuroscience literature on metaplasticity that controls under which circumstances and to which extent plasticity should occur; e.g., Abraham and Bear (1996), Schmidt et al. (2013). This has been used in Chap. 4, Sect. 4.4 to design a second-order adaptive Mental Network model, which also has been applied in Chap. 5 to model adaptive decision making under extreme emotions. Also for Social Science, some literature refers to second-order adaptive networks, but only a modest amount; e.g., Carley (2002, 2006). In Chap. 6, an example second-order reified adaptive Social Network model was addressed. So far about second-order adaptive networks; but how about adaptive networks of order higher than two? Recall that in Chap. 1, Sect. 1.3 such a question was discussed concerning the occurrence or relevance for real world applications of adaptive networks of order higher than two in the literature. The outcome seemed a bit disappointing. In the current and next chapter answers are obtained on this question, positive answers: the two chapters are discussing three examples of reified networks of order higher than two.

The current chapter focuses on a case study of evolutionary processes, and the orders of adaptation that are recognized in them or attributed to them; e.g., Fessler et al. (2005, 2015), Jones et al. (2005), Fleischman and Fessler (2011). In Chap. 1,

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Sects. 1.2.2 and 1.3.2 some input from that side was already pointed out. One of these case studies addresses how the existence of pathogens has led to the adaptation of developing a defense system with an internal component (internal immune system) and (maybe not at the same time) an external component based on disgust, sometimes called a behavioural immune system (Aarøe et al. 2017; Schaller 2016; Schaller and Park 2011). On top of that, (first trimester) pregnancy led to the adaptation of temporary suppression of this defense system to give the half-foreign conceptus a chance to get embedded. Moreover, above that, as another adaptation, for the first trimester of pregnancy, a strong feeling of disgust was developed to still strengthen the overall defense system by strengthening, in particular, the external component of it. For more information about this interesting research area, see Aarøe et al. (2017), Curtis et al. (2011), Fleischman and Fessler (2018), Jones et al. (2017), Lieberman et al. (2018), Oaten et al. (2009), Schaller and Park (2011), Schaller (2016), Tybur and Lieberman (2016).

The case study pointed out above is chosen here, analysed in some depth and modeled by a fourth-order reified network model. For this model, different scenarios were simulated, and mathematical analysis of its emerging behaviour in terms of equilibria was performed, part of which was also used to verify the model. In Sect. 7.2, the case study itself is briefly discussed. Section 7.3 introduces the fourth-order reified network model, and Sect. 7.4 the simulations with it. Section 7.5 addresses the mathematical analysis of the model's emerging behaviour, and verification of the model based on this analysis and simulations for the case study.

7.2 Higher-Order Adaptation in Evolutionary Processes

Viewed from a distance, evolutionary processes are adaptation processes that are changing the physical world by creating new causal pathways or blocking existing causal pathways. This can be described as changing the causal connections in such causal pathways from 0 or very low to high, or conversely. The adaptations are driven by changing environmental circumstances, making that organisms with more favourable causal pathways for these circumstances become more dominant. Then they determine the average causal pathways of the population to a higher extent: this leads to a shift in the average pathways by changes in the causal connections in these pathways. These circumstances can be considered as environmental properties. In particular, consider the quote shown in Chap. 1, Sect. 1.3.2:

> Also of relevance here, one form of disgust, pathogen disgust, functions in part as a third-order adaptation, as disease-avoidance responses are up-regulated in a manner that compensates for the increases in vulnerability to pathogens that accompany pregnancy and preparation for implantation – changes that are themselves a second-order adaptation addressing the conflict between maternal immune defenses and the parasitic behavior of the half-foreign conceptus (Fessler et al. 2005; Jones et al. 2005; Fleischman and Fessler 2011). (Fessler et al. 2015)

From this quote, it is suggested that three levels of adaptation might be considered applicable for the first trimester of pregnancy. However, also the occurrence of pathogens can be considered a form of adaptation for the wider ecological context. Therefore the following four adaptation orders can be distinguished:

- First-order adaptation:
  Pathogens occur, with causal pathways negatively affecting the causal pathways for good health.
- Second-order adaptation:
  An internal defense system occurs, with causal pathways which negatively affects the causal pathways used by pathogens.
- Third-order adaptation:
  For pregnancy, causal pathways are added to make the defense system's causal pathways less strong as the half-foreign conceptus might easily be identified as a kind of parasite and attacked.
- Fourth-order adaptation:
  Disgust during (first trimester) pregnancy adds causal pathways by which potential pathogens in the external world are avoided so that fewer risks are taken for entering pathogens while the internal defense system (the internal immune system) is low functioning. This strengthens the overall defense system by strengthening the external defense system (the behavioural immune system) by which the pathogens are addressed outside the body; this makes the causal pathway from (first trimester) pregnancy to suppress the causal pathways of the overall defense system less strong as the external component of the defense system strengthened by disgust is not addressed by it.

So, can this be used as a basis for a fourth-order reified adaptive network model? This will be addressed in Sect. 7.3.

7.3 A Reified Network Model for Fourth-Order Adaptive Evolutionary Processes

The Network-Oriented Modeling approach used to model these evolutionary processes is based on reified temporal-causal network models as presented in Chaps. 3 and 4; see also (Treur 2018a, b). Recall that a temporal-causal network model in the first place involves representing in a declarative manner states and connections between them that represent (causal) impacts of states on each other, as assumed to hold for the application domain addressed. The states are assumed to have (activation) levels, usually in the interval [0, 1], that vary over time. The following three notions form the defining part of a conceptual representation of a temporal-causal network model structure (Treur 2016, 2019a):

- **Connectivity**
  - Each incoming connection of a state *Y*, from a state *X* has a *connection weight value* $\boldsymbol{\omega}_{X,Y}$ representing the strength of the connection.
- **Aggregation**
  - For each state a *combination function* $\mathbf{c}_Y(..)$ is chosen to combine the causal impacts state *Y* receives from other states
- **Timing**
  - For each state *Y* a *speed factor* $\boldsymbol{\eta}_Y$ is used to represent how fast state *Y* is changing upon causal impact.

The notion of *network reification* as introduced in Chaps. 3 and 4 is a conceptual tool to model adaptive networks more transparently within a Network-Oriented Modelling perspective. Reification literally means representing something abstract as a material or more real concrete thing (Merriam-Webster and Oxford dictionaries). This concept is used in different scientific areas in which it has been shown to provide substantial advantages in expressivity and transparency of models, and, in particular, within AI; e.g., Davis and Buchanan (1977), Davis (1980), Galton (2006), Sterling and Beer (1989), Weyhrauch (1980). Specific cases of reification from a linguistic or logical perspective are representing relations between objects by objects themselves, or representing more complex statements by objects or numbers.

For network models, reification can be applied by reifying network structure characteristics (such as the $\boldsymbol{\omega}_{X,Y}, \mathbf{c}_Y(..), \boldsymbol{\eta}_Y$ indicated above) in the form of additional network states (called *reification states*, indicated by $\mathbf{W}_{X,Y}, \mathbf{C}_Y, \mathbf{H}_Y$, respectively) within an extended network. According to the specific network structure characteristic represented, *roles* **W**, **C**, **H** are assigned to reification states (or to values): *connection weight reification*, *combination function reification*, *speed factor reification*, respectively. Also, a role **P** for *combination function parameters* is used. A format based on *role matrices* **mb** (for base role), **mcw** (for connection weight role **W**), **mcfw** (for combination function weight role **C**), **mcfp** (for combination function parameter role **P**), and **ms** (for speed factor role **H**), is used to specify a reified network model according to these roles. Multilevel reified networks can be used to model networks which are adaptive of different orders. For more details, see Chaps. 3 and 4, or (Treur 2018a, b).

Inspired by the information on evolutionary processes in Sect. 7.2 but abstracting from specific details, a fourth-order reified adaptive network for these evolutionary processes has been designed. First, the general blueprint is discussed (Sect. 7.3.1), and next, the more specific network model (Sect. 7.3.2).

7.3.1 Adaptive Causal Modeling of Changing Causal Pathways in Evolutionary Processes

As pointed out in Sect. 7.2, first paragraph, evolutionary adaptation usually concerns affecting existing causal pathways by adding new causal pathways that weaken or strengthen the existing causal pathways. This indicates that levels of adaptation can be created where the causal pathways at one adaptation level are adapted by the causal pathways at the next level. The adaptation of a causal pathway can be done by strengthening or weakening one or more causal connections within such a causal pathway. This fits well in a reified network architecture where for each level, for connection weights in causal pathways at that level, reification states are introduced at the next level. The general representation then becomes in a simple form:

- **Base level**:
  causal pathway by a causal connection from a to b
- **First adaptation level**:
  causal pathway by a causal connection from a_1 to $\mathbf{W}_{a,b}$; this $\mathbf{W}_{a,b}$ represents the causal connection from a to b from the base level
- **Second adaptation level**:
  causal pathway by a causal connection from a_2 to $\mathbf{W}_{a_1,\mathbf{W}_{a,b}}$; this $\mathbf{W}_{a_1,\mathbf{W}_{a,b}}$ represents the causal connection from a_1 to $\mathbf{W}_{a,b}$ from the first adaptation level
- **Third adaptation level**:
  causal pathway by a causal connection from a_3 to $\mathbf{W}_{a_2,\mathbf{W}_{a_1,\mathbf{W}_{a,b}}}$; this $\mathbf{W}_{a_2,\mathbf{W}_{a_1,\mathbf{W}_{a,b}}}$ represents the causal connection from a_2 to $\mathbf{W}_{a_1,\mathbf{W}_{a,b}}$ from the second adaptation level
- **Fourth adaptation level**:
  causal pathway by a causal connection from a_4 to $\mathbf{W}_{a_3,\mathbf{W}_{a_2,\mathbf{W}_{a_1,\mathbf{W}_{a,b}}}}$; this $\mathbf{W}_{a_3,\mathbf{W}_{a_2,\mathbf{W}_{a_1,\mathbf{W}_{a,b}}}}$ represents the causal connection from a_3 to $\mathbf{W}_{a_2,\mathbf{W}_{a_1,\mathbf{W}_{a,b}}}$ from the third adaptation level
- **Fifth adaptation level**:
  etc.

This general pattern for hierarchical adaptation processes for causal pathways will be used to obtain a more specific reified network model for the multilevel adaptation processes described in Sect. 7.2.

7.3.2 The Reified Adaptive Network Model for the Described Fourth-Order Adaptation Case

In the considered reified network model four reification levels are considered, where for each level its causal pathway can be changed by causal pathways at one

Table 7.1 The states and their explanations

State		Explanation	level
X_1	s_1	Occurrence of pathogens	Base level
X_2	s_2	Occurrence of internal defense system	
X_3	s_3	Occurrence of pregnancy	
X_4	s_4	Occurrence of disgust	
X_5	s_5	Contextual circumstances	
X_6	e_1	Health level; on a causal pathway with a connection from s_5 for context	
X_7	$\mathbf{W}_{s5,e1}$	Reified representation state for the weight of the base level connection from s_5 for context to $e1$ for health level; on a causal pathway with a connection from s_1 for pathogens	First reification level
X_8	$\mathbf{W}_{s1,\mathbf{W}_{s5,e_1}}$	Reified representation state for the weight of the first reification level connection from s_1 for pathogens to $\mathbf{W}_{s5,e_1}$; on a causal pathway with a connection from s_2 for interrnal defense system	Second reification level
X_9	$\mathbf{W}_{s2,\mathbf{W}_{s1,\mathbf{W}_{s5,e_1}}}$	Reified representation state for the weight of the second reification level connection from s_2 for internal defense system to $\mathbf{W}_{s1,\mathbf{W}_{s5,e_1}}$; on a causal pathway with a connection from s_3 for pregnancy	Third reification level
X_{10}	$\mathbf{W}_{s3,\mathbf{W}_{s2,\mathbf{W}_{s1,\mathbf{W}_{s5,e_1}}}}$	Reified representation state for the weight of the third reification level connection from s_3 for pregnancy to $\mathbf{W}_{s2,\mathbf{W}_{s1,\mathbf{W}_{s5,e_1}}}$; on a causal pathway with a connection from s_4 for disgust	Fourth reification level

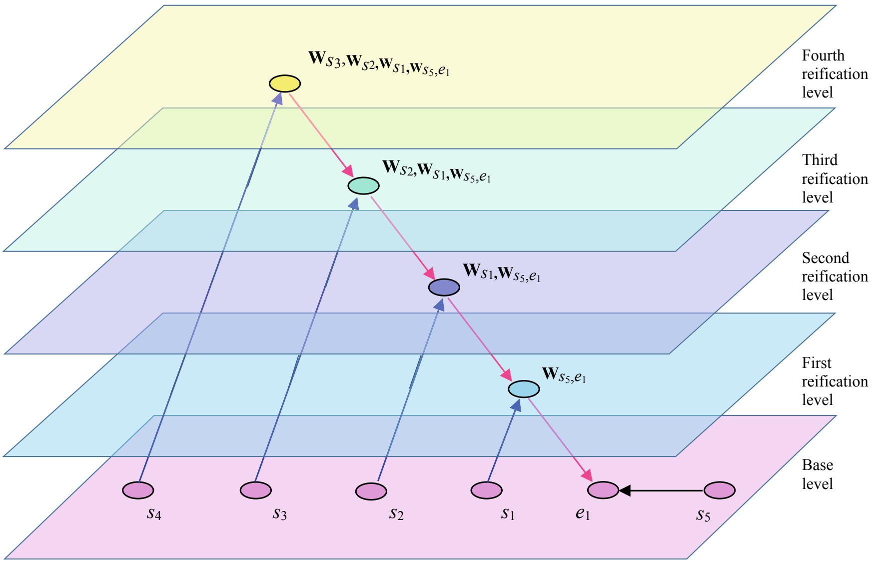

Fig. 7.1 Fourth-order reified network model for fourth-order adaptation in an evolutionary context

level higher. To limit the complexity of the overall model, the causal pathways at each level are kept simple; they will have just one causal connection. Table 7.1 explains the states of the network model.

Figure 7.1 shows a picture of the conceptual graphical representation of the reified network model, and Box 7.1 shows the role matrices **mb** (base connectivity),

mcw (connection weights), **ms** (speed factors), **mcfw** (combination function weights), **mcfp** (combination function parameters). Each role matrix has a format in which in each row for the indicated state it is specified which other states (red cells) or values (green cells) affect it and according to which role. In particular, in role matrix **mcw** the red cells indicate which states X_i play the role of the reification states for the weights of the connection indicated in that cell in **mb**. Note that this time there are no connections from a reification state to itself. Instead, the input states s_1, s_2, and s_3 have connections to themselves; these are used to give them appropriately timed entrance times, so that not everything happens at once.

The reified network model includes four reification states at four levels which each reify the connection weight of the causal pathway one level lower:

- $\mathbf{W}_{s_5,e_1}$ a first reification level state representing the causal connection from s_5 to e_1 from the base level
- $\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$ a second reification level state representing the causal connection from s_1 to $\mathbf{W}_{s_5,e_1}$ from the first reification level
- $\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$ a third reification level state representing the causal connection from s_2 to $\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$ from the second reification level
- $\mathbf{W}_{s_3,\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}}$ a fourth reification level state representing the causal connection from s_3 to $\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$ from the third reification level.

For the specific context described in Sect. 7.2, these elements are associated with

- for environmental context s_5 a causal pathway leads to a good health e_1
- pathogen state s_1 leads to disturbing the above causal pathway to a good health effect e_1
- well functioning internal defense system s_2 blocks the causal pathway for the effect of pathogens s_1 on the health pathway to e_1
- pregnancy in the first trimester s_3 needs less blocking of the effect of pathogens
- disgust s_4 is needed to compensate for the less blocking of foreign material.

Box 7.1 Role matrices for the fourth-order adaptive network model

mb	base connectivity	1
X_1	s_1	X_1
X_2	s_2	X_2
X_3	s_3	X_3
X_4	s_4	X_4
X_5	s_5	X_5
X_6	e_1	X_5
X_7	$\mathbf{W}_{s_5,e_1}$	X_1
X_8	$\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$	X_2
X_9	$\mathbf{W}_{s_2},\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$	X_3
X_{10}	$\mathbf{W}_{s_3},\mathbf{W}_{s_2},\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$	X_4

mcw	connection weights	1
X_1	s_1	1
X_2	s_2	1
X_3	s_3	1
X_4	s_4	1
X_5	s_5	1
X_6	e_1	X_7
X_7	$\mathbf{W}_{s_5,e_1}$	X_8
X_8	$\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$	X_9
X_9	$\mathbf{W}_{s_2},\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$	X_{10}
X_{10}	$\mathbf{W}_{s_3},\mathbf{W}_{s_2},\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$	1

ms	speed factors	1
X_1	s_1	0.08
X_2	s_2	0.05
X_3	s_3	0.015
X_4	s_4	0.008
X_5	s_5	0.2
X_6	e_1	0.5
X_7	$\mathbf{W}_{s_5,e_1}$	0.05
X_8	$\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$	0.05
X_9	$\mathbf{W}_{s_2},\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$	0.004
X_{10}	$\mathbf{W}_{s_3},\mathbf{W}_{s_2},\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$	0.004

mcfw	combination function weights	1 alogistic	2 compid
X_1	s_1	1	
X_2	s_2	1	
X_3	s_3	1	
X_4	s_4	1	
X_5	s_5	1	
X_6	e_1	1	
X_7	$\mathbf{W}_{s_5,e_1}$		1
X_8	$\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$		1
X_9	$\mathbf{W}_{s_2},\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$		1
X_{10}	$\mathbf{W}_{s_3},\mathbf{W}_{s_2},\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$		1

mcfp combination function parameters	function	1 alogistic		2 compid	
	parameter	1 σ	2 τ	1	2
X_1	s_1	18	0.2		
X_2	s_2	18	0.2		
X_3	s_3	18	0.2		
X_4	s_4	18	0.2		
X_5	s_5	18	0.2		
X_6	e_1	8	0.5		
X_7	$\mathbf{W}_{s_5,e_1}$				
X_8	$\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$				
X_9	$\mathbf{W}_{s_2},\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$				
X_{10}	$\mathbf{W}_{s_3},\mathbf{W}_{s_2},\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$				

iv	initial values	1
X_1	s_1	0.2
X_2	s_2	0.1
X_3	s_3	0.11
X_4	s_4	0.1
X_5	s_5	0.5
X_6	e_1	0
X_7	$\mathbf{W}_{s_5,e_1}$	0.8
X_8	$\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$	0.8
X_9	$\mathbf{W}_{s_2},\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$	0.8
X_{10}	$\mathbf{W}_{s_3},\mathbf{W}_{s_2},\mathbf{W}_{s_1},\mathbf{W}_{s_5,e_1}$	0.8

7.4 Simulation Experiments

Simulations have been performed using the dedicated software environment for reified network models described in Chap. 9 and Treur (2019b). To focus on different phases, three scenarios are considered successively, each with a longer time duration.

7.4.1 Simulation for Scenario 1: Occurrence of Pathogens and Defense System

This scenario focuses on a period in which pathogens occur, and subsequently a defense system against them is developed. Speed factors of X_3 (pregnancy) and X_4 (disgust) are set at 0 for this scenario. There are two orders of adaptation:

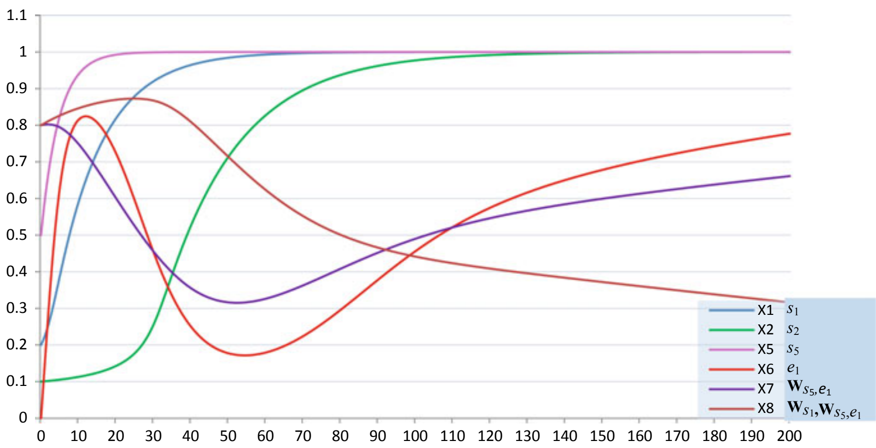

Fig. 7.2 Simulation for Scenario 1 with pathogens and internal defense system occurring, but no pregnancy nor disgust (yet)

• Adaptation 1 Pathogens are introduced	First-order adaptation
• Adaptation 2 Internal defense system is developed	Second-order adaptation

Before adaptation 1 health is good; after adaptation 1 health becomes bad, and after adaptation 2 health becomes good again. In Fig. 7.2 the simulation is shown.

The evolutionary story here is as follows. The red line starting at 0 displays the health level X_6 or e_1, which initially due to environmental context X_5 or s_5 (the pink line starting at 0.5) gets a high level above 0.8 as no pathogens have developed yet. After some time the first evolutionary adaptation (in the environment) is that pathogens X_1 (or s_1) develop, displayed by the blue curve starting at 0.2 and increasing up to 1. When these pathogens reach higher levels they negatively affect X_7 or $\mathbf{W}_{s_5,e_1}$ which represents the strength of the causal pathway from s_5 to e_1 for a good health level. Due to this negative effect on that causal pathway the health level e_1 goes down to a level as low as 0.2. However, after time 50 the internal defense system X_2 or s_2 develops, displayed by the green line starting at 0.1. When it reaches high levels after time 100, by attacking the causal pathway from s_1 to X_7 by which the pathogens have their bad effect (represented by X_8 or $\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$), it more and more positively affects the health level e_1, which in this case is rising to levels above 0.9.

Note that X_7 or $\mathbf{W}_{s_5,e_1}$ represents the connection weight in the causal pathway from environmental context X_5 (the pink line starting at 0.5) to health level X_6 or e_1. The effect of the pathogen on that causal connection is that it is blocked or at least decreased. This connection weight is displayed in the graph by the purple line for X_7 starting at 0.8 which indeed goes down after the pathogens appear. However, when the internal defense system X_2 or s_2 develops, after time 100 X_7 or $\mathbf{W}_{s_5,e_1}$ goes up again. The reason for this is that the defense system X_2 or s_2 causes that the connection weight for the causal pathway of the effect of the pathogens (represented by X_8 or $\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$) goes down. This X_8 is displayed by the brown line starting at 0.8; it indeed goes down after time 70 when the internal defense system appears. In this way, the internal defense system's causal pathway blocks or at least reduces the strength of the causal pathway of the effect of the pathogens on the pathway for good health.

7.4.2 *Simulation for Scenario 2: Occurrence of Pregnancy*

This scenario focuses on a somewhat longer period in which not only pathogens occur, and subsequently a defense system against them, but also after this, pregnancy occurs. Speed factor of X_4 (disgust) is set at 0 for this scenario. There are now three orders of adaptation:

• Adaptation 1 Pathogens are introduced	First-order adaptation
• Adaptation 2 Internal defense system is developed	Second-order adaptation
• Adaptation 3 Pregnancy introduced	Third-order adaptation

Before adaptation 1 health is good, after adaptation 1 health becomes bad, after adaptation 2 health becomes good again, and after adaptation 3 health becomes worse again. The simulation for this is shown in Fig. 7.3.

This scenario includes two states that were not displayed in Fig. 7.2, namely X_3 (which is s_3 for the pregnancy), and X_9 (which is $\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$). For the first phase until around time point 100 Scenario 2 is almost the same as Scenario 1. The main difference is that X_3 starts to increase after time point 70, and gets its causal effect

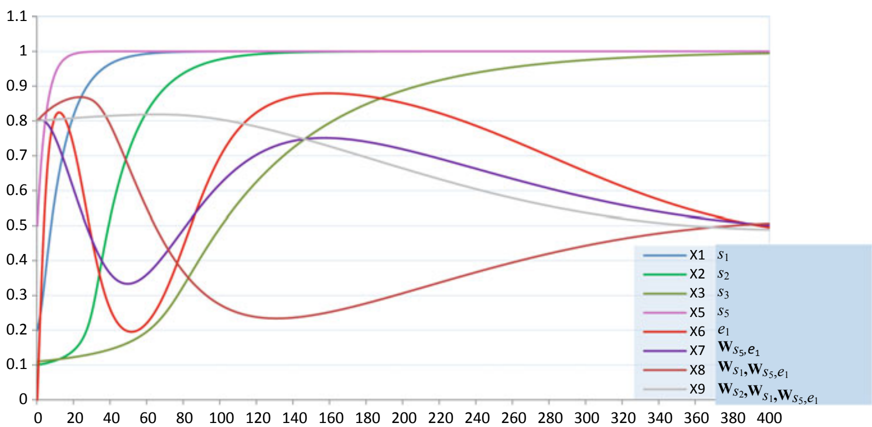

Fig. 7.3 Simulation for Scenario 2 with pathogens, internal defense system, and pregnancy occurring, but no disgust (yet)

on X_9, which starts to decrease. This makes the effect of the defense system s_2 on the causal pathway of the pathogens represented by $\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$ weaker. As a result of this weakened defense system the health level e_1 starts a downward trend from time point 140 on, whereas in Scenario 1 it is keeping an upward trend until time point 200 (and even further). This makes sense, as in Scenario 1 the well functioning defense system is able to maintain a good health level till the end of days. This is not the case from the moment that (first trimester) pregnancy occurred, hence the health level e_1 keeps a downward trend in Fig. 7.3.

7.4.3 Simulation for Scenario 3: Occurrence of Disgust

This scenario focuses on a still longer time period in which not only pathogens occur, a defense system against them is developed, and pregnancy occurs, but also disgust (in the first trimester of pregnancy) occurs. Now there are four orders of adaptation:

• Adaptation 1 Pathogens are introduced	First-order adaptation
• Adaptation 2 Defense system is developed	Second-order adaptation
• Adaptation 3 Pregnancy	Third-order adaptation
• Adaptation 4 Disgust	Fourth-order adaptation

Before adaptation 1 health is good, after adaptation 1 health becomes bad, after adaptation 2 health becomes good again, after adaptation 3 health becomes worse again, and after adaptation 4 health becomes better again. The simulation results for this scenario are shown in Fig. 7.4.

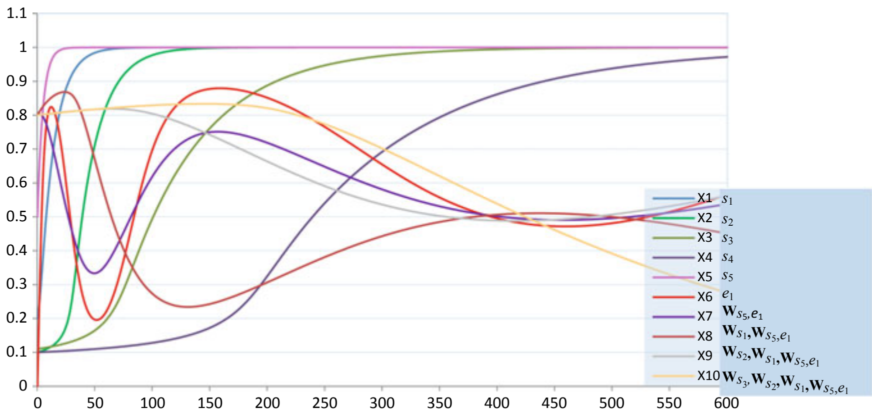

Fig. 7.4 Simulation for Scenario 3 with pathogens, internal defense system, pregnancy, and disgust occurring

This scenario includes two states that were not displayed in Fig. 7.3, namely X_4 (which is s_4 for the disgust), and X_{10} (which is $\mathbf{W}_{s_3,\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}}$). For the first phase until around time point 300 Scenario 3 is almost the same as Scenario 2. A difference is that X_4 starts to increase after time point 200, and gets its causal effect on X_{10}, which then starts to decrease. This makes the effect of the pregnancy s_3 on the causal pathway of the defense system (represented by $\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$) weaker. As a result of this weakened effect of pregnancy, the health level e_1 starts an upward trend again from time point 450 on, whereas in Scenario 2 it kept a downward trend until time point 400 (and even further). This makes sense, as in Scenario 2 the reduced functioning of the defense system is not able to maintain a good health level. This is different from the moment that disgust occurred, hence the health level e_1 finally gets an upward trend in Fig. 7.4.

For each of the discussed scenarios, one may wonder where the displayed trends, for example for the health level e_1, end when $t \to \infty$. This emerging behaviour will be analysed in Sect. 7.5.

7.5 Mathematical Analysis of the Emerging Behaviour and Verification of the Model

In this section the emerging behaviour of the fourth-order network model is analysed, first in Sect. 7.5.1 from a general perspective, and next in Sect. 7.5.2 for each of the scenarios. In Sect. 7.5.3, this analysis is used to perform verification of the designed network model.

7.5.1 General Approach to the Mathematical Analysis of Equilibria

First, a definition and criterion used for analysis of equilibria and verification of reified temporal-causal network models are given.

Definition 1 (**stationary point and equilibrium**) A state Y has a *stationary point* at t if $\mathbf{d}Y(t)/\mathbf{d}t = 0$.
The network is in *equilibrium* at t if every state Y of the model has a stationary point at t.

Applying this for the specific differential equation format for a temporal-causal network model, the more specific criterion in terms of the network structure characteristics $\boldsymbol{\omega}_{X,Y}, \mathbf{c}_Y(..), \boldsymbol{\eta}_Y$ is as follows:

Lemma 1 (**Criterion for a stationary point in a temporal-causal network**) Let Y be a state and $X_1, \ldots, X_k$ the states from which state Y gets its incoming connections. Then Y has a stationary point at t if and only if

$$\boldsymbol{\eta}_Y = 0 \quad \text{or} \quad \mathbf{c}_Y\big(\boldsymbol{\omega}_{X_1,Y}X_1(t), \ldots, \boldsymbol{\omega}_{X_k,Y}X_k(t)\big) = Y(t)$$

The latter equation is called a *stationary point equation*, or in case of an equilibrium an *equilibrium equation*.

This criterion will be used here to analyse the state values in an equilibrium. The states X_1 to X_5 are independent states as they have no incoming connections from other states. They can be handled separately. States X_7 to X_{10} depend on the independent states X_1 to X_4, respectively; they have a single incoming arrow with the complemental identity function **compid(..)** as combination function $\mathbf{c}_Y(V)$ for Y, defined by

$$\mathbf{compid}(V) = 1 - V \tag{7.1}$$

where V is a variable used for the single impact $\boldsymbol{\omega}_{X_i,X_j}X_i$. Then for state X_j depending on state X_i based on the above criterion (where now k = 1), the form of the equilibrium equation for X_j becomes

$$\mathbf{compid}(\boldsymbol{\omega}_{X_i,X_j}X_i) = X_j \tag{7.2}$$

which is

$$1 - \boldsymbol{\omega}_{X_i,X_j}X_i = X_j$$

where $\boldsymbol{\omega}_{X_i,X_j}$ is the value of the reification state $\mathbf{W}_{X_i,X_j}$ (which is also one of the X_k, actually for k = j+1) for this connection weight. So the equation becomes

$$1 - X_{j+1}X_i = X_j$$

From this, the following equilibrium equations can be found for X_7 to X_{10}.

$$\begin{aligned} X_7 &= 1 - X_8X_1 \\ X_8 &= 1 - X_9X_2 \\ X_9 &= 1 - X_{10}X_3 \\ X_{10} &= 1 - X_4 \end{aligned} \tag{7.3}$$

State X_6 depends on independent state X_5, but also on the connection weight represented by X_7. Based on the above criterion the equilibrium equation for X_6 is

$$X_6 = \mathbf{alogistic}_{8,0.5}(X_7X_5) \tag{7.4}$$

Box 7.2 Solving the general equilibrium equations by expressing the values for all states X_6 to X_{10} in the values of the independent states X_1 to X_5. Based on the general equilibrium equations, the equilibrium values can be expressed in terms of the equilibrium values for the independent states X_1 to X_5:

$$\begin{aligned} X_{10} &= 1 - X_4 \\ X_9 &= 1 - (1 - X_4)X_3 \\ X_8 &= 1 - (1 - (1 - X_4)X_3)X_2 \\ X_7 &= 1 - (1 - (1 - (1 - X_4)X_3)X_2)X_1 \end{aligned}$$

These expressions can also be rewritten as

$$\begin{aligned} X_{10} &= 1 - X_4 \\ X_9 &= 1 - X_3 + X_4X_3 \\ X_8 &= 1 - X_2 + X_3X_2 - X_4X_3X_2 \\ X_7 &= 1 - X_1 + X_2X_1 - X_3X_2X_1 + X_4X_3X_2X_1 \end{aligned}$$

Substituting the expression found for X_7 obtains:

$$X_6 = \mathbf{alogistic}_{8,0.5}((1 - X_1 + X_2X_1 - X_3X_2X_1 + X_4X_3X_2X_1)X_5)$$

So, also this is a function of the values of the independent states X_1 to X_5. For the nonzero independent states among X_1 to X_5 the equilibrium equation is

$$X_i = \mathbf{alogistic}_{18,0.2}(X_i)$$

and the equilibrium value is numerically approximated by 0.999999427374 (see Chap. 3, Sect. 3.7.4) which has a distance to 1 less than 10^{-6}.

7.5.2 *Mathematical Analysis of the Different Scenarios*

Each of the scenarios has different values for the independent states. Therefore, based on the general relations in Sect. 7.5.1, Box 7.2 above, for each of the scenarios, it is analysed which are the equilibrium values for all states. Also, a Scenario 0 is added in which only pathogens X_1 occur and no internal defense system X_2.

Scenario 0 (internal defense system X_2 = 0, pregnancy X_3 = 0, disgust X_4 = 0) In this scenario after substitution of the above values the outcomes are:

$$\begin{aligned} X_{10} &= 1 \\ X_9 &= 1 \\ X_8 &= 1 \\ X_7 &= 1 - X_1 \\ X_6 &= \mathbf{alogistic}_{8,0.5}((1 - X_1)X_5) \end{aligned} \tag{7.5}$$

As X_1 and X_5 are nonzero their equilibrium value is 0.999999427374 (see Chap. 3, Sect. 3.7.4) which has a distance to 1 less than 10^{-6}. So, approximately (deviation in the order of 10^{-6}) the values are obtained as shown in Table 7.2. The 0 for X_6 indicates bad health, which is to be expected as in this scenario pathogens have occurred but no defense system has developed yet.

Scenario 1 (pregnancy X_3 = 0, disgust X_4 = 0) In this scenario, after substitution of the above values the outcomes are:

$$\begin{aligned} X_{10} &= 1 \\ X_9 &= 1 \\ X_8 &= 1 - X_2 \\ X_7 &= 1 - X_1 + X_2X_1 \\ X_6 &= \mathbf{alogistic}_{8,0.5}((1 - X_1 + X_2X_1)X_5) \end{aligned} \tag{7.6}$$

Again, as X_1, X_2 and X_5 are nonzero, their equilibrium value is 0.999999427374 (see Chap. 3, Sect. 3.7.4) which has distance to 1 less than 10^{-6}. So, approximately the values are as shown in Table 7.2 (deviation in the order of 10^{-6}). The value 0.981684 for X_6 (=e_1) indicates good health, which is to be expected as in this scenario not only pathogens have occurred but also an internal defense system that

Table 7.2 The equilibrium values for the 4 scenarios based on the mathematical analysis

State		Scenario 0	Scenario 1	Scenario 2	Scenario 3
X_1	s_1	1	1	1	1
X_2	s_2	0	1	1	1
X_3	s_3	0	0	1	1
X_4	s_4	0	0	0	1
X_5	s_5	1	1	1	1
X_6	e_1	0	0.981684	0	0.981684
X_7	$\mathbf{W}_{s_5,e_1}$	0	1	0	1
X_8	$\mathbf{W}_{s_1}$,$\mathbf{W}_{s_5,e_1}$	1	0	1	0
X_9	$\mathbf{W}_{s_2}$,$\mathbf{W}_{s_1}$,$\mathbf{W}_{s_5,e_1}$	1	1	0	1
X_{10}	$\mathbf{W}_{s_3}$,$\mathbf{W}_{s_2}$,$\mathbf{W}_{s_1}$,$\mathbf{W}_{s_5,e_1}$	1	1	1	0

attacks them. This shows that the upward trend for the health level e_1 displayed in Fig. 7.2 after time point 50 will eventually end up in a very high health level.

Scenario 2 (disgust $X_4 = 0$) In this scenario after substitution of the above values the outcomes are:

$$\begin{aligned} X_{10} &= 1 \\ X_9 &= 1 - X_3 \\ X_8 &= 1 - X_2 + X_3X_2 \\ X_7 &= 1 - X_1 + X_2X_1 - X_3X_2X_1 \end{aligned} \tag{7.7}$$

Again, as X_1, X_2, X_3 and X_5 are nonzero, their equilibrium value is 0.999999427374 (see Chap. 3, Sect. 3.7.4) which has a distance to 1 less than 10^{-6}. So, approximately (deviation in the order of 10^{-6}) the values are as shown in Table 7.2.

The value 0 for X_6 indicates bad health, which is to be expected as in this scenario not only pathogens and an internal defense system have occurred but also a facility that suppresses that due to pregnancy. This shows that the downward trend for the health level e_1 displayed in Fig. 7.3 after time point 150 will eventually end up in a very low health level.

Scenario 3 (all independent states X_1 to X_5 are nonzero) In this scenario the general equations apply

$$\begin{aligned} X_{10} &= 1 - X_4 \\ X_9 &= 1 - X_3 + X_4X_3 \\ X_8 &= 1 - X_2 + X_3X_2 - X_4X_3X_2 \\ X_7 &= 1 - X_1 + X_2X_1 - X_3X_2X_1 + X_4X_3X_2X_1 \\ X_6 &= \mathbf{alogistic}_{8,0.5}((1 - X_1 + X_2X_1 - X_3X_2X_1 + X_4X_3X_2X_1)X_5) \end{aligned} \tag{7.8}$$

Again, as X_1, X_2, X_3, X_4 and X_5 are all nonzero, their equilibrium value is 0.999999427374 (see Chap. 3, Sect. 3.7.4) which has a distance to 1 less than 10^{-6}. So, approximately (deviation in the order of 10^{-6}) for the independent states the values 1 can be substituted in the above equations and the values shown in the last column in Table 7.2 are obtained. So, indeed also for this case a good health e_1, as expected. This shows that the upward trend for the health level e_1 displayed in Fig. 7.4 after time point 450 will eventually end up in a very high health level.

7.5.3 Verification of the Reified Network Model

For verification for Scenario 3, approximate equilibrium values have been determined by running the model (in about 10 s on an ordinary laptop) for 30,000 steps

Table 7.3 Outcomes at t = 3000 for a simulation of Scenario 3 with Δt = 0.1, compared to the equilibrium values from the analysis

state		simulation	analysis	deviation
X_1	s_1	0.999999	1	$-1\ 10^{-6}$
X_2	s_2	0.999999	1	$-1\ 10^{-6}$
X_3	s_3	0.999999	1	$-1\ 10^{-6}$
X_4	s_4	0.999999	1	$-1\ 10^{-6}$
X_5	s_5	0.999999	1	$-1\ 10^{-6}$
X_6	e_1	0.981646	0.981684	$-3.8\ 10^{-5}$
X_7	$\mathbf{W}_{s_5,e_1}$	0.999738	1	−0.00026
X_8	$\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}$	0.000243	0	0.000243
X_9	$\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}$	0.999775	1	−0.00023
X_{10}	$\mathbf{W}_{s_3,\mathbf{W}_{s_2,\mathbf{W}_{s_1,\mathbf{W}_{s_5,e_1}}}}$	$2.11\ 10^{-5}$	0	$2.11\ 10^{-5}$

with Δt = 0.1 in the dedicated software environment described in Chap. 9. The outcomes at t = 3000 are shown in Table 7.3, and compared there to the equilibrium values from the analysis in Sect. 7.5.2. The deviation is in the order of 10^{-4} to 10^{-6}, which is fair and gives evidence that the implemented model is correct.

7.6 Discussion

In this chapter, a fourth-order reified network model was introduced to describe different orders of adaptivity found in a case study on evolutionary processes; e.g., Fessler et al. (2005, 2015), Jones et al. (2005), Fleischman and Fessler (2011). The network model describes how the causal pathways for newly developed features in this case study affect the causal pathways of already existing features, which makes the pathways of these new features one order of adaptivity higher than the existing ones, as they adapt the previous adaptation. The network reification approach has shown to be an adequate means to model this in a transparent manner. In future research, it can be explored how the network model introduced here can be extended and whether this also works for other evolutionary case studies. For more literature, see, for example, Aarøe et al. (2017), Curtis et al. (2011), Fleischman and Fessler (2018), Jones et al. (2017), Lieberman et al. (2018), Oaten et al. (2009), Schaller and Park (2011), Schaller (2016), Tybur and Lieberman (2016).

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