Fostering students' systems thinking in secondary biology education

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Table of contents

“When you have seen one ant, one bird,
one tree, you have not seen them all.”

- E. O. Wilson -

Chapter 1

General introduction

A world of systems

A crowd of people, a flock of birds, the vascular system, a thermostat, the solar system, a nature reserve, a computer; these are all examples of systems and come in all types of shapes and forms. The meaning of the term 'system' can be understood by its origin in the Greek language; the noun σύστημα (sústēma) means "whole made of several parts or members" and the verb συνίστημι (sunístēmi) means "I place together, associate, unite". So, systems are representations of parts of our reality defined by people. Despite the enormous range of types of systems, there are great similarities in the way scientists describe them: all systems consist of components, the interactions of which lead to new, emergent, properties at the system level that are not present in the individual components. The word 'emergence' has its origin in Latin: the verb emergere means "bring forth, bring to light, arise out or up, come forth, come up, come out, rise". An example of emergent behaviour that you can experience yourself is when you become part of an enthusiastic crowd of people, cheering or 'doing the wave' for the same sports team or artist. Thousands of people come together at events to feel this thrill. While the spectators mostly do not know each other, the crowd naturally assembles as a group due to many individual interactions. The spectators react as one group to the actions that take place on stage or on the field. Another observable emergent property is the movement of flocks of birds, swarms of insects and schools of fish. Collective motion of a large number of autonomous entities emerges because each of the components follows a few simple individual rules: it looks as though a super-organism has emerged.

Systems thinking and its importance

Systems thinking is the ability to gain understanding of systems by analysing how the different parts of a system interrelate and how a system itself works within the context of larger systems. This way of thinking is important to make sense of the increasingly complex world around us. Complex problems cannot be solved by linear thinking. Change in one of the components affects various other components, often in unexpected ways. Therefore, it is important to take a systems perspective, in which systems are seen as whole entities that show emergent properties that can be explained by identifying the underlying interrelationships between the system components. Each of the system components is itself a (sub)system which has the same type of characteristics as the entire system.

Systems thinking in education

Education plays an important role in fostering students' systems thinking (Tripto, Ben-Zvi Assaraf, Snapir, & Amit, 2017). In the Netherlands, systems thinking has been included as a domain-specific skill in the examination requirements for secondary biology education (Boersma, Kamp, van den Oever, & Schalk, 2010). In the American Next Generation Science Standards (NGSS), systems thinking is known as a crosscutting concept that is applicable across all science domains (NGSS Lead States, 2013). Knowledge of the basic principles of systems enables transfer and cross-fertilization between disciplines (Fisher, 2018; Goldstone & Wilensky, 2008; Yoon et al., 2017). For example, knowledge of the principle of negative feedback in one system can promote understanding of feedback in other systems in other contexts as well (Snapir, Eberbach, Ben-Zvi Assaraf, Hmelo-Silver, & Tripto, 2017).

In this dissertation, the focus is on the development of students' systems thinking in secondary biology education. Historically, biology has been divided into many specialised fields, such as microbiology, ecology, evolution, genetics, and so on. Since 2000, some biologists have tried to gather knowledge from these different specialised fields to understand complex biological systems as wholes. This up-and-coming multidisciplinary field is called *systems biology* (Ideker, Galitski, & Hood, 2001; Kitano, 2001). Systems biologists try to explain how biological properties emerge from the dynamic interactions of genes, proteins, molecules, cells and organisms by using experimental data, mathematical models and computational simulations (Cvijovic et al., 2016). Education could benefit from the insights of systems biologists by embedding a systems perspective in current secondary biology education, in which students learn how biological properties emerge from the interactions between system components.

Traditional textbooks for secondary biology education present biology topics in separate chapters, addressing cells, food and digestion, ecology, and so on. Several studies (Sorgo & Siling, 2017; Verhoeff, Waarlo, & Boersma, 2008) have determined that this fragmented presentation of biology does not lead to students' development of a coherent understanding of biology, although such an understanding is important for understanding the complexity of life. A core set of characteristics can be used as a lens to explain and predict complex natural phenomena from a systems perspective and thereby develop a coherent and scientifically based view of life (NGSS Lead States, 2013; Verhoeff, Knippels, Gilissen, & Boersma, 2018).

Defining systems thinking

The question remains what essential characteristics are involved in understanding of biology from a systems perspective. Comparison of systems thinking definitions used in the educational research literature shows that researchers have emphasized different system characteristics. These differences are due to explicit or implicit reference to the systems theories in the field of biology, where systems thinking originally originated from General Systems Theory (GST), Dynamical Systems Theories (DST) and Cybernetics (Boersma, Waarlo, & Klaassen, 2011). These three systems theories offer different perspectives on systems. GST, introduced by Ludwig Von Bertalanffy (1968), focuses on the hierarchical structure of systems in terms of the system components and their relations. Any system is itself also part of a bigger system, but can also be divided in smaller (sub)systems. DST, or chaos theory, focuses more on non-linear processes (Prigogine & Stengers, 1984).

Living systems are open systems and maintain themselves through the continuous exchange of matter, information and energy with the surrounding environment. Moreover, they change over time through ontogenetic and evolutionary influences. Cybernetics, introduced by Norbert Wiener (1948), focuses on the regulation of systems by feedback loops. Some system components can form a control loop, in which the effects of a change affect the actual cause (Von Bertalanffy, 1968). While positive feedback loops enhance the effect of a change in a system, negative feedback loops seek to reduce the effect of changes.

Integral approach to fostering students' systems thinking

Once the essential characteristics that apply to biological systems are clear, the next question is how these characteristics can be used to foster students' understanding of a wide range of biology topics. Several researchers have designed and evaluated teaching and learning approaches to implementing systems thinking for specific biology topics, such as cell biology (Verhoeff et al., 2008), physiology (Ben-Zvi Assaraf, Dodick, & Tripto, 2013; Snapir et al., 2017; Wellmanns & Schmiemann, 2020) and ecology (Mambrey, Schreiber, & Schmiemann, 2020; Westra, Boersma, Waarlo, & Savelsbergh, 2007). There is potential for an integral pedagogy that provides guidelines for teachers to use when incorporating systems thinking in their regular biology lessons for a wide range of biology contexts.

Main aims and research question

The main aims of this dissertation are: (1) to identify important elements of systems thinking for secondary biology education and (2) to describe an integral approach to fostering students' systems thinking in secondary biology education. The research question is:

> *How can students' systems thinking be fostered within secondary biology education?*

Methodological framework

Participants

In order to sustainably bridge the gap between the scientific field of biology and current secondary biology education, the following stakeholders were involved: systems biologists, teacher educators, pre-service and in-service teachers and secondary school students. Systems biologists work in the research field of systems biology and were involved in this study to help us to develop a better understanding of systems thinking in relation to biology education. Teacher educators and biology teachers (the educational practitioners) were involved to determine what they already knew about systems thinking and to what extent they paid attention to it in their own instruction. Teachers were also involved in the design process because of their practical expertise in biology education. Finally, students (15–16 years old) in senior general secondary education (in Dutch: 4 havo) were involved to determine the effect of the teaching and learning approach that was designed.

Lesson study

In this dissertation, lesson study (LS) was employed as the main research method used to design and evaluate lessons aiming to foster students' systems thinking.

LS (Murata, 2011) consists of several steps in which a team of teachers, and in our case also researchers, collaboratively design, enact and evaluate a lesson. When a designed lesson was taught by one of the teachers, the other LS team members observed specific students, using an observation schedule. These observation notes and students' worksheets were used as input to redesign the lesson, after which the adjusted lesson was enacted in a different class by another teacher from the LS team. The role of the teachers was to formulate student learning goals, determine teaching and learning activities to achieve these goals, choose students who should be observed during the lessons by the observers and teach the lessons. The role of the researchers was to chair the LS meetings, introduce the teachers to relevant educational research literature on systems thinking, discuss the lesson design, summarize the meetings, and elaborate on the educational materials.

While LS had its origin in Japan, nowadays it is practiced in schools all over the world, and a whole new research community is arisen around LS (Fernandez & Yoshida, 2004; Hart, Alston, & Murata, 2011). For instance, since 2007, the annual World Association of Lesson Studies (WALS) conference is held to share experiences regarding LS. This approach is often used in the context of teacher professional development (Lewis, Perry, & Murata, 2006), but because of the cyclic nature, LS can be seen as a form of Design Research and can therefore be used for research purposes as well (Bakker, 2018). LS offers opportunities as a research method, as the close observation of students during the lessons and analysis of student products gives in-depth insight into students' learning. Moreover, LS plays an important role in bridging the gap between research and educational practice because of the close interplay between researchers, teachers and students.

Dissertation outline

Chapters 2 to 5 describe three different phases of our investigation: (1) Define systems thinking for secondary biology education; (2) Design lessons in order to come to design guidelines for fostering students' systems thinking; (3) Validate the applicability of the design guidelines by educational practitioners (Figure 1.1). These chapters have been or will be published as articles in scientific journals. Chapter 6 is the general conclusion and discussion related to the preceding studies. Each chapter addresses specific research questions (Table 1.1).

Chapter 2 presents a current state analysis of the perspectives of systems biologists, biology teacher educators and secondary biology teachers on systems thinking in biology education and how these perspectives can be related to three relevant systems theories (GST, Cybernetics and DST). This chapter also gives an overview of the main elements of systems thinking for secondary biology education (the first aim of this dissertation). Moreover, it describes to what extent systems thinking has found its way into current teaching practice, that is, university-level teacher training and secondary biology education.

Chapter 3 describes the first two LS cycles, in which two lessons were designed and evaluated in close collaboration with two teachers. The lessons were taught during one school year and led to guidelines for introducing students to systems thinking in upper secondary biology education. Lesson 1 focused on the application of eight system characteristics: *boundary, components, interactions, input and output, feedback, dynamics,* and *hierarchy*, with *emergence* as an overarching system characteristic. Lesson 2 focused on improving students' understanding of the characteristics of feedback and dynamics by their use of a qualitative modelling approach.

Chapter 4 describes the third and fourth LS cycles in which students were asked to visualize and reason about two complex problems. Lessons 3 and 4 led to guidelines to support students to visualize and reason about complex problems from a systems thinking perspective.

Chapter 5 reports about the validation by educational practitioners of the applicability of the guidelines developed in Chapter 4. The design guidelines were disseminated to pre- and in-service biology teachers and teacher educators in the context of a workshop. A description is given of how this workshop contributed to pre- and in-service biology teachers' systems thinking content knowledge and their efficacy for developing a lesson in which systems thinking is integrated. Moreover, biology teacher educators' content knowledge and pedagogical content knowledge related to teaching systems thinking are addressed.

Chapter 6 presents an overall conclusion and discussion related to the different studies, in terms of what systems thinking entails in the context of secondary biology education and how it can be fostered by teachers. Moreover, contributions, limitations and directions for further research are addressed.

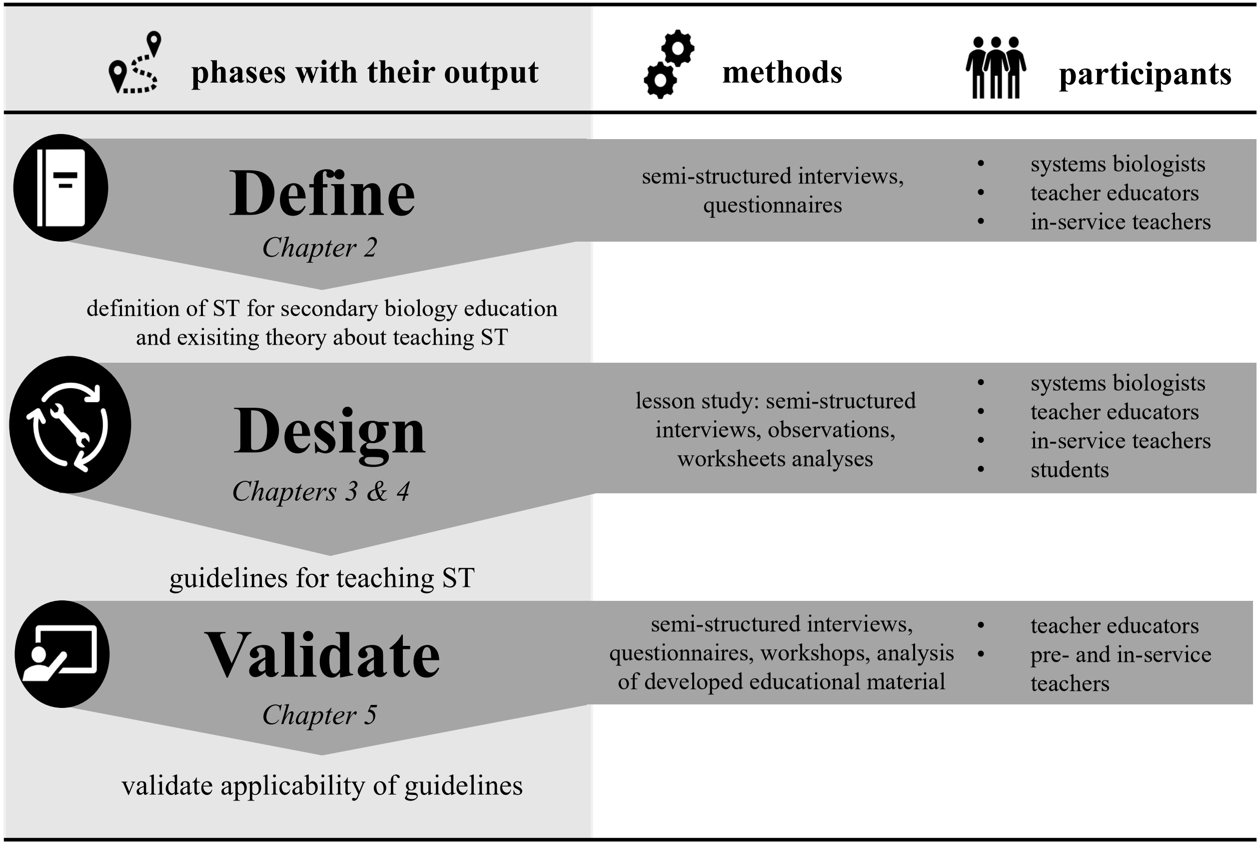

Figure 1.1. Research framework for fostering students' systems thinking (ST) in secondary biology education.

Table 1.1. Overview of the different studies presented in this dissertation.

Chapter	Title	Research question(s)
2	Teachers' and educators' perspectives on systems thinking and its implementation in Dutch biology education	*To what extent is the implementation of systems thinking in Dutch biology education in line with experts' perspectives on systems thinking, and with three systems theories?*
3	Bringing systems thinking into the classroom	*What design guidelines for introducing systems thinking emerged during the use of lesson study in a secondary biology classroom?*
4	Fostering students' understanding of complex biological systems	*(1) How do modelling activities, cross-level reasoning and systems language change students' understanding of complex biological systems?* *(2) To what extent do students experience systems thinking as a valuable approach to understanding biology?*
5	From empirical research to daily practice: embedding systems thinking in biology education	*To what extent does a teacher professional development activity on systems thinking in biology education, based on the design guidelines, contribute to:* • *pre- and in-service biology teachers' systems thinking content knowledge and their efficacy for developing a lesson in which systems thinking is integrated?* • *biology teacher educators' content knowledge and pedagogical content knowledge related to teaching systems thinking in university-level biology teacher training?*
6	General conclusion and discussion	*How can students' systems thinking be fostered within secondary biology education?*

Chapter 2

Teachers' and educators' perspectives on systems thinking and its implementation in Dutch biology education

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Abstract

Systems thinking, the ability to reason about systems in abstract terms, fosters students' coherent understanding of biology. This study aimed to determine to what extent the integration of systems thinking in Dutch biology education is in line with perspectives from systems theories and experts. We related the perspective on systems thinking of systems biologists (n = 7) to those of biology teachers (n = 8) and educators (n = 9). The resulting perspectives were interpreted in terms of three systems theories, General Systems Theories (GST), Dynamical Systems Theories (DST) and Cybernetics. Thirdly, we determined to what extent and how teachers and educators pay attention to systems thinking in their teaching practice. This was all done by the use of open-ended interviews and online questionnaires. The results show that the systems biologists and teacher educators involved implicitly refer to three systems theories, whereas the teachers refer to the GST and Cybernetics only. Despite this, the results suggest that the implementation of systems thinking in Dutch university teacher training and secondary biology education falls short of expectations. These outcomes underline the importance of teacher (educator) professional development on teaching systems thinking to bridge the gap between research and teaching practice.

Introduction

Biologists study living organisms varying from cells, plants, and human behaviour to ecosystems. To understand how these organisms function biologists switch constantly between different levels of biological organization, i.e., from the molecular to the ecosystem level and back (Knippels & Waarlo, 2018). Biologists are used to think within and between these levels of organization, are able to identify patterns, and to transfer their insights to other contexts, but for non-biologists, like students in secondary school, this is very challenging (Knippels & Waarlo, 2018; Ummels et al., 2015; Verhoeff et al., 2008).

For biology teachers it is essential to realize that biology comprises a specific way of thinking, and uses specific terminology to talk about biological phenomena and processes. These different biological topics are often taught as separate topics with limited integration, such as plant biology, respiration, endocrine regulation and ecology, which may lead to compartmentalized learning by students (Tripto, Ben-Zvi Assaraf, & Amit, 2013; Verhoeff, Boerwinkel, & Waarlo, 2009). Teachers have an important role in promoting and assisting students in developing a coherent conceptual understanding of biology and helping them to overcome this problem.

One approach that is suggested in literature to achieve a more coherent understanding of biology is called 'systems thinking'. This way of thinking can be described as the ability to reason about systems in abstract terms. The National Research Council (NRC, 2012, p. 84) identifies ‘systems and system models’ as a crosscutting concept, which focuses on “defining the system under study, specifying its boundaries and making explicit a model of that system”. Crosscutting concepts “help provide students with an organizational framework for connecting knowledge from the various disciplines into a coherent and scientifically based view of the world” (NRC, 2012, p. 83). Systems thinking as a crosscutting concept can be widely applied in education, e.g., in geography (Cox, Elen, & Steegen, 2018; Rempfler & Uphues, 2012), sustainable development (Schuler, Fanta, Rosenkränzer, & Riess, 2018), chemistry (Hrin, Milenković, Segedinac, 2017), and biology (Tripto et al., 2013).

Systems thinking is especially important in biology education because it reflects biological reasoning: “being able to apply fundamental principles and rules to complex dynamic systems” (C. D. Wilson et al., 2006, p. 323). Focusing on systems thinking as one of the fundamental principles of biology may lead to an improvement of students’ coherent understanding (Verhoeff et al., 2008). Systems thinking can be used as a guiding principle within the various topics of the secondary biology curriculum in which the universal principles of biological systems play a central role: biological systems have a concrete or more abstract boundary, consist of components that interrelate with each other, have input and output, have self-regulating closed networks, are dynamic, are nested and have emergent properties (Boersma et al., 2011; Verhoeff et al., 2018).

The importance of systems thinking in biology education is also reflected by the number of studies that report on teaching and learning approaches to foster or assess students' systems thinking. For instance, Tripto et al. (2013) concluded that concept maps are an effective tool to provide a detailed picture of students' systems thinking development. Hmelo-Silver, Jordan, Eberbach, and Sinha (2017) showed that the use of a Components-Mechanisms-Phenomena (CMP) conceptual representation in combination with modelling practices in the context of ecosystems increases students' understanding of natural systems. The CMP representation supports students to think about the components (C) of a particular phenomenon (P) and how they interact to result in a specific mechanism (M) of the phenomenon. Riess & Mischo (2010) showed that students' systems thinking can be effectively promoted by dynamic computer simulations in combination with lessons which explicitly cover aspects of systems theory. Verhoeff et al. (2008) developed and tested a systems modelling teaching and learning strategy in the context of a cell as a system. The results support their assumption that modelling activities enable students to acquire a coherent understanding of biology. However, they also noticed that fostering students' systems thinking requires more effort than one series of lessons focused on one topic: modelling activitities should be used more frequently and within different biological topics (Verhoeff et al., 2009). The results of the aforementioned studies show that systems thinking should have a prominent place throughout the curriculum and raise the question of how an explicit teaching and learning pedagogy can be shaped.

However, the literature on systems thinking research is yet to show consensus on what systems thinking entails. Many researchers who report about systems thinking use their own model, including sub-skills, to describe systems thinking. Ben-Zvi Assaraf and Orion (2005) developed the Systems Thinking Hierarchical (STH) model. Hmelo-Silver et al. (2017) developed the Components-Mechanisms-Phenomenon (CMP) model, and Verhoeff et al. (2008) used a model derived from the General Systems Theory to describe systems thinking. Although all these models share some similarities, the differences can be attributed to references, explicit or implicit, to the key concepts of different systems theories, i.e., General Systems Theory (GST), Dynamical Systems Theories (DST) and Cybernetics (Boersma et al., 2011). Each systems theory has its own focus and related systems concepts (Table 2.1).

Table 2.1. Three systems theories, their focus and key concepts. The original table is with permission copied from Verhoeff et al. (2018)

Systems theory	Focus on	Key concepts
General Systems Theory (GST)	Hierarchical (nested) open systems	Identity, system boundary, level of organization, components, in- and output.
Dynamical Systems Theories (DST)	Complex self-organizing systems	Self-organization, emergence, nonlinearity, equilibrium states.
Cybernetics	Self-regulating closed networks	Feedback, self-regulation, equilibrium.

GST focuses on the hierarchical structure perspective (Von Bertalanffy, 1968), DST focuses on the dynamic perspective of biological systems (Prigogine & Stengers, 1984; Thelen & Smith, 1994), and Cybernetics focuses on the regulatory perspective (Wiener, 1948). According to Boersma et al. (2011) and Verhoeff et al. (2018) systems thinking should focus on the systems concepts of all three systems theories. Application of the systems concepts can be the basis for exploring and analysing complex biological phenomena as biological systems.

Overall, the importance of systems thinking is clear. However, there are many perspectives on what systems thinking implies, and there is no pedagogy that describes explicitly how systems thinking can be fostered by teachers within biology education. Nevertheless, in the Netherlands systems thinking has been included since 2010 as a domain-specific skill in the examination requirements for secondary biology education (Boersma et al., 2010, p. 33). The present study is a current state analysis of the perspectives of systems biologists, biology teacher educators and secondary biology teachers on systems thinking in biology education and how these can be related to the three systems theories, as well as the implementation of systems thinking in teaching practice.

So, the first aim of this study is therefore to determine the perspective of current systems biology experts on systems thinking in relation to biology education and to what extent the systems biologists' perspective matches the perspectives of biology teachers and educators and the three systems theories. The second aim is to determine to what extent systems thinking has found its way into teaching practice, i.e., university teacher training and secondary biology education.

The main research question is:

> *To what extent is the implementation of systems thinking in Dutch biology education in line with experts' perspectives on systems thinking, and with three systems theories?*

The following four sub-questions were addressed:

1) What should be the focus of systems thinking in relation to biology education according to systems biologists?

2) What does systems thinking in relation to biology education imply according to biology teacher educators and teachers?

3) To what extent are the perspectives of systems biologists, biology teacher educators and secondary biology teachers related to the three systems theories?

4) To what extent do biology teacher educators and secondary biology teachers pay attention to systems thinking in teaching practice?

Methods

Participants

Three groups of participants were involved in this study: systems biologists, teacher educators and biology teachers.

Systems biologists (n = 7; 2 females and 5 males) were selected from four Dutch universities. They are professor or PhD in the field of systems biology, and all have their own research specialism varying from synthetic biology, bioinformatics, computational developmental biology, medical systems biology to molecular systems biology. They all teach a course on systems biology at university level, but do not have a specific teacher educational background. They were involved as systems thinking experts to determine their perspective on systems thinking in relation to biology education.

Biology teacher educators and biology teachers were involved in this study to determine what they think systems thinking implies in biology education, and to investigate to what extent they pay attention to systems thinking in their teaching practice, respectively in university teacher training and upper-secondary education. In the Dutch teacher education system, teachers qualify through attending a teacher track in higher professional education or at university. In this study we involved biology teacher educators (n = 9; 4 females and 5 males) from all six university teacher training institutes in the Netherlands.

Attending the university teacher track results in a grade one teacher qualification; teachers are qualified to teach at all levels of secondary education. After lower-secondary education (13–15 years) students in the Netherlands have to choose whether they want biology as an examination subject or not in upper-secondary education (16–18 years). Biology teachers (n = 8; 2 females and 6 males) were selected from six Dutch schools, with the criterion that they have more than five years' experience in teaching upper-secondary biology education.

Data collection and analysis

Data were gathered by the use of interviews and an online questionnaire. To answer sub-question 1 and 2 open-ended face-to-face structured interviews were conducted with all participants. The main purpose of the interviews was to investigate what the participants understand by with systems thinking in relation to biology education. Based on the interviews, aspects of systems thinking were selected and these were used as input for the first part of an online questionnaire (Q-part 1) that was presented to all participants approximately three months after the interviews (Appendix 2.1). The purpose of Q-part 1 was to determine whether the systems biologists, teachers and educators confirmed the aspects that were selected from the interviews as important aspects of systems thinking (sub-question 1 and 2). To answer sub-question 3, the systems thinking aspects that had been taken from the interviews were compared and linked to the key concepts of the three systems theories (Table 2.1) to determine to which systems theories the participants implicitly or explicitly referred in their perspective on systems thinking in the questionnaire (sub-question 3). To answer sub-question 4 the teacher educators and teachers were asked in the second part of the online questionnaire (Q-part 2) to indicate to what extent and how they pay attention to these aspects of systems thinking in their own teaching practice.

Open-ended interviews

The main question of the interview was: What is your perspective on systems thinking in relation to biology education? The participants were asked to elaborate on this question. If a teacher educator or teacher did not know what was meant by systems thinking the definition that is included in the biology examination requirements was shown (Boersma et al., 2010, p. 33):

> *Within different contexts a student is able to make a distinction between different levels of organization, elaborate on relationships within and between levels of organization and explain how biological units at different levels of organization can maintain and develop themselves.*

The participants were asked to elaborate on this description. In the interviews with teacher educators and teachers the following question was asked: "Can you provide some concrete examples from your own teaching practice where you pay attention to (aspects of) systems thinking?”. The interviews were conducted in Dutch (except one with a non-native systems biologist), audio recorded, and lasted between 30 and 75 minutes. Audio recordings were transcribed verbatim; the text fragments used in this article were translated into English by the first author and were revised with the help of a native speaker. Data-analysis started by selecting the text fragments in which participants articulated their view on systems thinking. The text fragments were categorised bottom-up using an inductive coding approach (Denscombe, 2014, pp. 106-121). Coding of the interview transcripts resulted in a coding scheme, which illustrates aspects of systems thinking. This coding scheme was used to code all transcripts. An external coder was provided with a codebook, which included the coding scheme and an example of a text fragment that was categorised using this code, and coded three of the 24 transcripts to determine the inter-rater reliability. Cohen’s kappa was .83, indicating that the coding procedure was reliable.

Online questionnaire

After analysing the transcripts of the interviews online questionnaires were administered. The questionnaire consisted of a part for all participants (Q-part 1), and a part for teacher educators and teachers only (Q-part 2) (Appendix 2.1). In Q-part 1, a description was given of the different aspects of systems thinking that had been extracted from the interviews. The participants had to indicate whether they considered each of these as an important aspect of systems thinking, and whether they missed any aspects. In Q-part 2, the teacher educators and teachers had to indicate on a five-point Likert scale to what extent they paid attention to the listed aspects in their own teaching practice. Additionally, they were asked to give concrete examples of teaching and learning activities in which they already pay attention to one or more aspects of systems thinking. One systems biologist and one teacher did not respond to the questionnaire. Their answers were not included in the data analysis of the questionnaire

Results

The first section below presents an overview of the systems biologists' perspective on systems thinking in relation to biology education (sub-question 1) and to the systems theories (sub-question 3). The second section presents the teacher educators' and teachers' perspective on systems thinking in biology education (sub-question 2) in relation to the three systems theories (sub-question 3). The third section presents to what extent teacher educators and teachers pay attention to systems thinking in their own teaching practice (sub-question 4). The original names of the participants have been replaced with letters and a number, i.e., systems biologists SB1-7, teacher educators TE1-9, and teachers T1-8.

Systems biologists' perspectives on systems thinking in relation to the three systems theories

Five different aspects of systems thinking were identified from the interviews: identify the system, input and output, emergence, development and modelling (Table 2.2). All systems biologists (6 out of 6) indicated each of the aspects as an important aspect of systems thinking in the questionnaire. The different aspects of systems thinking show overlap with key concepts of one or more systems theories (Table 2.2). GST focuses on the structure of a system, which includes drawing a systems boundary around the systems' components ('identify the system'). GST also includes that systems are open and exchange matter, energy and information with the environment ('input and output'), and relates to the hierarchy of a system ('emergence'). Cybernetics focuses on the regulatory perspective, which is included in 'input and output', i.e., the output has an effect on the input. DST focuses on the dynamics of systems, which includes the 'development' of biological systems and 'emergence'. The dynamic interactions between the systems' components result in emergent properties, which emerge at the system level and cannot be observed in the underlying levels. 'Modelling' can be categorised to all three systems theories, because each systems theory has its own theoretical systems model. In summary, the systems biologists involved in this study emphasize systems thinking aspects that can be found in all three systems theories.

Table 2.2. Five important aspects of systems thinking according to the systems biologists involved in this study. Column 1 presents the five aspects that had been extracted from the bottom-up coding approach. Column 2 gives a description of each of the codes. Colom 3 gives an example of a quote that was categorised to this aspect. Column 4 'systems theories' represents the linkage of an aspect with one or more systems theories. The C stands for Cybernetics.

Systems thinking aspects	**Description**	**Example of a quote**	**Systems theories**		
			GST	**C**	**DST**
Identify the system	Biological phenomena can be seen as systems: they can be distinguished from their environment with a boundary and they consist of different interacting components.	SB5: *When you investigate a system, you have to be able to identify the most important players.* […] *What are the most important players and what are the interactions between these players? So actually, being able to define a system and the players involved in the system is an important point.*	x		
Input and output	Biological systems are open systems; they interact with their environment. Matter, energy and/or information enter the system (input), then the system itself can be seen as a black box where all sorts of processes take place and after that, matter, energy and/or information comes out (output). Open systems are also self-	SB3: […] *and there is exchange across that boundary, because a sheep, for example, perceives things, there is heat exchange, it takes up nutrients, it excretes things, etcetera.*	x	x	

Systems thinking aspects	Description	Example of a quote	Systems theories		
			GST	C	DST
	regulating and dynamic. Most systems balance around a set point. With the aid of feedback mechanisms / control circuits, the system ensures that a deviating value is brought back to the set point. At the level of the cell and the organism, this process is called homeostasis.				
Emergence	The components of a system work together to achieve a certain goal or function at a higher organizational level. This is called emergence. To be able to explain this phenomenon, you have to descend to the underlying levels or ascend from the parts to the top. This is also called yo-yo strategy or vertical coherence.	SB2: […] *trying to understand the system based on the components and their interactions. Thus, the properties of the components and their interactions. Therefore, it has a lot to do with emergent properties that cannot be seen in the individual components. It is when they start interacting that you suddenly see* [a new] *behaviour.*	x		x
Development	A system has a certain development, e.g., in terms of developmental biology (how does an individual develop during his life) or in terms of evolution.	*SB4: For example, the state of a system may depend on the history. You may take a certain route on the way there, but that you should do something different on the way back. It is not all the same.*			x

Systems thinking aspects	Description	Example of a quote	Systems theories		
			GST	C	DST
Modelling	A quantitative computational model or qualitative model in which a biological system is visualized or where predictions about the system can be made.	SB6: *The entire network is branched and it becomes too complex and therefore you need mathematical techniques, or at least modelling* […]. *You need a systematic method to write everything down and to indicate the interactions, because that is too complex for the human mind. So, they* [students] *need mathematics in order to be able to model.*	x	x	x

Teacher educators' and teachers' perspectives on systems thinking in relation to the three systems theories

Interesting to note is that six out of eight teachers did not know what was meant with systems thinking in biology education or only could give a brief definition, so they had to be introduced to the definition that is included in the biology examination requirements. One teacher educator mentioned that he finds it very difficult to describe what systems thinking exactly implies in terms of learning goals. TE1: "That is what I find difficult when you are going to work with that skill [systems thinking]; what should students be able to do in terms of systems thinking?" Table 2.3 presents the number of teachers and educators who indicate a specific aspect as an important aspect of systems thinking in the questionnaire.

Table 2.3. Overview of the results from the questionnaires, displaying the number of participants that indicated a specific aspect as important in the questionnaire as well as whether they apply the specific aspect regularly or more often in their teaching practice.

	Indicated as important		Indicated as applied in teaching	
Systems thinking aspects	**Teacher Educators**	**Teachers**	**Teacher Educators**	**Teachers**
Identify the system	5/9	7/7	2/9	5/7
Input and output	8/9	7/7	3/9	6/7
Emergence	9/9	6/7	5/9	4/7
Development	8/9	4/7	4/9	3/7
Modelling	8/9	5/7	5/9	3/7

Teacher educators

The teacher educators indicated that they thought most of the aspects that are included in the three systems theories were important. There was only a small difference in opinion concerning the aspect 'identify the system' of the GST. A possible explanation for this is that some teacher educators do not think it is important to use the word 'system' or 'boundary' explicitly in teaching practice and therefore did not indicate 'identify the system' as important TE6, for example explains systems thinking in terms of identification of the system, emergence, and input and output, but he not directly would use the word system in practice:

> *I see systems thinking as a specific form of thinking in biology in which you can view the parts of an organism as a system. A cell, or an organism or an organ or an ecosystem.* [...] *In other words, where you try to teach students to find all kinds of relationships within the system. You also try to place the system in relation to the environment and of course between systems on different organizational levels. Then you use the yo-yo strategy to make connections between different systems. From a disease* [organismal level] *you often, for example, go to the genes* [molecular level] *and along the way you pass the organs* [organ level] *and cells* [cellular level] *and switch back to the disease* [organismal level] *again. So you could say it* [systems thinking] *is thinking from big to small or going back and forth from big to small and from small to big. And also that a system is not closed: something goes in and something goes out. That is also something that is characteristic to a system,* ***while I would not directly use the word system in the classroom.***

Most of the teacher educators saw modelling as an important aspect of systems thinking. They identified modelling as a tool to visualize biological systems, which can be done quantitatively or qualitatively. TE7:

> *I think that models are very important. So to be able to model.* [...] *It does not necessarily have to be a computer model, but the visualization of the processes is important. BINAS [*textbook with science images that is used by students in secondary education] *is of course full of all kinds of diagrams and images of processes that are invisible to the naked eye, but it is difficult for students to comprehend these diagrams and images. I think it is very important that they physically construct and understand these visualizations in a broad perspective, from diagrams and graphs, but also making stop-motion videos of meiosis or something else.*

Biology teachers

The biology teachers mostly emphasized the systems concepts of the GST and Cybernetics focusing on the structure and regulation of biological systems. Interestingly, in the interviews none of the teachers explicitly mentioned finding it important that students should be able to identify the system of interest. T3 addresses this:

> *What I find important for students to know is that everything influences each other. If they see it as a system or not, that does not really interest me. They probably do not see it as a*

> *system. However, I think it is important that they realize that it all reacts to each other and interacts with each other and has an influence on each other, and that this happens on all levels.*

No examples of quotes about ‘input and output’ can be found in the interviews with teachers, while all teachers indicate this as an important aspect in the questionnaire. Four teachers indicated ‘development’ as an important aspect in the questionnaire, but during the interviews none of the teachers mentioned the development of biological systems. Almost all teachers indicated modelling, qualitative or quantitative, as an important aspect of systems thinking to visualize biological systems. T4 explains that thinking in models can be used to understand systems:

> *That students get to know that through thinking in models, as I call it, you try to give the best possible explanation for what happens in an ecosystem. That system, that model that you have formed or the way you now think about it could be better, but that requires more research, more measurements and more time. So it is the best explanation for now.*

Missing aspects

Additionally, we asked the participants whether they missed an aspect of systems thinking in our interpretation of the interviews into five different aspects of systems thinking (Question 2 in Appendix 2.1). The participants did not come up with new aspects, only with suggestions for small adjustments. For example, TE7 and TE8 both recommended to split 'input and output' into two aspects. TE8: "I think that you could split up the first category ['input and output'], especially because thinking in feedback loops is such an important part of the biology curriculum." In retrospect, this might have been better, especially because it would have been easier to determine how many participants relate systems thinking to Cybernetics. We now also think it would have been better to rename the aspect 'development' as 'dynamics', because that fits the description of the aspect and the DST better.

Implementation of systems thinking in teaching practice

Table 2.3 shows the number of teacher educators and teachers who indicated paying attention to systems thinking aspects regularly or often.

University teacher training

During the interviews seven of the nine teacher educators mentioned that they briefly introduce systems thinking in teacher training as an educational approach. TE3 and TE9 mentioned they do not use the term 'systems thinking' explicitly. TE9:

> *Definitely. I now notice that I do not always refer to it as systems thinking. I am paying attention to the different levels of organization, emergent properties and make the importance*

> *of this clear for students. However, I find the term or concept 'systems thinking' confusing because it is not always used in the same way in literature. In my opinion this term does not add something to student understanding.*

According to the teacher educators there is not enough time to extensively elaborate on systems thinking. TE2:

> *We do not have time for something complex like concept-context education, let alone for systems thinking.* [...] *Systems thinking is not a skill that you can teach within a month. It is something that should get attention through the whole year and it should be done gradually.*

Therefore, while most teacher educators only inform the pre-service teachers about systems thinking, they do not aspire to enable them to implement it in practice directly. TE4: "I see this [pedagogical] part of the teacher training also partly as planting seeds that I hope will grow over the coming years." The seven teacher educators who introduce systems thinking give their students an assignment to design a set of lessons that foster students' systems thinking. It is remarkable that the teacher educators themselves conclude that the products of students, who have chosen for the elaboration on systems thinking, mostly focus on switching between different levels of organization ('yo-yo strategy'), and not on other aspects of systems thinking. The results from the questionnaire show that five of the nine teacher educators regularly or often pay attention to 'emergence', so this may explain the focus on the levels of organization by students. The results also show that four of the nine teacher educators regularly or often pay attention to modelling, but from the examples that are given it seems that they do not pay attention to 'modelling' in the context of systems thinking specifically. TE7:

> *I am not using models explicitly in the context of systems thinking, but I do pay a lot of attention to the use of models. Systems thinking is actually so implicit in many aspects of biology, and thus in modelling, therefore it* [modelling] *is a form of systems thinking.*

Upper-secondary biology education

Most teachers, five of the seven, indicate they pay attention regularly or often to 'identify the system' (Table 2.3). T6 gives an example of how he pays attention to this aspect: "As an introduction to ecosystems. I use various slides with examples of 'typical' ecosystems. What are characteristic (a)biotic factors? Where do they differ from other ecosystems?" Several teachers provide examples of topics where they pay attention to the aspect 'input and output'. T7: "For example the nitrogen cycle where we will follow the route of nitrogen into the human body." T4:

> *Blood pressure control, respiratory rate, blood sugar level,* [and] *body temperature, are good examples of systems where the input is interpreted by the different sensors in the control*

> *system, compared to set values and* [then] *an output is caused by effectors.*

T6: “Dissimilation. What goes into the cell, and what goes out of it to make (an)aerobic dissimilation possible?” Four teachers regularly or more often address the aspect ‘emergence’, and provide examples of topics where they pay attention to this aspect. T1: “Cooperation between the vascular system and the respiratory system for better sport performances.” T6: “Immune response (specific). White blood cells (cellular level) work together to keep of an individual healthy (organismal level).” T7: ‘For example, when we talk about form and function, how the [form of the] beak of a bird originates from DNA, via cells and tissues.” The aspect ‘development’ receives less attention from the teachers in this study (Table 2.3). It is striking that only one teacher, T4, tries to teach several biological concepts throughout the year from an evolutionary perspective, and refers to Dobzhansky (1973, p. 125) “Nothing in biology makes sense, except in the light of evolution”. Two teachers indicate that they pay attention to ‘development’, but only mention examples that are directly linked to the topics embryonic development or evolution and do not introduce this aspect in other biological topics. Three of the seven teachers indicate that they regularly or often pay attention to the aspect ‘modelling’ (Table 2.3). T4 mentions that he would like to make more use of modelling in his teaching practice, especially the use of dynamic models and that students should be able to design or adjust a model of a biological phenomenon, but that they do not have such programs and/or facilities at their school. T7 uses IP-Coach, a computer modelling program, when he is teaching ecology. All teachers point out that they teach students to visualize biological phenomena and interpret existing pictures, diagrams, and figures.

Conclusion and discussion

This article started by articulating the importance of systems thinking for biology education, but also raised questions about what systems thinking exactly implies and how it has been integrated in biology education since 2010. The main research question was:

> *To what extent is the implementation of systems thinking in Dutch biology education in line with experts' perspective on systems thinking, and three systems theories?*

According to the systems biologists in this study, current secondary biology education should address the investigation of the universal characteristics of biological systems by students: identification of the system, input and output, emergent properties and the development of systems over time. Moreover, attention should be paid to modelling, such as visualizing biological phenomena into systems models, but also predicting of systems behaviour through the use of models. In this expert perspective on systems thinking we identified implicit links to the three systems theories (Table 2.2). The systems biologists' perspective is in line with Boersma et al. (2011) and Verhoeff et al. (2018) who argued that the systems concepts of the three systems theories should be the focus of students' conceptual development. In comparison, we identified the same implicit links to the three systems theories in the perspective of the teacher educators of six different teacher training institutes, whereas we identified only implicit links to the GST and Cybernetics in the perspective of the teachers who were involved in this study. Although the involved teacher educators refer implicitly to all three systems theories, it seems that they pay limited attention to systems thinking in their practice because they "do not have time for something complex". The results show that teachers rarely include systems thinking in their teaching practice, and when they do this, it is mostly done implicitly.

In conclusion, the perspectives of teachers and educators are mostly in line with those of the systems biologists and with the three systems theories. However, the corresponding systems thinking aspects appear to be not fully implemented in the teaching practice of these teachers and educators. Though the present study is a qualitative approach with a limited number of participants the results indicate that systems thinking in Dutch (pre-service and secondary) biology education does still need more attention. This is regrettable because systems thinking can promote an integrated view on biology as a science, which is important as biology covers living system at many different levels and from many perspectives (e.g., Knippels & Waarlo, 2018).

For a more fruitful and sustainable future implementation of systems thinking in biology education, we suspect that both teacher educators and teachers should be involved in training activities to learn more about systems thinking and its implementation in biology education to eventually foster students' systems thinking as a crosscutting concept. The outcomes of this study underline the importance of current and future studies on professional development for teachers in relation to teaching systems thinking (e.g., Rosenkränzer, Hörsch, Schuler, & Riess, 2017; Rosenkränzer, Kramer, Hörsch, Schuler, & Riess, 2016; Schuler et al., 2018; Yoon et al., 2017). For example, Yoon et al. (2017) studied what type of professional development support teachers need to teach about complex systems in education. Moreover, the results emphasize the need for more research on bridging the gap between research, curriculum development, university teacher training and educational practice. A next step in our research will be to involve teachers and educators in the process of developing and testing teaching and learning material to create insight into how to shape an explicit teaching and learning pedagogy to foster students' systems thinking within biology education.

Chapter 3

Bringing systems thinking into the classroom

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Abstract

Systems thinking is the ability to reason about biological systems in terms of their characteristics and can assist students in developing a coherent understanding of biology. Literature reports about several recommendations regarding teaching systems thinking, while it seems that systems thinking has not reached classroom practice. The main aim of this study was to identify design guidelines to implement systems thinking in upper-secondary biology education. Based on the recommendations of literature and experience a teacher team developed, tested and evaluated two lessons in two upper-secondary biology classes (15–16 years old students, n = 26, n = 19) using lesson study. Lesson 1 focused on the application of seven of the eight system characteristics: boundary, components, interactions, input & output, feedback, dynamics, and hierarchy. Lesson 2 focused on the improvement of students' understanding of the characteristics feedback and dynamics by using a qualitative modelling approach. Based on classroom observations, student products and interviews, the results suggest that a first step is made: most students are able to name and apply the seven system characteristics. It seems important to pay attention to the: (1) introduction of the seven characteristics; (2) application of the characteristics in a wide variety of contexts; (3) individual characteristics; (4) explicit use of system language.

Introduction

Systems thinking or (complex) system learning has recently received a lot of attention in science education research. According to Yoon, Goh, and Park (2018) the emphasis on systems thinking started after publication of the Benchmarks for Scientific Literacy in 1993 (American Association for the Advancement of Science, 1993). Since then, systems thinking has been included in many curriculums internationally. For example, the Next Generation Science Standards (NGSS) includes the crosscutting concept 'systems and system models' which focuses on defining systems, specifying their boundaries and using models (NGSS Lead States, 2013).

Science education researchers work towards teaching and learning approaches that foster students' systems thinking in various science education fields, from earth science (Ben-Zvi Assaraf, & Orion, 2005), geography (Cox et al., 2018), sustainable development (Molderez, & Ceulemans, 2018), chemistry (Hrin et al., 2017) to biology (Ben-Zvi Assaraf et al., 2013). The current study focuses on systems thinking in biology education.

Defining systems thinking

Even though most studies (e.g., Hmelo-Silver, Marathe, & Liu, 2007; Raved, & Yarden, 2014; Verhoeff et al., 2008) claim that systems thinking can improve students' coherent understanding of biology, different definitions have been used to describe systems thinking varying from basic to elaborated definitions. The National Research Council (NRC, 2010, pp. 63–64) defined systems thinking as:

> *the ability to understand how an entire system works, how an action, change, or malfunction in one part of the system affects the rest of the system; adopting a 'big picture' perspective on work. It includes judgment and decision-making; system analysis; and systems evaluation as well as abstract reasoning about how the different elements of a work process interact.*

Evagorou, Korfiatis, Nicolaou and Constantinou (2009, p. 655) describe systems thinking as "the ability to understand and interpret complex systems." Ben-Zvi Assaraf and Orion (2005) developed a Systems Thinking Hierarchical (STH) model that reflects their definition of systems thinking. This model is built on four levels of a sequential growth of levels of systems thinking, which include the ability to: 1) identify the system components and processes; 2) identify relationships between separate components and the ability to identify dynamic relationships between the system components; 3) understand the cyclic nature of systems and organize components and place them within a network of relationships, and make generalizations; 4) understand the hidden components of the system and the system evolution in time (prediction and retrospection). Ben-Zvi Assaraf and Orion indicate that each group of skills should serve as the basis for the development of the next higher group of skills. Based on experts' way of thinking about complex systems, Liu and Hmelo-Silver (2009) describe systems thinking in terms of structure, behaviour and function. Structure represents the system components and the relations between them. Behaviour represents the dynamic interactions between the system components and existing mechanisms in the system. Function represents the essence of the system and its components. Breaking down complex systems into structure, behaviour and function (SBF) can assist students to understand complex systems. Later on, this SBF model is refined into the Components-Mechanisms-Phenomena (CMP) conceptual representation (Hmelo-Silver et al., 2017). This representation supports students to think about the components (C) of a particular phenomenon (P) and how they interact to result in a specific mechanism (M) of the phenomenon. Sommer and Lücken (2010) describe systems thinking as the ability to identify and describe the structure of a system and the ability to understand its operating principles. They operationalized different system characteristics (i.e., elements, relationships, identify, integrity/emergence, dynamics, effects) into abilities regarding modelling and dealing with system properties.

As illustrated, there are many different descriptions of systems thinking (abilities). According to Boersma et al. (2011) this is due to the implicit or explicit emphasis on the key concepts of one or more systems theories that systems thinking was originally derived from, i.e., General Systems Theory (GST), Dynamical Systems Theories (DST) and

Cybernetics. Each of these theories focuses on a different perspective of (biological) systems, i.e., their hierarchical structure (GST), dynamic behaviour of systems (DST) and self-regulation (Cybernetics).

In a previous study (Gilissen, Knippels, Verhoeff, & van Joolingen, 2020), the perspectives of current systems biology experts were studied in the light of these three systems theories. This study led to a description of systems thinking in terms of the system characteristics as summarized in Table 3.1. In addition, one overarching system characteristic can be identified – i.e., emergence – which can be described as: "The whole is more than the sum of its part" (Aristotle). Systems have properties which emerge from the interactions between the components of the system, but do not belong to any part of that system. For example, a single ant cannot accomplish complex tasks, but a group of collaborating ants, an ant colony, is able to build hills and move huge amounts of food. In our view, emergence also reflects the combination of the seven system characteristics to understand a system as a whole and thus can be seen as an overarching eighth system characteristic.

In this chapter we use the following definition of systems thinking: the ability to reason about biological phenomena in terms of system characteristics to create a more coherent understanding of biology as a whole.

Table 3.1. Summary of the three systems theories in terms of eight system characteristics. This table is based on the system theoretical concepts of three systems theories described by Boersma et al. (2011) and the input from systems biologists and biology teacher educators in a previous study (Gilissen, Knippels, Verhoeff, & van Joolingen, 2020).

System characteristics		Systems theory			Description
		GST	C	DST	
Emergence: Behaviour or properties that arise on the systems level caused by the interactions of the system components	Boundary	x			A system can be identified by determining the system boundary.
	Hierarchy	x			A system consists of partial systems, but is also a partial system in a higher-order system itself. The different (partial) systems can be categorised at the different levels of biological organization, i.e., from molecular to the biosphere level.
	Components	x	x	x	Biological systems consist of different components which play a role in (partial) system(s).
	Interactions	x	x	x	The different system components interact with each other.
	Input output	x	x	x	Biological systems are open systems which exchange matter, energy and/or information with the environment.
	Feedback		x		Systems are self-regulating. Some of the system components form a control loop. Negative feedback loops tend to reduce the fluctuations in the input, whether caused by changes in the input or by other disturbances. Positive feedback loops increase the effect of a disturbance in a system.
	Dynamics			x	The input and output of a system can change (regularly) over time (seconds, minutes, hours, days, months, years).

Recommendations from literature

In literature, several recommendations are given on how to support students' systems thinking. Verhoeff et al. (2018) indicate that a trajectory targeting the development of a complete system concept by students should include the characteristics of all three systems theories. These characteristics can be used as a metacognitive tool for students to acquire more understanding of biological phenomena. Attention should be paid to the step from empirically observable phenomena to a systems theoretical conceptualization of such phenomena from the three perspectives. They suggest that it is possible to start by approaching a biological phenomenon from one systems theoretical perspective, guided by conceptual representations or models like Verhoeff et al. (2008) did. Later on, other biological topics can be approached from a systems theoretical perspective also. Thereby, it is important that each of these topics are approached in such a way that they cover different levels of biological organization (Knippels, 2002; Knippels & Waarlo, 2018).

Because many system characteristics are defined as abstract entities, modelling, qualitatively or quantitatively, provides a way to make the invisible visible (Hmelo-Silver et al., 2007). Qualitative modelling approaches focus on representation of systems in a more abstract way showing some system characteristics (Verhoeff et al., 2008) and quantitative modelling approaches focus on the (mathematical) prediction of the system's behaviour (Wilensky & Reisman, 2006). In both modelling approaches the focus is on identifying the system components ('agents') and their interrelations ('actions'). Verhoeff et al. (2018) recommend qualitative modelling to develop an initial system concept. An example of a qualitative design approach is that of Hmelo, Holton, and Kolodner (2000) who taught students about the human respiratory system by designing artificial lungs and building partial working models.

Another recommendation that is given by several researchers (i.e., Hmelo-Silver et al., 2007; Jordan, Hmelo-Silver, Liu, & Gray, 2013; Tripto, Ben-Zvi Assaraf, Snapir & Amit, 2016; Tripto, Ben-Zvi Assaraf, & Amit, 2018; Westra, 2008) is to make use of explicit approaches and scaffolds to improve students' systems thinking and their use of system language. Tripto et al. (2016) interviewed students non-explicitly and explicitly with system language with the aim to encourage students to organize their knowledge. The results seem to indicate that the explicit system language interview questions encourage metacognitive thinking processes because students made more use of system language themselves. Our interpretation of these explicit approaches and scaffolds is that teachers use the system characteristics explicitly during teaching and learning activities to get students acquainted with the application of system language when reasoning about biological phenomena. This will lead to more abstract reasoning about systems by students which should make the transfer to other contexts easier.

In summary, several recommendations are given in literature on how to support students' systems thinking. Nonetheless, the results of a previous study (Gilissen, Knippels, Verhoeff, & van Joolingen, 2020) suggest that Dutch secondary biology teachers rarely include systems thinking in their teaching practice, while systems thinking has been included as a domain-specific skill in the curriculum for secondary biology education since 2010 (Boersma et al., 2010, p. 33). To improve the implementation of systems thinking in education teachers need to be supported to foster students' systems thinking. Literature provides recommendations regarding teaching systems thinking, but in our view, there seems to be a lack of an integral pedagogy that provides clear guidelines for teachers to implement systems thinking in their regular lessons. Therefore, the main aim of this study was to identify design guidelines to implement systems thinking in upper-secondary biology education by designing and evaluating a teaching and learning strategy, together with teachers, based on the recommendations from literature. The research question is:

> *What design guidelines for introducing systems thinking emerged during the use of lesson study in a secondary biology classroom?*

Methods

Overall research design

The lessons were designed in the context of two lesson study cycles. Lesson study (LS) is an approach in which a team of teachers (sometimes assisted by researchers) collaboratively designs, performs, observes, and evaluates a lesson (Fernandez & Yoshida, 2004; Hart et al., 2011). In observing the lesson, focus is on individual student learning. While LS is commonly used as a teacher professional development approach (Lewis et al., 2006), this approach also shares some features with design research and is nowadays also used for research purposes (Bakker, 2018; Gilissen, Knippels, & van Joolingen, 2021a; Jansen, Knippels, & van Joolingen, 2021). In this study LS is not primary used as a professional development approach, but as a research approach to gain new scientific knowledge about student learning, specifically regarding systems thinking in biology education. Student learning can be made visible with the LS approach because specific students are observed individually, student worksheets are analysed and interviews are conducted with individual students, for example to determine what they think they learned during the lesson, and to questioning them about specific events during the lesson. Another advantage of LS is the close involvement of teachers in the design and evaluation of the lessons.

In this study two LS cycles were performed. Each LS cycle consists of a series of steps. First, the team determines the student learning goals of a lesson and discussed which key activities could be used to achieve these goals. Second, the lesson is taught by the first teacher while the other three team members observe specific case students to determine the effect of key activities on student learning and whether they achieved the learning goals. Third, the lesson was evaluated and improved and taught a second time in another class by the second teacher. In total, we report on four different cases which are related: Lesson 1 in class 1 (1α), adjusted version of Lesson 1 in class 2 (1β), Lesson 2 in class 1 (2α), adjusted version of Lesson 2 in class 2 (2β).

Participants

Convenience sampling was used to select the participants for this study. Systems thinking is part of the national curriculum in The Netherlands, and therefore we have chosen to involve teachers and students of a general Dutch secondary school.

The LS team consisted of the first author, two teachers, and an observer. Julia (pseudonym), a woman, has a background in physiotherapy and has eight years of experience as secondary biology teacher. Frans (pseudonym), a man, has a background in tropical forestry and has ten years of experience as secondary biology teacher. The school facilitated their participation by reducing their workload for other tasks. The first author, a woman, has five years of experience as secondary biology teacher. She functioned as knowledgeable other (Takahashi, 2014) in the LS team: she chaired, prepared and summarized the meetings of the LS team. The school belongs to a school community in the eastern part of the Netherlands and offers senior general secondary education and pre-university education. During the lessons and the evaluation meetings the LS team was accompanied by an extra observer, i.e., the second or third author or a staff member of the school.

For each lesson, three case students (and three back-up students) were selected in each class. For the first lesson, it was not possible to select students on their average scores, since students did not have biology the previous year. Therefore, the selection was based on teachers' knowledge about student engagement during classroom activities, because the teachers did not have insight in students' capabilities in biology at the beginning of the schoolyear.

Case student A represented an obviously motivated and hard-working student, student B represented a quiet but hard-working student, and student C represented a passive student. For the second lesson, it was possible to make a selection based on students' average scores on the regular biology test that was conducted in the first period of the school year: case student A scored high on the insight and application questions, student B scored especially good on the application questions, student C scored especially good on the reproduction questions. Pseudonyms are used for the different case students (Table 3.2).

The 60-minute lessons were performed in two senior general secondary education biology classes (n = 26, n = 29, 15–16 years old students) during the first two months of the school year. The students who were present during both lessons and for whom parents provided informed consent were included in this study (class of Julia, n = 14 (7 girls and 7 boys), class of Frans, n = 19 (9 girls and 10 boys).

Table 3.2. Pseudonyms of the case students and teachers in Lesson 1 and 2.

Case student	Class 1	Class 2	Description
Lesson 1			
A	Arthur (male)	Anna (female)	obviously motivated and hard-working student
B	Belle (female)	Berit (female)	quiet but hard-working student
C	Chloe (female)	Cas (male)	a passive student
Lesson 2			
A	Amy (female)	Alain (male)	scored high on the insight and application questions
B	Bowe (male)	Boris (male)	scored especially good on the application questions
C	Coco (female)	Celia (female)	scored especially good on the reproduction questions
Teacher	Julia (female)	Frans (male)	

Note: The first letter of the case students' name represents which type of student they represent.

LS cycles

In Figure 3.1 an overview is given of the different steps that are taken in each of the two LS cycles. During a kick-off day, the first author informed the teachers about the workings of LS, and presented recommendations from literature about systems thinking in biology, which are described in the introduction. During this day, the LS team discussed about possible ways to implement systems thinking in biology education. In the three preparation meetings of LS cycle 1 (approximately 2 hours each), the team determined specific student learning goals for Lesson 1 and 2, discussed which key activities could be used to achieve this goal and designed the lesson with input from recommendations in literature and their own practice. The team selected three different case students to observe during the lessons. The team described the expected behaviour for each case student during each lesson activity in an observation schedule. Julia performed the designed lesson, while the other three members each observed a specific case student and described the behaviour in the observation schedule. After the lesson, the observers conducted a short interview (approximately 5 minutes) with the case students, e.g.:

- What have you learned this lesson?
- What did you value in this lesson?
- How can this lesson be improved?

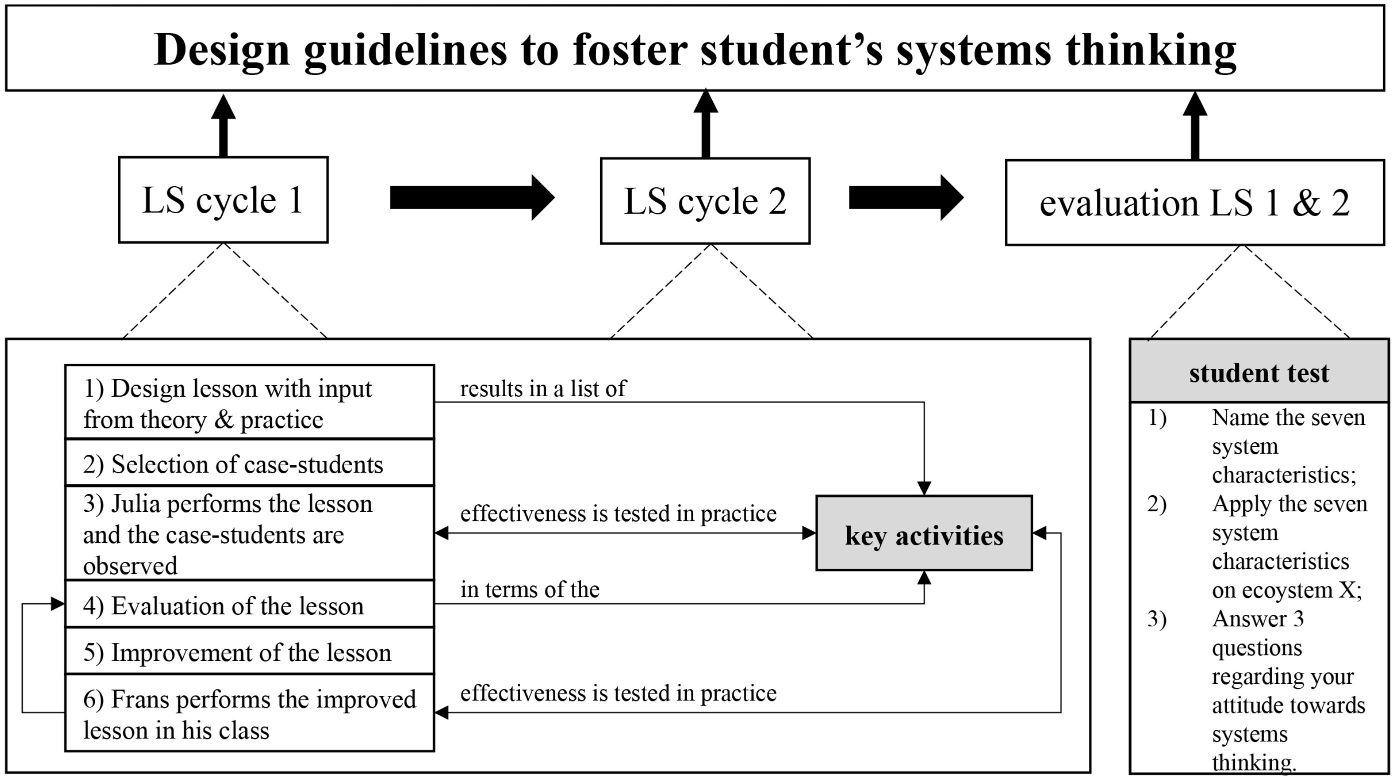


Figure 3.1. A representation of the outline of this study to arrive at design guidelines to foster students' systems thinking. During the two LS cycles different key activities are designed, tested and evaluated. By using the observation notes, student worksheets, post-lesson interviews, and the student test results the effectiveness of these key activities is determined which resulted in design guidelines to foster students' systems thinking.

In the post-lesson discussion (approximately 1 hour), the team evaluated and improved the lesson based on the observation notes from the lesson made by the observers, student answers on the worksheets, and the input from the case students during the interview. Frans performed the improved lesson in his class. During the post-lesson discussion of the improved lesson the team evaluated which key activities were crucial to achieve the student learning goal. Afterwards, aforementioned steps were repeated for the second LS cycle which consisted of four preparation meetings of approximately 2 hours each.

Evaluation LS cycles

After enactment of each of the two lessons the case students of both classes (n = 12) were interviewed individually (approximately 20 minutes) by the first author while the other students received the same questions on a paper-and-pencil test (Appendix 3.1). The aim of the interview and paper-and-pencil test was to determine to what extent the students achieved the learning goals in terms of naming and applying the characteristics, and therefore determine the effectiveness of the key activities (Figure 3.1). The students were asked to name the different system characteristics. Additionally, they received an image of ecosystem X, a pond with some plants and animals, and were asked to apply the system characteristics to this system. All students were asked to answer three additional questions:

- Do you experience systems thinking as important? Explain your answer.
- Do you use systems thinking by yourself? In what situation?
- How often and in which way does your teacher pay attention to systems thinking?

Data collection

Lesson 1 was performed in the first period of the school year (beginning of October 2019), and Lesson 2 in the second period (end of November 2019). The evaluation of the two cycles took place mid-December 2019. The designed and tested lessons consist of specific key activities to support students' systems thinking (Table 3.4). While repetition of the key activities took place in the regular biology lessons, this study focused on the lessons only. During this study, various data-sources were collected and processed with different purposes (Table 3.3).

Data analysis

This study focuses on student learning regarding systems thinking. We have tried to make a narrative of student learning during the different key activities in the two lessons. This could be done by finding indications for student learning in the different data-sources (Table 3.3):

- Based on the summaries of the audio-recorded LS meetings the first researcher identified which design choices have been made by the LS team. In the results section a description of these design choices is given which resulted in different key activities.

- The first author also checked the *fidelity of implementation*: did the teacher perform the lesson as intended (Bakker, 2018, pp. 82-83). The video recordings, in which the whole class situation is recorded, were compared with the lesson plan to determine whether the teacher implemented it as intended. In the results, we noted when a teacher deviated from the plan.

- The observers made notes of quotes and specific behaviour of individual case students during the different key activities. In the results section these observation notes have been used to demonstrate how students performed during the different key activities.

- Most key activities included a worksheet for students to write their answers down (Table 3.4 and 3.6). During the LS meetings answer sheets were developed to score student products. Using intersubjective agreement (Patton, 2003) the LS team scored the answers good or wrong. In the results section we report about the achievement of the learning goals by the (case) students.

- The post-lesson interviews with the case students were transcribed verbatim and are used to describe what improvements are proposed by the case students, and to determine what they have learned from the lesson. In the results section we use quotes to describe students' attitude and learning.

Table 3.3. Overview of the various data sources that were collected in this study.

Data source	**Processed**	**Purpose of collecting the data-source**
LS meetings	Audio-recorded and summarized	Identify design choices of the LS team based on implications from literature and/or practice
Video recordings lessons	Video-recorded	Determine fidelity of implementation by the teacher (Bakker, 2018)
Observation notes lessons	Transcribed	Determine learning progress of students during the different key activities
Student products of the lesson	Digitized and scored by the LS team using intersubjective agreement (Patton, 2003)	
Post-lesson interviews with case students	Audio-recorded and transcribed verbatim	Determine learning progress of students and identify ideas for improvement of the lesson which has been used as input for the design of the improved lesson
Paper-and-pencil test after LS cycle 1 and 2	Digitized and scored by the first author	Determine learning progress and attitude towards systems thinking of students, and to determine to what extent their teachers pay attention to systems thinking in classroom.
Interviews with case students after LS cycle 1 and 2	Audio-recorded, transcribed verbatim and scored by the first author	

- The evaluation at the end of LS 1 and 2 included interviews with case students and paper-and-pencil test for the rest of the students. The first researcher scored how many system characteristics the students were able to name, and determined whether they were able to apply the system characteristics to an ecosystem context. Quotes of students have been used to give insight in students' attitude towards systems thinking and to determine how much attention their teacher paid attention to systems thinking in practice.

Table 3.4. Key activities of Lesson 1α.

Lesson 1α	
KA1.	**Introduction system characteristics in a teacher-student conversation – 25 minutes** • The teacher gave some examples of systems and introduced the eight system characteristics through the use of icons on a tangram (Figure 3.2). The teacher asked the students to apply the characteristics to a well-known non-biological system in which the system characteristics could be made very clear, i.e., the school.
KA2.	**Application of the system characteristics on a well-known biological system – 20 minutes** • The students applied the characteristics to a well-known biological system, i.e., the cell, in groups of 3 or 4 students. The cell was chosen, because this topic had just been taught to the students.
KA3.	**Naming and describing system characteristics – 15 minutes** • The students had to individually name and describe the characteristics in their own words.

Results

This section describes the design and evaluation process of the two LS cycles in terms of design choices, the (improved) key activities and their (learning) effect on case students and the entire class, and the evaluation of the two cycles. Each result is based on one or more data sources (Table 3.3) which are mentioned explicitly in the text.

Design choices Lesson 1

The focus of the first LS cycle was to introduce students to the eight system characteristics which were extracted from three systems theories (Table 3.1). Since Hmelo-Silver et al. (2007), Jordan et al. (2013), Tripto et al. (2016, 2018) and Westra (2008) indicate that an explicit approach improves students' systems thinking and their use of system language, the team decided to explicitly introduce the characteristics to students. Additionally, they decided to start with the explicit introduction of the concepts from all three systems theories and related system language instead of focusing on one systems theory to support students' holistic view on systems. The learning goal of Lesson 1 was: students are able to name, apply and describe the system characteristics.

To assist students in remembering the characteristics, the different system characteristics were visualized using icons in a tangram as a metaphor for a system (Figure 3.2). The individual pieces represent specific system characteristics, and together they illustrate the concept of emergence: the different pieces form a shape together, e.g., a square.

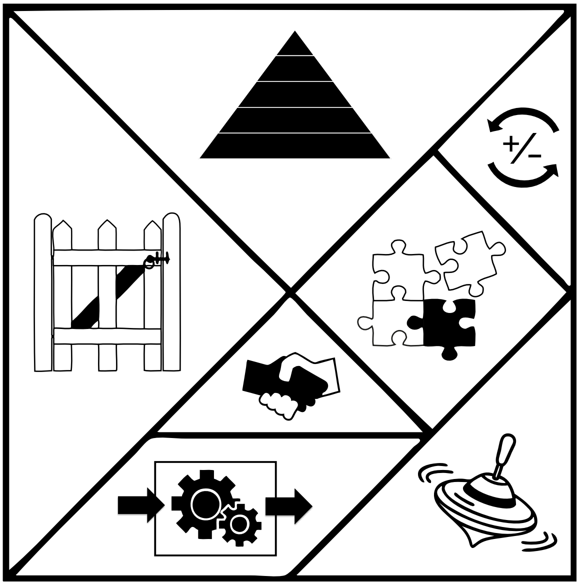


Figure 3.2. This tangram was created as a prompt for a system in which the eight system characteristics can be distinguished: boundary = fence, components = puzzle pieces, interactions = handshake, input and output = scheme with arrows, feedback = plus minus with arrows, dynamics = humming top, hierarchy = pyramid. The different parts of the tangram together illustrate the concept of emergence, because the pieces together form a bigger shape (in this case a square, but it could also be another shape).

The team formulated guiding questions related to the eight system characteristics, which could be used by students as a cognitive toolbox to investigate the different characteristics of the system (Table 3.5). Lesson 1 consisted of three key activities (KA) (Table 3.4).

Table 3.5. The guiding questions are related to the eight system characteristics and can be used by students as a cognitive tool to investigate the characteristics of a specific system.

System characteristic	Guiding question
Boundary	Where can you draw a systems boundary? What belongs to the system, and what belongs to its environment?
Hierarchy	In which subsystems (and to which larger system) can you divide the system? And, to which levels of organization does these (sub)systems belong?
Components	Which components does the system consist of? What is the function of the individual components within the system?
Interactions	What are the relations between the different system components?
Input and output	What (energy, information or matter) enters the system? And what leaves the system?
Feedback	Which feedback loops are present in the system components? • Does the feedback lead to opposing changes within the system? → negative feedback • Does the feedback lead to enhancing changes within the system? → positive feedback
Dynamics	Which regular changes occur in the input and output? In what way do changes take place within the system over time (hours, days, months, years)?
Emergence	How does the different components together result in emergent behaviour?

Results LS 1

Results KA1: Introduction of system characteristics in a teacher-student conversation

The observation notes indicated that Arthur and Chloe were listening to the teacher, but did not give input to the conversation. Belle answered one of the teacher's questions, i.e.: Julia: "What is the boundary of the school as a system?" Belle: "A fence or something literally. Figuratively: age limit." When the teacher finished the first activity Chloe said: "A half-hour instruction is far too long: it is impossible." In the post-lesson interview Chloe also mentioned that the introduction was very clear, but that it was too long: "I think we may have needed the information, but a certain point it became a bit too much."

Results KA2: Application of the system characteristics on a well-known biological system

The observers noted that after the introduction the students could easily start with the second activity. This was also confirmed by Belle in the post-lesson interview who indicated that the introduction activity fitted well with the group activity. The observation notes indicate that the students worked actively together to come to a description of the cell from a systems perspective, so it seems that the group task evoked student discussion. Analysis of the student worksheets show that the student groups in class 1 applied the characteristics boundary, components, interactions and input output mostly correctly (Table 3.6). Several groups did not describe the characteristics hierarchy, feedback and dynamics, and if an answer was given, most of the time it was incorrect. These results might indicate that students encounter more difficulties with the application of the characteristics hierarchy, feedback and dynamics.

Results KA3: Naming and describing system characteristics

After the application of the system characteristics the students had to describe the characteristics in their own words. An observer noted that Arthur first looked at the tangram before he wrote down the different characteristics. When the observer asked Arthur in the post-lesson interview if he thought he would be able to name the different characteristics in the next lesson, the student answered: “I think I need to see the icons, then it would be easier.” This indicates that the icons assist students in remembering the system characteristics more easily. The results of the students on the individual task are presented in Table 3.6. Analysis of the worksheets indicate that most of the students were able to name the different system characteristics and to describe the characteristics boundary, components, interactions and input output. Students seem to have more difficulties with describing the characteristics hierarchy, feedback and dynamics.

Table 3.6. Number of students in class 1 and 2 that were able to apply, name and describe the different system characteristics during key activities 2 and 3 in Lesson 1.

Key activity	Learning aim	Class	Total	System characteristics						
				Boundary	Hierarchy	Components	Interactions	Input output	Feedback	Dynamics
KA2	Application of the system characteristics on a well-known biological system	1	6 groups of students	6	1	6	6	5	1	2
		2	6 groups of students	5	5	5	5	5	3	4
KA3	Naming system characteristics	1	14 students	14	13	13	14	14	14	14
		2	19 students	16	4	12	9	16	3	3
	Describing system characteristics	1	14 students	13	4	12	10	13	6	4
		2	19 students	7	7	6	9	11	2	1

Notes: The third column represents the number of students (class 1, n = 14, class 2, n = 19) or groups of students. Key activity 2 was a group assignment: each group consisted of 2 to 4 students, and key activity 3 was an individual assignment.

A few examples of worksheet answers that are scored as (partially) incorrect are:

- Hierarchy "The ranking: who is higher or lower in ranking." (Chloe)
- Feedback: "Without feedback you do not know what to improve." (Arthur)
- Dynamics: "The system is always in motion." (Belle)

Based on above answers, it seems that students use the daily life meaning to describe hierarchy and feedback instead of the biological (system) meaning and language. The characteristic dynamics is described in a very general way, and it is not clear whether students understood what exactly is meant with this characteristic (Table 3.1 for our definition). The results suggest that students need more in-depth support to develop an adequate understanding of all eight system characteristics related to biology.

Improvements made to Lesson 1a

The team decided to shorten KA1, because the observers noted that students were not actively engaged in the conversation with the teacher, and Chloe explicitly mentioned during the lesson and in the post-lesson interview that 25 minutes of listening is too long. Therefore, KA1 has been changed to a plenary explanation by the teacher with a maximum of 10 minutes. The members of the team concluded in the evaluation meeting that they missed an opportunity to evaluate the answers of KA2. Therefore, they included a feedback moment in the improved lesson, in which the groups had to exchange their answers to give feedback on each other's answers. Afterwards, the received feedback was discussed within the groups.

Results improved Lesson 1β

To check whether the shorter explanation did not have a negative effect on students' learning outcomes, the results of class 1 (analysis of student worksheets) on KA2 were compared with class 2 (Table 3.6). The results suggest that the groups in class 2 made the task slightly better than class 1. The students also described hierarchy, feedback and dynamics correctly more often. After KA2, the groups exchanged their filled in assignments to give feedback with a red pencil. A student in the group of Berit immediately asked: "Without an answer sheet?" The group of Cas also asked for an answer sheet. The observers noted that students compared the answers with their own answers and rated them with points or grades, though this was not in the teacher's instruction. After the feedback session the groups received their own work back. The students looked critically at the feedback, and asked each other how well they had made the assignment, i.e., "How well did you make it [the assignment]?". The groups of Anna and Berit did not agree with the received feedback. The reactions of the students, described by the observers, suggest that they are used to their being only one right answer. In the context of applying the system characteristics, several (correct) answers can be given depending on the underpinning and the systems perspective that is used. The scores on KA2 (analysis of the worksheets) suggest that class 2 would have scored better on KA3, but this was not the case (Table 3.6). The students often described the system characteristics in the context of the cell as a system, while the intended instruction of the task was to describe the characteristics in general terms. The video-recording of the lesson showed that the teacher's instruction of KA3 was not clear for the students, and did not follow the lesson plan:

> Frans: *What did you write down first and which example did you include?*
>
> Student: *Boundary.*
>
> Frans: *And what did you write down?*
>
> Student: *I thought we should do the same as before, so I wrote down the cell membrane.*

Because of the inadequate instruction, the results of class 2 for KA3 are not really representative of students' capacity. However, it is interestingly to see that especially the characteristics hierarchy, feedback and dynamics were named correctly less often by the students in class 2.

Evaluation LS cycle 1

During the evaluation meeting the LS team concluded that a first step had been made: students are aware of the presence of systems (in biology) and the corresponding system characteristics. Frans added: “Students need to see more examples of systems to be able to get a deeper understanding of systems.” This is also in line with student learning results regarding the characteristics hierarchy, feedback and dynamics, because students often describe these characteristics from their daily life perspective instead of from a systems perspective. The feedback activity did not work out as the team hypothesized. It appears that students need more specific guidance to give feedback to each other. It also seems that students are used to their being only one right answer, which does not have to be the case when applying the system characteristics. For example, in KA2 different examples can be given for each of the characteristics, e.g., the cell consists of various feedback loops.

Design choices Lesson 2

The main aim of Lesson 2 was to repeat the application of the different system characteristics in a new context, to support students’ system understanding of specific characteristics and use of system language. LS cycle 2 took place when the topic homeostasis was being taught. The team chose to focus the lesson on the human regulation of blood glucose. According to the teachers this topic is perfect to pay in-depth attention to the abstract characteristics feedback and dynamics. In the pre-lesson, the students had to describe the boundary, components, input output and hierarchy of glucose regulation system after a short introduction by the teacher. The students also had to describe the interactions between the components by completing a scheme of the glucose regulation.

To visualize the abstract system characteristics in the context of the glucose regulation the team has chosen to incorporate a modelling activity (Figure 3.3) which is recommended by Hmelo-Silver et al. (2007). The learning aims of Lesson 2 are: 1) Students are able to recognize and describe the system characteristics in a new biological context; 2) Students are able to formulate questions related to the system characteristics to identify and unravel an unknown system. Lesson 2 consisted of five key activities (Table 3.7).

Results LS 2

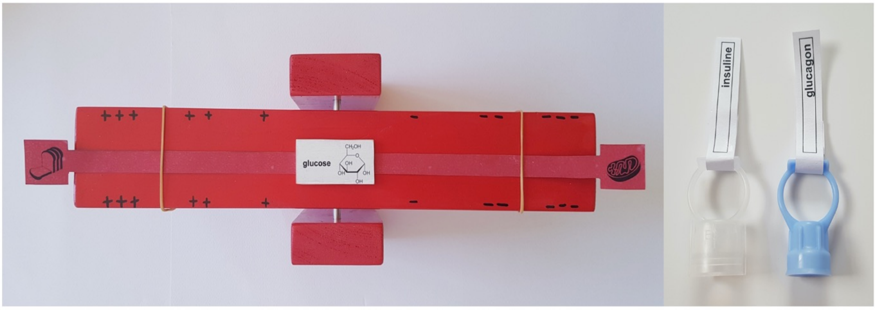
Results KA4: Visualizing the blood glucose regulation

Based on the observation notes, it seems that, to start with, all case students encountered difficulties or felt insecure about indicating the glucose level for the different activities in mmol, e.g.: Amy: "What should I write down here [on the axis]? How much?" The questions of the case students led to in-depth group discussions about how the

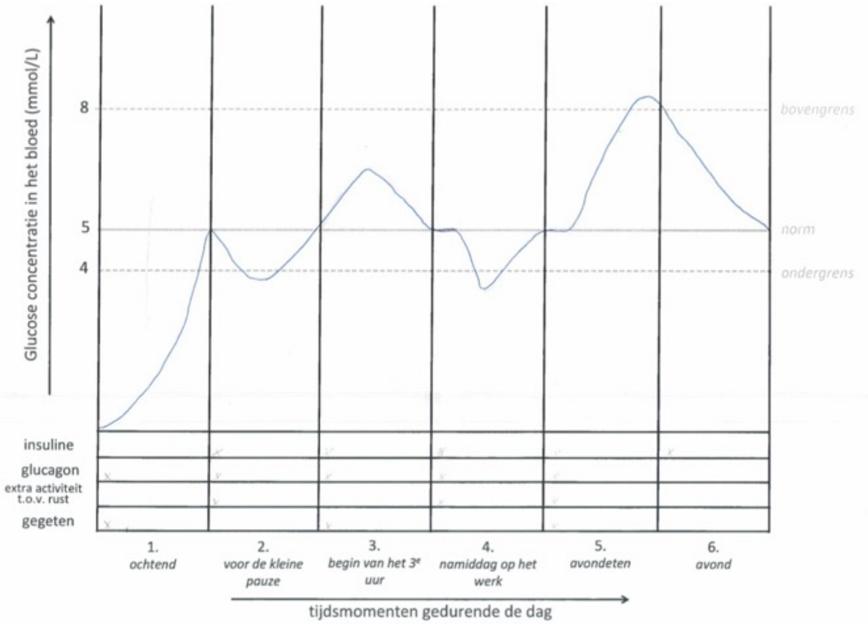
Table 3.7. Key activities Lesson 2α.

Lesson 2α	
KA1.	**Visualizing the blood glucose regulation in a role-playing game – 20 minutes**
	• Three or four students played the roles of control centrum, the alpha and bèta cells in the pancreas. They visualized the glucose regulation of Glucia over one day with a seesaw and small weights (the hormones glucagon and insulin) (Figure 3.3). The case student had to draw a graph of the fluctuating glucose level.
KA2.	**Explaining glucose fluctuation in graph – 10 minutes**
	• The students had to explain the different causes of the glucose fluctuations in the drawn graph.
KA3.	**Describing feedback and dynamics – 10 minutes**
	• The students had to describe the system characteristics feedback and dynamics for the context of the glucose regulation individually.
KA4.	**Recognizing dynamic behaviour – 10 minutes**
	• After a short evaluation of the different drawn graphs in relation to the causes of the fluctuations, the teacher asked students: "Can you think of another (biological) system which shows dynamic behaviour?"
KA5.	**Formulation questions to unravel system X – 10 minutes**
	• Students formulated questions to unravel what system X is and how it works, individually. The aim of this activity was to determine whether the students formulated questions implicitly or explicitly to the system characteristics.

glucose level is regulated and affected by intake of food and activity. Interestingly, based on student worksheets all groups drew the glucose line across the upper and lower limit. This was, for example, the case when Glucia woke up in the morning and was very hungry (<4 mmol), or after dinner, when she ate too much (>8 mmol) (Figure



A



B

Figure 3.3. Seesaw and graph used during modelling activity (KA4). During this activity students had to visualize the human glucose regulation with a seesaw and small weights which present the hormones insulin and glucagon (A) in a role-playing game in groups of four and in a graph (B). The graph is an example of one of the student groups. The y-axis presents the glucose concentration (mmol/L) and the x-axis presents different moments of the day, e.g., morning, lunch, dinner, evening.

3.3B). However, most students only represented the fluctuations of glucose influenced by intake of food or activity, and did not notice that the glucose level is also regulated by glucagon and insulin.

Results KA5: Explaining glucose fluctuation in graph

Analysis of the worksheets showed that the students indicated for each individual activity whether there was an influence of food intake or activity and glucagon or insulin. Thus, it was not clear from their graph whether they understood the cause-effect relations over time. For example, food intake causes an increase of glucose, which causes an increase of insulin, which causes a decrease of glucose.

Results KA6: Describing feedback and dynamics

Based on students' worksheets, almost all (case) students were able to describe the characteristics feedback and dynamics for the example of glucose regulation (Table 3.8).

- Amy gave a correct description of dynamics: "Sometimes the blood glucose level rises or falls. Eating increases the glucose level, but sometimes it is difficult to estimate how much it will exactly rise."
- Bowe described the dynamics partially correct: "By making other substances. It makes insulin or glucagon to maintain

Table 3.8. Number of students in class 1 and 2 that were able to describe feedback and dynamics (key activity 6), and that were able to formulate questions to unravel system X (key activity 8) in Lesson 2.

Key activity	Learning aim	Class	Total	System characteristics						
				Boundary	Hierarchy	Components	Interactions	Input output	Feedback	Dynamics
KA6	Describing feedback and dynamics	1	n = 14						14	14
		2	n = 19						13	14
KA8	Formulating questions to unravel system X	1	n = 14	7	3	8	5	9	3	4
		2	n = 19	5	6	4	2	6	6	0

Note: The third column represents the number of students (class 1, n = 14, class 2, n = 19).

the [glucose] system." This description lacks what is changing (glucose level) and only gives a partial answer on the causes of the change (glucose level is also influenced by the intake of food and activity).

- Coco described feedback correctly: "As soon as your body measures that there is too much or too little glucose your body will adjust it. There is negative feedback, because it [glucose level] returns back to the set point."

Results KA7: Recognizing dynamic behaviour

As intended, the teacher showed the different graphs to the class and pointed out that the students did not represent the fluctuation of glucose between the activities caused by glucagon and insulin. The observers noted that the students did not ask questions during the evaluation. After the evaluation, the teacher asked the students if they could think of another example of a biological system which shows dynamic behaviour. The observers indicated that the case students were not able to come up with an example. Other students came up with the following examples: change of hormones during pregnancy, increase and decrease of heartrate, and uptake and release of water in the cell by osmosis.

Results KA8: Formulation questions to unravel system X

Amy formulated seven questions on her worksheet to unravel system X:

> *What tasks does system X have? What goals does system X have? What is the input and output? Does the system have a cycle? Is the system in the human body? What is the size of the system? Is the system switched on by something, for example by eating?*

Only question 3 explicitly refers to a system characteristic input output. The remaining questions implicitly refer to the system characteristics boundary, components, dynamics and hierarchy. Bowe formulated three questions: “Which components are included? What is the input and output? How are the components collaborating?” All questions refer explicitly to components, input output and interactions. Coco formulated two questions: “What are the boundaries of the system? What is the input and output? These questions explicitly refer to the boundary and input output.

Analysis of the answers of the worksheets of the entire class are represented in Table 3.8. The results show that only a few students formulated questions that implicitly or explicitly refer to one or more system characteristics, except one student:

What is the boundary? What components does it consist of? What are the functions of the components? What is the input? What is the output? Does it have a negative or positive feedback? How does the system change within time? How do the components work together?

Improvements made to Lesson 2a

During the post-lesson interview, the case students mentioned that they did not know how the lesson could be improved:

- Amy appreciated the lesson and says: “The textbook was not clear [about glucose regulation], but now it is clear. Glucagon and insulin ensure that the glucose set-point will be achieved. [...] It was clear. First the instruction. I thought it was good to draw the graph, with several tasks (roles), after that to discuss it. I thought that was a good idea.”
- Bowe indicated the lesson as: “Good enough.”
- Coco appreciated the different activities: “The way of working. That you all had an individual role in the role-playing game, that you know what you have to do.”

The team concluded that the represented (causes of) fluctuations of glucose by students in activity 1 and 2 were not detailed enough. A cause for this was the format of the graph on the worksheet. The x-axis of the graph represented different moments during the day (Figure

3.3), e.g., morning, morning break, afternoon, while the description of Glucia's day also included sub activities within these moments, e.g., in the morning Glucia wakes up, eats a sandwich and cycles to school. The goal was to explain each fluctuation in glucose level. Therefore, the team decided to change the x-axis from different activities to time in hours of the day. Additionally, the students in the improved lesson would receive four different coloured pens during activity 2 (explaining the graph), each pen with its own sticker: intake of food, activity, glucagon and insulin. The students had to indicate to which cause an increase or decrease of glucose could be ascribed by using the different pens. They had to identify what Glucia does (eating or activity) and how her body is reacting (release of glucagon or insulin).

Results improved Lesson 2β

The worksheets with the graphs of the different groups, made during KA4, were compared to determine whether the adjusted format of the graph had an effect on the representation of the glucose level. Whereas the groups of the case students in class 1 all drew the glucose line across the upper and lower limit, all case students in class 2 drew the glucose level between the lower and upper limit. Additionally, the students did not indicate glucose fluctuations between two longer eat moments caused by glucagon. In KA5 Alain marked an increase of glucose from the intake of food and a decrease of glucose from activity or insulin. It seems that the student did not fully understand the effect of glucagon, because this colour was used for a moment of glucose decrease. Boris marked an increase of glucose with glucagon or the intake of food. The release of insulin after food consumption was represented, causing, together with more activity, a decrease of the glucose level. Celia especially represented the influence of food intake and activity on the respectively increase and decrease of glucose. The role of glucagon or insulin was not very clear in the graph. The results of class 2 regarding the description of feedback and dynamics (KA6) were compared with class 1 to see whether the adjusted format of the graph led to a difference in scores between the two classes (Table 3.8). It seems that the students in class 1 scored a little better on the task than class 2. Respectively six and five students in class 2 were not able to describe feedback and dynamics properly, whereas only one student in the first class who did not describe feedback properly.

Evaluation LS cycle 2

The results of activity 1 and 2 suggest that students find it difficult to distinguish between two factors that can be related to a decrease or increase of glucose. Frans said in the evaluation meeting: “They struggled with the fact that two things are taking place in the graph simultaneously. They don’t want to see the complexity.” The results of KA7 suggest that most of the students achieved the first learning goal: to be able to recognize and describe the characteristics feedback and dynamics in the glucose regulation. The results of KA8 suggest that most students did not achieve the second learning goal: to formulate questions to identify and unravel how system X works. The formulated questions, that show implicit or explicit references with the system characteristics, are most of the time related to components and input output.

Evaluation both LS cycles

Naming and application of the system characteristics by students

The scores of the students in class 1 and 2 on the paper-and-pencil tests in terms of naming and applying the system characteristics are presented in Table 3.9. In class 1, the students remembered the characteristic boundary, input output and feedback the best, and hierarchy the least (Table 3.9). It seems that the students of this class encountered difficulties with applying the characteristic hierarchy: Some students refer in their description to 'food chains': "There are animals at the water that are higher in the food chain than other animals." Other students are talking about a certain 'ranking': "Certain biological aspects have more influence and power than others"

In class 2, the students remembered the characteristics boundary and input output the best, and hierarchy and dynamics the least. It seems that the students of this class encountered difficulties with applying the characteristics hierarchy, feedback and dynamics. Examples of wrong answers: hierarchy – "That one animal is higher [in ranking]

Table 3.9. Number of students in class 1 and 2 that were able to name and apply the different system characteristics in the paper-and-pencil test after the two lessons.

Learning goal	Class	Total	System characteristics						
			Boundary	Hierarchy	Components	Interactions	Input output	Feedback	Dynamics
Naming system characteristics	1	n = 14	14	4	9	10	14	11	10
	2	n = 19	14	2	6	9	13	7	3
Application system characteristics on an ecosystem	1	n = 14	11	11	1	10	11	9	10
	2	n = 19	14	13	3	12	7	4	5

Note: The third column represents the number of students (class 1, n = 14, class 2, n = 19).

than the other.”, feedback – “I would not know how to apply it to a system, but just the good and bad points, say what is good about a system and what is less good about a system.”, dynamics – “Not too much of everything, not too little of everything.”

Students’ attitude towards systems thinking

In class 1, all six case students indicated the value of systems thinking in biology education:

- Arthur: “[...] because I then retook the biology test and then I applied it [system characteristics] and then I achieved a higher mark. [...] Look how everything is related with each other. Making interrelations like that.”
- Belle: “[The characteristics] feedback and input and output really helped me to understand biology better.”
- Chloe indicated the value of systems thinking, but also indicates that she experienced it as an additional burden. “If you can receive grades for it then I would find it really helpful, but otherwise I think it is too much. But it does offer a slightly different view [on biology], you start looking at things differently due to the use of that [system characteristics], especially if you understand those correctly.”

- Amy: “These things [system characteristics] are logical themselves. You know them, but you have to remember that they are really there. I really learned that. Recognize that these system characteristics are always present in systems.” She also indicated that she uses the system characteristics herself: “Just during the assignments or during a test you think about the seven things [characteristics] which are applicable for all systems and then you start to think better about what this could be. […] Then you start thinking about each thing [characteristic] and how you can find it [in the system].”
- Bowe: “I would say that I get to know a system a little better, that I know more about it directly, that it then lingers more in my head.”
- Coco: “There are just so many things that you can divide under these [system characteristics].”

In class 2, also all six case students indicated in the interview the value of systems thinking. The systems perspective offers them a way to organize biology, e.g.:

- Berit: “To understand it [biology] better and that you have an overview of what belongs [to the system] and how it works.”
- Celia: “I think it is nice, but I just have to learn them [characteristics] a bit better so they can assist me in biology, because I find biology quite difficult so I would like to understand it better.”

- Alain: indicated that he made use of the system characteristics in his own way: “In the end it is nice because it gives you a better overview of the things you learn. In the notebook of mine I also have this diagram in my own words and then I try to process the information of the lesson in this diagram. So I give it some kind my own twist. […] that just gives a lot of overview when I am learning. Suppose I have a test in a week, then I take the notebook and the text book and the diagram and then I first determine the systems and the parts that are involved, and how the different parts work on their own and how they work together. If I have this clear for myself, I will put it away for a moment and then I will go deeper into that.”

While Alain for example already applied the system characteristics himself, other students did not make use of the system characteristics themselves, e.g.:

- Boris: “There are so many systems in biology and I think it is helpful to think about all these systems and the corresponding system characteristics, but at this moment it does not give me much assistance when I am making the [biology] assignments.”

Systems thinking in the regular lessons

According to the students in class 1, Julia referred to the different system characteristics within the regular lessons. Arthur: “If she is explaining something then she sometimes refers to the corresponding system characteristic." Chloe: "She shows the picture [tangram] very often and then she refers for example to the boundary or the glucose control or something different." Bowe: "Then she shows a new system, for example muscles and nerves. Then she applies the characteristics again." Coco: "She refers to this [tangram]. I think she says that you have to think about the boundary [of the system], and which components [the system consists of]." Most students indicated that Julia pays enough attention to systems thinking, but Coco indicated that she would appreciate some extra explanation regarding the meaning of the characteristics: "Yes, to freshen up our memory, I think it can be done more often."

According to the students in class 2, Frans regularly paid attention to the system characteristics in the regular lessons by referring to them and by applying them to different contexts, e.g., Anna: "Just naming it. He simply explains something and then he says this is input and output. He mentions that every lesson and sometimes he comes back to those parts [the system characteristics]." Cas:

> *Every two weeks he repeats that* [system characteristics], *but he does not explicitly comment on it. Then he has this plate* [tangram] *hanging on the wall and then he says this is the hierarchy, but he does not explicitly explain what that means again.*

Cas indicated that he would like to have some extra explanation about the meaning of the different characteristics. Boris indicated that the teacher spent too much time on systems thinking:

> *I think personally that we pay a bit too much time in that, because the biology itself sometimes suffers from it. We are now far too much concerned with all those blocks* [system characteristics] *and the real knowledge is receiving less attention.* [...] *As a student I want to have instruction about the theory we need to know for the test. Something like that* [system characteristics] *is fun sometimes, i.e., one a week maybe or every two weeks, but now I think we spend too much time on it.*

Conclusion and discussion

While the importance of systems thinking is recognized internationally, and several recommendations can be found in literature regarding teaching systems thinking, to our knowledge systems thinking did not find its way into the regular biology lessons yet. In the context of lesson study (LS) two lessons were designed, tested and evaluated with the aim to triangulate these recommendations from literature and bring them into classroom practice.

The strength of this study is the use of lesson study as a research instrument. In this set-up, teachers are involved from the design to the evaluation phase which leads to ownership, but also to implementation integrity because the teachers know what they want to achieve with the lesson and with which teaching and learning activities they want to do this. One of the biggest advantages of LS are the close observations of case-students during the lessons and the interviews afterwards which give in-depth insight in the learning (and thinking) of different types of case students.

Based on the findings of this study we formulated four design guidelines that seemed effective in supporting students' systems thinking:

1) **Get students acquainted with the eight system characteristics that are related to the three systems theories.** This design guideline is in line with Verhoeff et al. (2018) who indicate that students should develop a systems concept from all three systems theories where systems thinking originally is derived from (Boersma et al. 2011). Students are not used to see biological phenomena as systems which have universal characteristics. A way to get students acquainted with this is to introduce different types of (non)biological systems and describe the system characteristics in general terms and in the context of a specific system which is well-known to students, for example as we did with the school as system. To assist students in remembering the different system characteristics the metaphor of the tangram pieces with icons can be used (Figure 3.2). Based on the results of KA3 (Table 3.6), the introduction of the system characteristics in the context of the school as a system together with the tangram as metaphor seem to assist students in remembering the characteristics. Based on the observation notes, we also saw that students first looked at the tangram before they wrote down their answers. Moreover,

quotes from the interviews with the case students after LS 1 and 2 show that students see the value of systems thinking and some of the case students already use the characteristics without explicit instruction from their teacher.

2) **(Let students) apply the system characteristics to a wide variety of contexts during the school year, varying from the cellular to the biosphere level, at different times within the school year.** Knippels (2002) and Verhoeff et al. (2018) recommend to approach various biological contexts and levels of organization from a systems perspective. In this way students develop a better understanding of the different characteristics and recognize their broad applicability. In this study, the students applied the characteristics in two contexts: the cell and the human glucose regulation. With assistance of the guiding questions, which are related to the system characteristics, students described both systems in terms of their characteristics. During the interviews with the case students after LS 1 and 2, it became clear that students do know most of the system characteristics, and that they are applicable to more (biological) systems. However, we also saw that students still had some difficulties with naming the system characteristics and applying them to a new context, e.g., as we saw in the in the evaluation test (Table 3.9). This suggests that students need to practice more often with the characteristics in different contexts.

3) **Focus on one or two system characteristics specifically to deepen and/or improve students understanding of these characteristics in relation to the others.** From our study, it seems that students need more support to understand the characteristics hierarchy, feedback, and dynamics. Based on student answers, we think that students thought of the daily life meaning of the

characteristics feedback and hierarchy instead of their meaning in biology. This could be induced by using an example from students' daily life, e.g., the school as a system. Also, students found it difficult to describe the meaning of the characteristic dynamics. This is in line with Hmelo-Silver et al. (2007) who already concluded that students have more difficulties with the dynamic behaviour of systems because these processes are invisible. When it seems that students do not understand a specific characteristic it is possible to focus on this characteristic in a specific lesson. This can be in the context of the topic that is taught at that moment or by comparing different contexts with each other. In this study, we paid specific attention to feedback and dynamics in the context of the glucose regulation. The students first had to describe the system in general: what is the boundary of the system?, what are the components of the system?, what is the input and output? Afterwards the students visualized the system in a modelling activity and they had to identify the feedback mechanisms and the dynamic behaviour in this specific context and in other biological contexts. This activity led to a better understanding of dynamic behaviour and feedback from a biological systems perspective by students.

4) **Pay attention to the use of system language and encourage students to do so.** This guideline is in line with several researchers (i.e., Hmelo-Silver et al., 2007; Jordan et al., 2013; Tripto et al., 2016, 2018; Westra, 2008) who all claim that systems thinking should be taught explicitly. To get students used to the use of system characteristics (system language) and to see the wide applicability of them (see also guideline two), teachers can explicitly use the characteristics in their instructional vocabulary. Moreover, teachers can encourage students to use system language when they are reasoning about biological phenomena or by reformulating their answers by making use of the system characteristics. In the

evaluation interviews we saw that students recognized that the teachers paid attention to systems thinking in the regular lessons, because the teacher was using systems language explicitly.

Overall, in this case study the described recommendations from literature are empirically substantiated and expanded by a team of teachers. A first step is made in introducing students to systems thinking. The students are aware of the different system characteristics and are able to apply them in different biological contexts. However, students' understanding of one of the overarching system characte-ristics, i.e., emergence, was not studied, because students first need to develop a basic understanding of the other system characteristics. This could be a next step in a follow-up study.

Moreover, the case students in both classes indicated systems thinking as important to understand (systems in) biology. Nevertheless, only two students indicated that they themselves made explicit use of systems thinking. They used the characteristics to create an overview of their biological knowledge which assisted them in preparing for a biology test. Thus, it seems that most students do not yet internalize systems thinking as a metacognitive tool yet. Verhoeff et al. (2008) also encountered the difficulty of developing a motive for students to apply a system concept. In a follow-up study attention should be paid to fostering students' internalization of systems thinking. The challenge is to let students experience systems thinking as a way to create a more coherent view of biology, and as a way to reason about biological systems in abstract terms to gain more insight in biological systems and to solve complex problems.

Chapter 4

Fostering students' understanding of complex biological systems

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Abstract

The main aim of this study is to teach students to take a systems perspective in understanding complex biological problems. Two lessons were designed and tested in two secondary classes (15–16 years old), using a lesson study approach. Three students from each class were observed more closely when visualizing and reasoning about two complex biological problems. The results, based on student worksheets, peer discussions, classroom observations and interviews, indicated that students were able to visualize complex problems with the aid of a systems model based on eight system characteristics: boundary, components, interactions, input and output, feedback, hierarchy, dynamics and emergence. Moreover, explicit scaffolds encouraged students to reason across different levels of biological organization. Based on the findings, four design guidelines were formulated: 1) Start with a central complex problem/question; 2) Let students visualize a complex biological problem using a systems model; 3) Assist students in reasoning step-by-step within and between the levels of biological organization; 4) Make students explicitly aware of the use of the system characteristics in various contexts. As systems thinking assists students to create an overview of a system and to reason about a complex problem systematically, systems thinking is also valuable outside the biology classroom.

Introduction

An ant colony, the economic system of a country, the digestive system, or a family are all examples of systems. A system is a collection of components that interact with each other; the way one of these components functions can have an effect on the system as a whole. *Systems thinking* is the ability to interpret and understand these complex systems (Evagorou et al., 2009). It can be used as an approach for reasoning about complex problems in which different (sub)systems are involved; for example: How do ants work together in a colony? What is the effect of a war on the economic system? How does a protein deficiency lead to a bloated belly?

In recent education-related literature, various articles can be found that focus on students' systems thinking, in subjects ranging across geography (Cox, Elen, & Steegen, 2019; Mehren, Rempfler, Buchholz, Hartig, & Ulrich-Riedhammer, 2018), technology (Barak, 2018), chemistry (Orgill, York, & MacKellar, 2019; Samon & Levy, 2020) and biology education (Tripto et al., 2018). However, differences can be found in the definitions that are used to describe systems thinking for the different educational domains (Bergan-Roller, Galt, Chizinski, Helikar, & Dauer, 2018; Yoon et al., 2018). According to Boersma et al. (2011), these differences are due to implicit or explicit reference to one or more systems theories. Historically, systems thinking originated from three different types of systems theories: General Systems Theory (GST), Dynamical Systems Theories (DST) and Cybernetics.

These three systems theories offer different perspectives on systems. GST focuses on the hierarchical structure of systems in terms of the system components and their relations (Von Bertalanffy, 1968). DST focuses more on non-linear processes (Prigogine & Stengers, 1984). Cybernetics focuses on the regulation of systems by feedback loops (Wiener, 1948). According to Verhoeff et al. (2018), it is important to pay attention to the characteristics addressed in all three systems theories to develop a good understanding of systems.

In a previous study (Gilissen, Knippels, Verhoeff, & van Joolingen, 2020), the perspectives of current systems biology experts were studied in light of the three systems theories. This study led to a description of eight universal system characteristics that apply to biological systems: Each system is distinguished from its environment by a boundary and consists of several components that have interactions. In each system there is an input and output of energy, information and matter, and there are feedback loops to maintain the system. In addition, systems are dynamic because (regular) changes occur in the input or output, or through (developmental) changes over time, and systems have a certain hierarchy: they can be divided into different levels of biological organization. These characteristics together result in emergent behaviour of systems: properties that emerge on a specific level of biological organization through the interactions of the underlying components, for example, a school of fish that swims in harmony. The system characteristics can assist students to develop a more coherent understanding of biology: the characteristics can not only give more insight into the structure and functioning of living systems in general, but can also be used to get to know more about a specific biological system (Gilissen, Knippels, & van Joolingen, 2020; Verhoeff et al., 2018).

In the Netherlands, systems thinking has been part of the secondary biology curriculum since 2010 (Boersma et al., 2011, p. 33). However, a recent study (Gilissen, Knippels, Verhoeff, & van Joolingen, 2020) indicated that Dutch biology teachers are in need of support for incorporating systems thinking in their daily teaching practice.

Therefore, in a follow-up study, Gilissen, Knippels, and van Joolingen (2020) made a first attempt to foster students' systems thinking in secondary biology education. In two lessons, they introduced students to the concept of systems and the corresponding system characteristics. The results showed that students developed a basic understanding of the eight system characteristics. Based on the results of the lessons, the researchers concluded that it is important to introduce the system characteristics in a well-known biological context and to pay in-depth attention to the characteristics of feedback, hierarchy and dynamics, because these were considered difficult by students compared to the others. As students developed a basic understanding of the concept of systems and the system characteristics in the previous study, the next step is to teach students to take a systems perspective to understand complex biological phenomena.

Recommendations from the literature

Three major elements can be found in the literature to foster students' systems thinking: 1) *modelling activities*: visualization of the (sub) systems involved in terms of the eight system characteristics; 2) *cross-level reasoning*: reasoning within and between the different levels of biological organization; 3) *systems language*, namely, using the eight system characteristics to describe and talk about systems (Appendix 4.1).

Modelling

Systems thinking is often mentioned in combination with modelling (Bergan-Roller et al., 2018; Dauer, Momsen, Speth, Makohon-Moore, & Long, 2013; National Research Council, 2012; Verhoeff et al., 2008). Models can act both as representations in which students make a visualization of the system of interest and as a tool to shape their own reasoning (Forbes, Zangori, & Schwarz, 2015). According to K. J. Wilson et al. (2020, p. 5) models can change students' views on biological processes "from the static into the dynamic, the flat to the 3D, and siloed to integrated". Two types of models are computational and qualitative. Experts in the field, such as systems biologists, especially make use of computational models. Computational models can be used to simulate systems' dynamic behaviour, for example, by performing a simulation in which a system component is added or removed (Yoon et al., 2013, 2016; Yoon & Hmelo-Silver, 2017). An example of a qualitative model is a concept map. With concept mapping, it is possible to externalize students' systems thinking (Brandstädter, Harms, & Grosschedl, 2012; Dauer et al., 2013; Tripto et al., 2013, 2018). Another example of a qualitative model is the systems model by Verhoeff et al. (2008), which presents the structure of systems (Figure 4.1). In summary, literature shows that modelling activities can be used to visualize biological phenomena and to assist students' reasoning.

Cross-level reasoning

Systems thinking is known as an approach for examining complex problems and systems (Bergan-Roller et al., 2018; Jacobson, 2001; York, Lavi, Dori, & Orgill, 2019). The essence of understanding a complex biological problem from a systems perspective is to understand the causality of the interactions between the components between and within different levels of biological organization (hierarchy) that result in emergent behaviour. Students need to learn to reason across the different levels of biological organization when explaining complex biological phenomena (Asshoff, Düsing, Winkelmann, & Hammann, 2020; Knippels & Waarlo, 2018), for example, by asking students to explain a phenomenon at one level using concepts and processes from a different level (Marbach-Ad & Stavy, 2000). An approach to assisting students in reasoning between the different levels of biological organization is called *the yo-yo learning and teaching strategy* (Knippels, 2002; Knippels & Waarlo, 2018). This strategy specifically emphasizes the hierarchy of systems and the interactions between and within

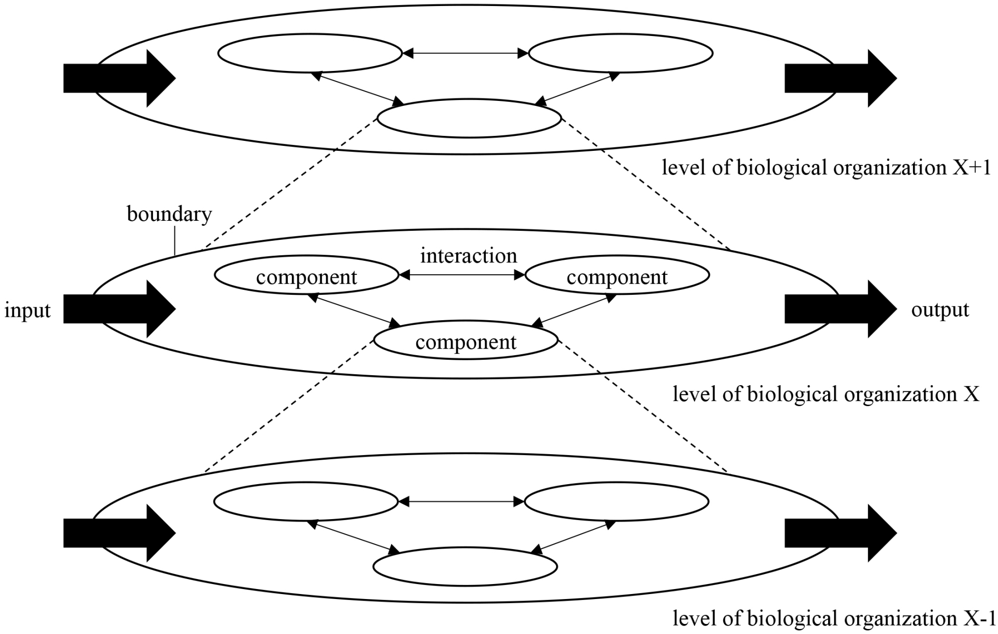

Figure 4.1. The systems model used in this study. This model presents the general structure of biological systems in terms of the following system characteristics: boundary, components, interactions, input and output, and hierarchy (different levels of biological organization). Feedback can be found in the interactions between some of the components. The dynamic features of a system are more difficult to represent because the systems model is a static representation of a biological system and emergence arises on a specific biological level of organization by the interaction of the underlying components. This figure is based on the systems model used by Verhoeff (2003).

the different levels of biological organizations. To foster students' reasoning between these levels, students should be involved in a guided learning dialogue that starts with the introduction of a central question. Partial problems or questions can serve as a content-related motive to explore the different levels of organization. Moving down to lower levels of organization provides causal explanations and moving up provides functional explanations (Knippels & Waarlo, 2018). Afterwards, it is important for students, in terms of development of metacognition, to reflect about what levels of organization were considered when reasoning about the problem (Asshoff et al., 2020). In summary, the literature shows that teachers have to scaffold students in reasoning between the different levels of biological organization when explaining complex biological phenomena.

Systems language

While reasoning about a complex biological problem, experts seem to use significantly more systems language, that is, references to system characteristics, in comparison to novices (Jacobson, 2001). Moreover, experts integrate structures, behaviours and functions in their reasoning, while novices focus more on the perceptually available, static structures of the subsystems involved (Hmelo-Silver et al., 2007). Many studies have recommended stimulating the development of students' systems language, because it seems to encourage students' systems thinking (Gilissen, Knippels, & van Joolingen, 2020; Tripto et al., 2016; Verhoeff et al., 2008, 2018). This can be done by explicit use of systems language by the teacher during teaching and learning activities. Our hypothesis is that explicit attention to the eight system characteristics in teaching and learning activities can be used to get students acquainted with application of the system characteristics when reasoning about biological phenomena (i.e., taking a systems perspective). In summary, the literature shows that explicit attention should be paid to the eight system characteristics in teaching and learning activities.

Research focus

The main aim of this study is to teach students to take a systems perspective in understanding complex biological problems. Based on the three main recommendations from literature, two lessons were designed and evaluated in which students had to reason about two complex biological problems in terms of the eight system characteristics (Appendix 4.1). Moreover, as we aim for students to internalize systems thinking in the future, it is important to investigate to what extent students experience systems thinking as a valuable approach. The following research questions were addressed:

> *1. How do modelling activities, cross-level reasoning and systems language change students' understanding of complex biological phenomena?*

> *2. To what extent do students experience systems thinking as a valuable approach to understanding biological phenomena?*

Method

Overall research design

In this study, we employed lesson study (LS) as the main research method (Murata, 2011) for designing and evaluating two lessons. In a LS cycle, a small group of teachers collaboratively set a goal, select and plan a lesson, teach the lesson with peer observation, debrief the lesson, refine and reteach the lesson and evaluate the whole cycle (Allen, Donham, & Tanner, 2004). LS is often used in the context of professional development (Lewis et al., 2006), but because of its cyclic nature, LS can be seen as a form of design research, and therefore be used for research purposes as well (Bakker, 2018; Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2003; Design-Based Research Collective, 2003). In this study, we used LS as a research method to gain insight into students' understanding of complex problems from a systems perspective. LS plays an important role in bridging the gap between research and educational practice because of the close interplay between researchers, teachers and students. Involvement of the teachers in the design and enactment of the lessons gives higher chances of good fidelity of implementation (Bakker, 2018, pp. 82-83), because the teachers are aware of the underlying principles of the lesson. The close observation of students during the lessons and analysis of student products gives insight into students' learning.

Participants

The three authors (the researchers), two teachers (Julia and Frans [pseudonyms]), and an observer formed the LS team. The first researcher has five years of experience as a secondary biology teacher and is a colleague of the teachers involved. She was present during the whole LS trajectory and chaired, prepared and summarized the different meetings. The other two researchers attended a couple of meetings. The researchers functioned as knowledgeable others (Takahashi, 2014) and provided the teachers with relevant literature. Julia has eight years' experience as a secondary biology teacher and has a background in physiotherapy. Frans has ten years' experience as a secondary biology teacher and has a background in tropical forestry. The lessons were taught in a school in the eastern part of the Netherlands that offers senior general secondary education and pre-university education. During the lessons and the evaluation meetings, the LS team was accompanied by one extra observer, a colleague of the teachers. In each class, three students, the *case students*, were selected. The selection of students was based on their scores on a regular biology test at the beginning of the school year, in terms of three cognitive levels. The test questions were categorised in terms of what they aim to assess: students' insight, ability to apply their knowledge and factual knowledge. Insight is the highest level and factual the lowest. In each class, case student A scored especially high on the insight and application questions, student B on the application questions, and student C on the factual questions. Pseudonyms were used for the six case students (Table 4.1).

Table 4.1. Pseudonyms of the case students and teachers. The first letter of the case students' name represents which type of student they represent. Case student A scored high on the insight and application questions in a regular biology test, student B on the application questions, student C on the factual questions.

Case student	Class 1	Class 2
A	Alec (male)	Abel (male)
B	Boaz (male)	Britt (female)
C	Caro (female)	Chris (male)
Teacher	Julia (female)	Frans (male)

The 60-minute lessons were taught in two senior general secondary education biology classes (Julia's class, n = 26 (14 girls and 12 boys), and Frans's class, n = 29 (14 girls and 15 boys), 15- to 16-year-old students. Parental consent was obtained for all involved students. Senior general secondary education is called 'havo' in Dutch. It takes five years, and prepares students for higher professional education.

LS cycles

The LS team together enacted four LS cycles within one school year (Figure 4.2). In the first and second cycles, students were introduced to the concept of systems and the eight system characteristics (Gilissen, Knippels, & van Joolingen, 2020). In the third and fourth cycles, students had to visualize and reason about two complex biological systems in terms of the eight system characteristics. This study reports on the final two lessons, which from now on will be called Lesson 1 and 2.

Each of the LS cycles consisted of four preparation meetings (approximately 2 hours each), 2 enacted lessons (original and revised) with a post-lesson evaluation in-between, and afterwards an evaluation meeting (approximately 2 hours), see Figure 4.2. During the preparation meetings, the team determined the learning goals, and designed the lesson with input from the literature provided by the researchers and teachers' didactic and pedagogical experience. One teacher taught the designed lesson, while the other three members of the LS team each observed a specific case student and described the student's behaviour for each teaching and learning activity using an observation schedule. The observation schedule included the goals of each activity, expected student behaviour and a place to write down the actual behaviour of the student. The schedule was discussed with the observers to make sure that they took adequate notes. After each lesson, the observers conducted a brief individual interview (approximately 5 minutes) with the case students and audio-recorded this. Examples of questions are: What have you learned in this lesson? What did you value in this lesson? How do you think this lesson can be improved?

Based on students' answers, the observers asked more in-depth questions. After each lesson, the team had an evaluation meeting (approximately 1 hour) in which they evaluated and improved the lesson based on their observations and the input from the case students during the interview. The other teacher then taught the improved lesson in his/her class. During the evaluation of the improved lesson,

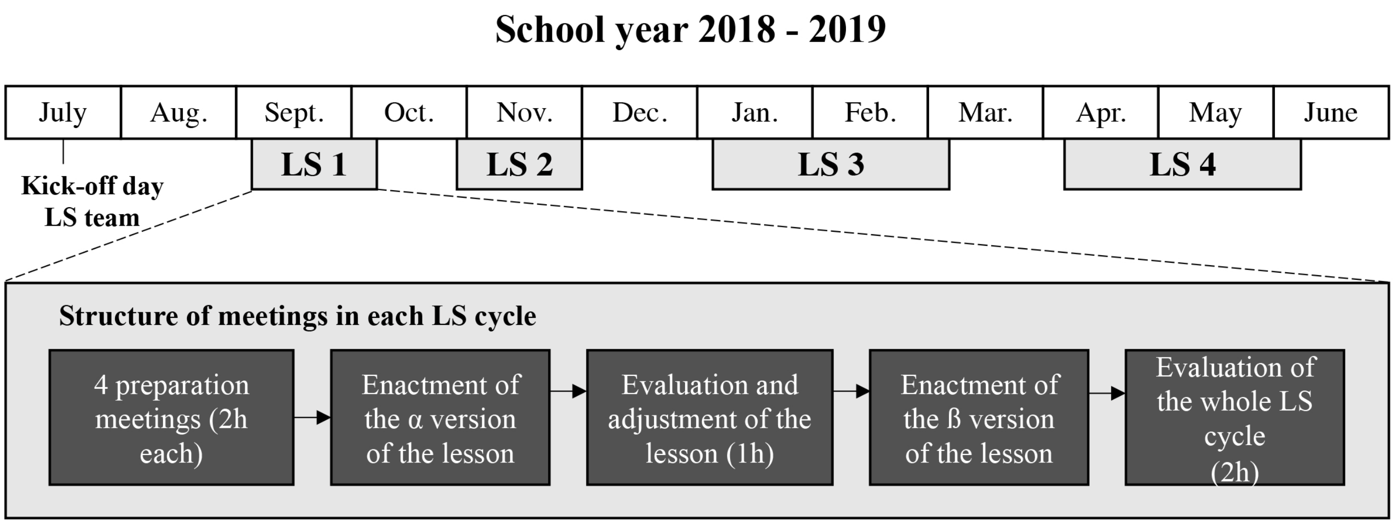

Figure 4.2. Timeline of the four LS cycles within the 2018-2019 school year.

the team evaluated what the critical key activities were to achieve the student learning goal. The first version of the lesson is indicated with α, and the revised version is indicated with β. Julia enacted lessons 1α and 2β, and Frans lessons 1β and 2α.

Design of the lessons

Lessons 1 and 2 both started with the introduction of a complex biological problem, after which students had to visualize the problem and reason about it. The purpose of this activity was for students to identify and visualize the system of interest and to think of possible explanations (and not per se a correct scientifically based answer) and reason about the problem from a systems perspective. Tables 4.2 and 4.3 show an overview of the key activities (the term KA is used when a reference is made to a specific key activity) of lessons 1 and 2. The aim of Lesson 1 was to determine to what extent students were initially capable of visualizing the problem with the aid of the guiding questions related to the eight system characteristics (Table 3.5), and to determine to what extent students were initially able to reason step-by-step between the different levels of biological organization. Based on the results of Lesson 1, and informed by the recommendations from the literature provided by the researchers, the LS team determined how they could assist students in visualizing and reasoning about another context in Lesson 2. The aim of Lesson 2 was to determine to what extent a systems model assists students to visualize the problem in terms of the system characteristics and to

Table 4.2. Overview of the key activities (KA) of Lesson 1 and the revisions that have been made after evaluation of the α version of the lesson.

Lesson 1
Learning goals: • Students are able to visualize the complex Mount Everest Tibetan problem with the aid of the system characteristics and guiding questions; • Students are able to formulate hypotheses in terms of cause-and-effect relations to explain why Tibetan people are more capable of climbing Mount Everest than Dutch people are.
KA1. Teacher introduces the complex question: Why are Tibetan people more capable of climbing Mount Everest than Dutch people are? The teachers used news articles reporting about research regarding this question to motivate students. KA2. Visualization of the problem with the aid of the guiding questions related to the system characteristics (Table 3.5). Students first visualized the problem individually, and then worked in groups of four to combine their visualizations into one visualization. At the end of this activity, the teacher showed the students his/her own visualization of the problem. KA3. Reasoning about the problem. Students, in groups of four, received a paper worksheet on which they could formulate: a) the possible cause of the problem; b) the effect on Dutch people; 3) their hypothesis related to the evolutionary adaptations of Tibetan people. At the end of this activity, the teacher showed the hypothesis tested by researchers and the related conclusions.
Revisions after Lesson 1α → Lesson 1ß **KA2:** Besides visualization in terms of the system characteristics, students were asked to determine and visualize the subsystems that are involved in the problem. **KA3:** Students received a worksheet with questions to scaffold students' reasoning between the different levels of biological organization more gradually and explicitly: • What factors from the environment could be a cause? • What consequence does factor X have for Dutch people? • What evolutionary adaptation(s) could Tibetan people have to explain their capability to climb Mount Everest? • At what biological organizational level does this adaptation take place? • What is the effect of this adaptation on a higher and/or lower level of organization? • Do you think this adaptation is likely? Explain your answer. As an example, the team elaborated on one hypothesis, answering abovementioned questions in detail.

Table 4.3. Overview of the key activities (KA) of Lesson 2 and the revisions that have been made after evaluation of the α version of the lesson.

Lesson 2	
Learning goal:	
•	Students are able to visualize the biological problem, starvation of red deer in the Oostvaardersplassen, using the systems model, and they are able to use the systems model to reason about the complex question regarding the red deer.
KA4.	Introduction of the systems model as a method for visualizing biological phenomena from a systems perspective. As an example, the 'Tibetan problem' of Lesson 1 was visualized in a systems model and explained to the students (Appendix 4.2).
KA5.	Introduction of the complex question: What measures can be taken to prevent high starvation mortality of red deer during the winter in the Oostvaardersplassen (a Dutch enclosed landscape nature reserve)? by the teacher with the aid of some news articles reporting about this problem.
KA6.	Visualization of the problem with the aid of the guiding questions related to the system characteristics (Table 3.5) and the systems model. Students did this assignment in pairs. The students received the systems model on paper. The ecosystem level was already filled in, and the students had to fill in the population and organism levels themselves. At the end of this activity, the teacher showed the students an example of a possible visualization of the problem.

KA7. Reasoning about the problem (in pairs). Students first had to think of possible measures to reduce red deer mortality by starvation, before reasoning about the effects of the measure, ‘introduction of the wolf’, on different levels of organization, namely, the ecosystem, population and organism levels. The teacher first gave an example (according to the guidelines of the yo-yo strategy) with the measure, ‘add input to the system: additional feeding of the red deer’, in which the reasoning starts on the level of the ecosystem before descending to the population level and the organism level, and then back to the ecosystem level (Appendix 4.3). Afterwards, students were shown a graph that was generated by a computer model and showed the effect of the measure in terms of the number of red deer and other animals, amount of grass, and death by starvation. The students had to describe what they observed in the graph and explain to what extent the graph was in line with their own initial observation. Next, students had to predict, observe and explain the measure, ‘add the component wolf’, by themselves. During this activity, they could make use of their completed systems model.

Revisions after Lesson 2α → Lesson 2ß

The team decided that students should be able to reason about one of their own chosen measures in more detail. Also, the decision was made not to show the graphs of the computer model. The graphs showed some irregularities; for example, the amount of grass continued to decrease while the number of animals also decreased, which we could not solve easily with the computer model we used. Because our learning goal was to show students how the systems model can be used to reason about complex problems, we thought it would be better to focus on that and not on interpreting the partially incorrect computer model, because this requires other modelling/reasoning skills. Therefore, we also decided not to report on students’ observations regarding the graph. In the revised lesson (2ß), the students could choose one measure, for example, the introduction of the wolf, for which they had to describe its effects on different levels of biological organization.

what extent partial questions scaffold students' cross-level reasoning. Note: In Lesson 1, students worked in groups of four, and in Lesson 2 it was in pairs.

Data-collection and analysis

During this study, data from various sources were collected and processed with different aims (Table 4.4). We have translated some of the data (instructional materials, student products, observation notes) for use in this article.

Table 4.4. Overview of the various data sources that were collected in this study.

Data source	Processed	Aim
LS meetings	Audio-recorded and summarized	Identify design choices and conclusions of the LS team based on implications from literature, practice and the other three data sources.
Observation notes lessons	Transcribed	Determine learning progress of students regarding complex problem solving from a systems perspective in terms of visualization, reasoning and use of systems language.
Student products of the lessons	Digitized, categorised and described	
Post-lesson interviews with case students	Audio-recorded and transcribed verbatim	Determine students' learning progress and attitude towards systems thinking, and identify ideas for improvement of the lesson that can be used as input for the design of the improved lesson.

- Summaries of the audio-recorded LS meetings: the first researcher highlighted the design choices that were made based on recommendations from the literature and/or from the LS team expertise, which resulted in the different key activities. Moreover, the summaries of the audio-recorded post-lesson discussions were used to highlight the choices that were made to revise the lessons.
- Video-recorded lessons: the enacted lessons were compared with the original lesson plans to determine whether the teachers implemented the lesson as intended, that is, fidelity of implementation (Bakker, 2018). If a teacher deviated from the plan, this is noted in the results.
- Observation notes: the transcribed notes were used to illustrate what a specific student did or said during the different key activities. Moreover, the notes were coded by the first author according to the main categories: modelling activities, cross-level reasoning, and systems language. The following example shows an observation note (for KA2 of Lesson 1β, Table 4.2) from the categories of modelling activities and systems language:

  Student 1: *What is the boundary?*

  Student 2: *Human body.*

  Abel: *By boundary they mean the whole problem, so it also* *includes the environment and the atmosphere.*

Abel: *The respiratory system is a component.*

Student 1: *But also a system.*

Abel: *Yes, but here it is also a component.*

Based on the abovementioned notes, it seems that these students based their model (modelling activities) on two system characteristics: boundary and components. The students used these two system characteristics explicitly (systems language) in their conversation. The coded notes were combined with insights from the analysis of the student products.

- Student products: most key activities (Tables 4.2 and 4.3) included a worksheet for students to write their answers down. The worksheets were analysed in terms of students' ability to model a complex problem or reason about the problem, and their use of implicit or explicit systems language:

  - KA2 of Lesson 1: students' models were categorised into three types: 1) students described each of the system characteristics for the context (e.g., Figure 4.3); 2) students visualized only some subsystems (e.g., Figure 4.4); combination of type 1 and 2 (e.g., Figure 4.5).
  - KA3 of Lesson 1 and KA7 of Lesson 2: student worksheets were used to determine which levels of biological

organization were implicitly or explicitly used by the students in their reasoning and in what order.

  - KA6 of Lesson 2: students' visualizations using the systems model were used to determine whether the students wrote down the correct components, interactions, and input and output for the population and organism levels in their model.
  - Additionally, all worksheets were coded in terms of implicit or explicit usage of systems language. By explicit use, we mean that the students mentioned one of the system characteristics, and by implicit use, we mean that students described the system characteristics but did not use the term itself.

- Post-lesson interviews: the transcribed interviews were used to describe what improvements to the lesson were proposed by the case students, and to determine to what extent students experienced systems thinking as a valuable approach for understanding biological phenomena. In the Results section, we use quotes to describe students' attitudes and learning experiences concerning systems thinking.

Results

In this section we describe to what extent modelling activities, cross-level reasoning and use of systems language changed students' understanding of complex biological systems (RQ 1), see also Appendix 4.1. Moreover, we describe to what extent students experienced systems thinking as a valuable approach to understanding biological phenomena (RQ 2).

Modelling activities

In Lesson 1, students were asked to visualize the Tibetan problem with the aid of the eight system characteristics (Table 4.2). The aim was to determine how students initially model a complex biological problem in terms of the system characteristics.

In Lesson 1α, two types of models were seen: individual descriptions of the system characteristics (type 1) and division of the problem into subsystems (type 2). Caro's group described the characteristics individually for the context of the Tibetan problem (Figure 4.3). Alec's and Boaz's groups visualized different subsystems of the problem; for example, Boaz's group visualized the Mount Everest on the ecosystem level, Tibetan people on the population and organism levels and genes on the cellular level (Figure 4.4). The type 1 models suggest that students did not know how to visualize the system characteristics on paper other than by describing them. The type 2 models suggest that students were able to determine the system of interest and divide it into subsystems on different levels of biological organization, which can be related to the characteristic of hierarchy; an important skill in systems thinking.

In Lesson 1β, students were asked to visualize the problem in terms of the system characteristics and to identify the subsystems involved (a type 3 model). Chris's group visualized the problem in this way and identified four different subsystems: Mount Everest as an ecosystem, Tibetan people and Dutch people, and the respiratory system (Figure 4.5). Additionally, they zoomed in on the respiratory system and explicitly described each of the system characteristics for this system.

Based on the findings for Lesson 1 (α & β), the LS team concluded that students need more assistance in creating a coherent model of the problem, in which the system characteristics are presented in a more meaningful way instead of describing them and in which it becomes clear how different subsystems are related. Therefore, in Lesson 2 (α & β; Table 3), students were introduced to the systems model of Verhoeff et al. (2008), which presents the structure of biological systems in terms of the eight system characteristics (Figure 4.1). This choice was based on the study by Forbes et al. (2015), who concluded that models can assist students to visualize and reason about biological phenomena, and on the study by Verhoeff et al. (2008), who found positive results for using the systems model to visualize the system's structure. The aim of this lesson was to determine to what extent the systems model assists students in modeling a complex biological problem from a systems perspective. Based on students' systems models (e.g., Figure 4.6) of KA6 (Table 4.3), it seems that the students were able to visualize most aspects of the red deer problem in the systems model. The students indicated the main system components and the underlying interactions and the input and output of the subsystems on the population and organism levels. Some students used upward and downward pointing arrows to illustrate an increase or decrease in input or output, (e.g., Figure 4.6: arrows next to birth, mortality, O2 and food and waste products), which is an implicit example of dynamics because it reflects a change in the input and output (see definition in Table 3.1).

Although most students represented input and output in the systems model, the observation notes showed that students experienced some difficulties with it:

- Abel: "I do not quite understand what the input and output does." Abel also pointed this out during the post-lesson interview: "[...] frankly, it makes it less clear rather than more, because, say, birth is also input, that was explained, but I think birth is a change within the boundaries and not just something that comes from outside. I think it is output rather than input, because there is food coming, water comes in, oxygen comes in, and that is used by the deer, and for my idea birth would be output rather than input."

- Britt indicated food as input and emission as output. When her neighbor asked for an explanation, she said: “Because I just saw food and emission ‘things’ on the image [the systems model example of the teacher].” This indicates that Britt did not know what input and output mean, because she just copied the teacher’s answers.

Cross-level reasoning

In Lesson 1 students were asked to formulate a hypothesis to explain why Tibetan people are naturally more capable of climbing Mount Everest than Dutch people are (Table 2). The aim was to determine to what extent students are initially able to reason between the different levels of biological organization.

In Lesson 1α, it seems that all case students were able to formulate the main cause of the problem: the low oxygen level at Mount Everest, and the effect on Dutch people: suffering from low blood oxygen. The worksheets for KA3 (Table 2) showed that their reasoning stayed on a very general descriptive level, for example:

- Alec: “Tibetan people make more EPO (erythropoietin), which leads to more red blood cells and more uptake of oxygen.” Alec described one cause (more production of EPO) and its

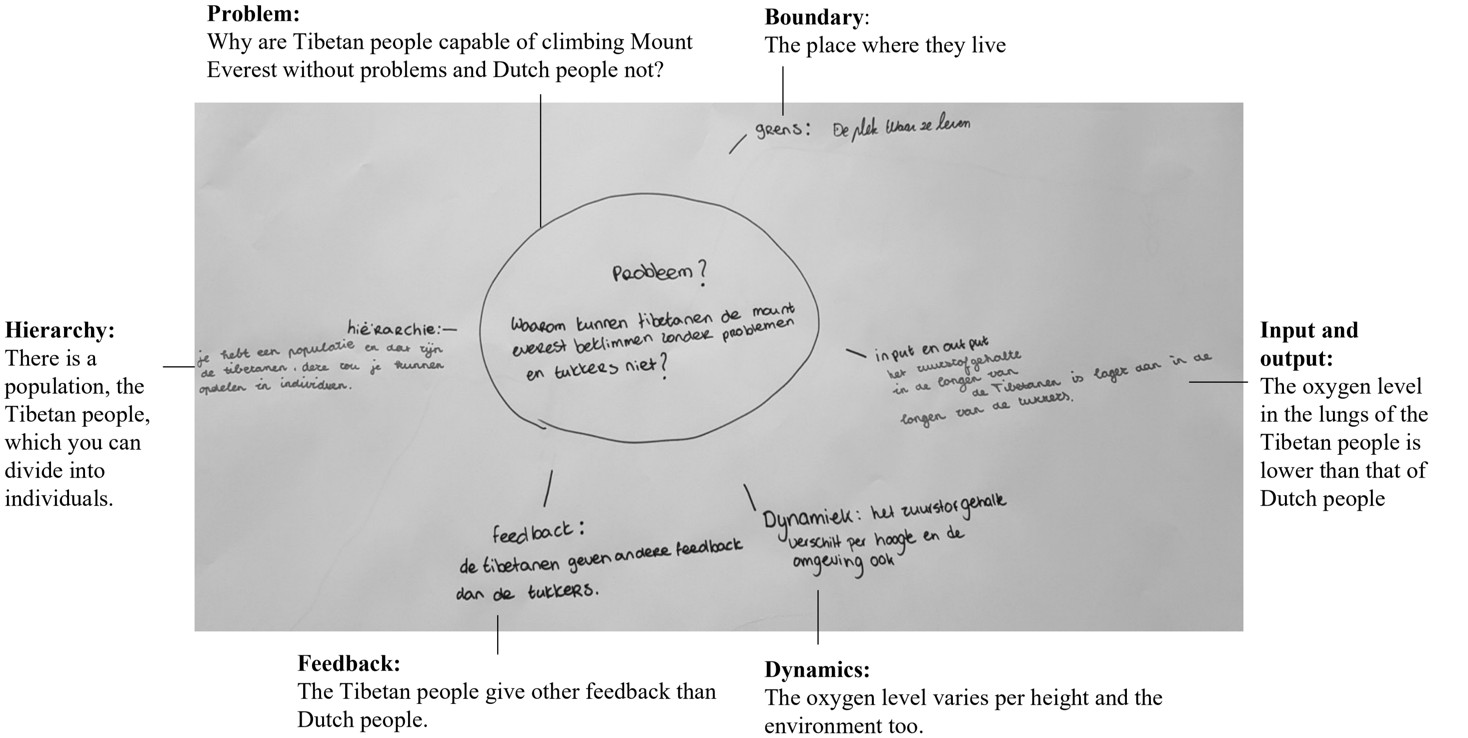

Figure 4.3. Example of students' visualizations of the Tibetan problem. Caro's group (Julia's class) visualized the Tibetan problem in terms of the different system characteristics (type 1 model)

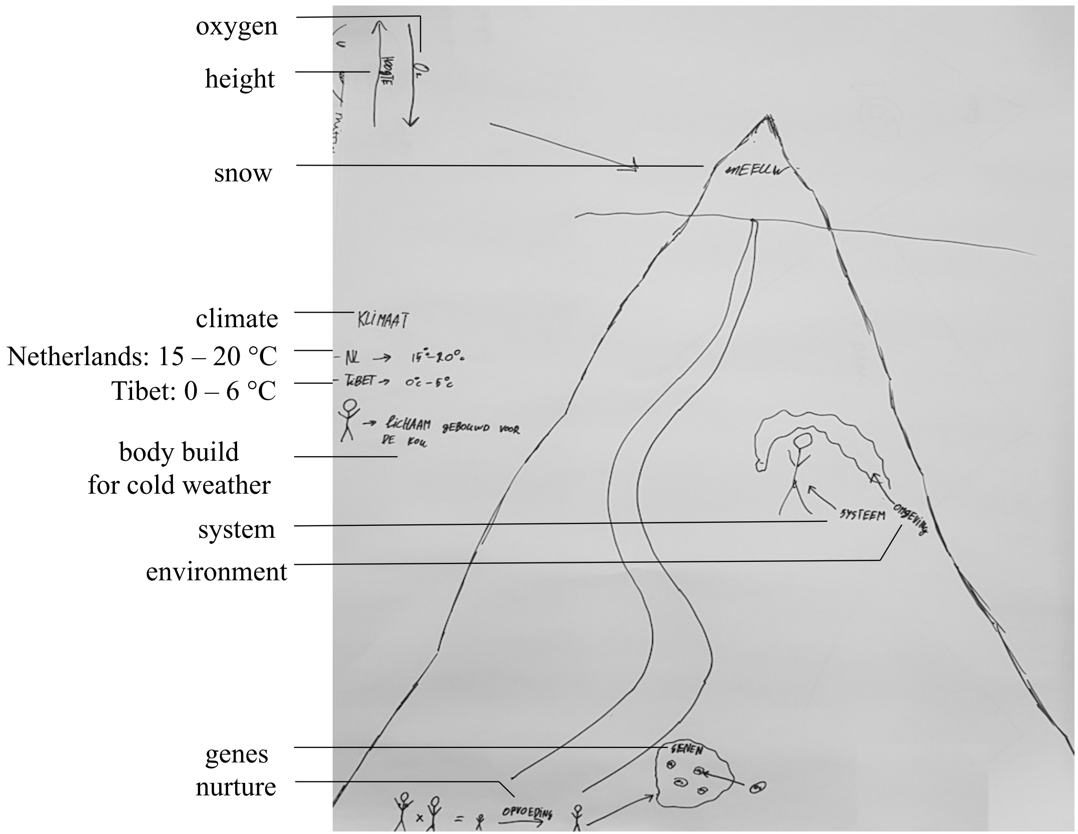

Figure 4.4. Example of students' visualizations of the Tibetan problem. Boaz's group (Julia's class) implicitly visualized four subsystems on different levels of organization (type 2 model).

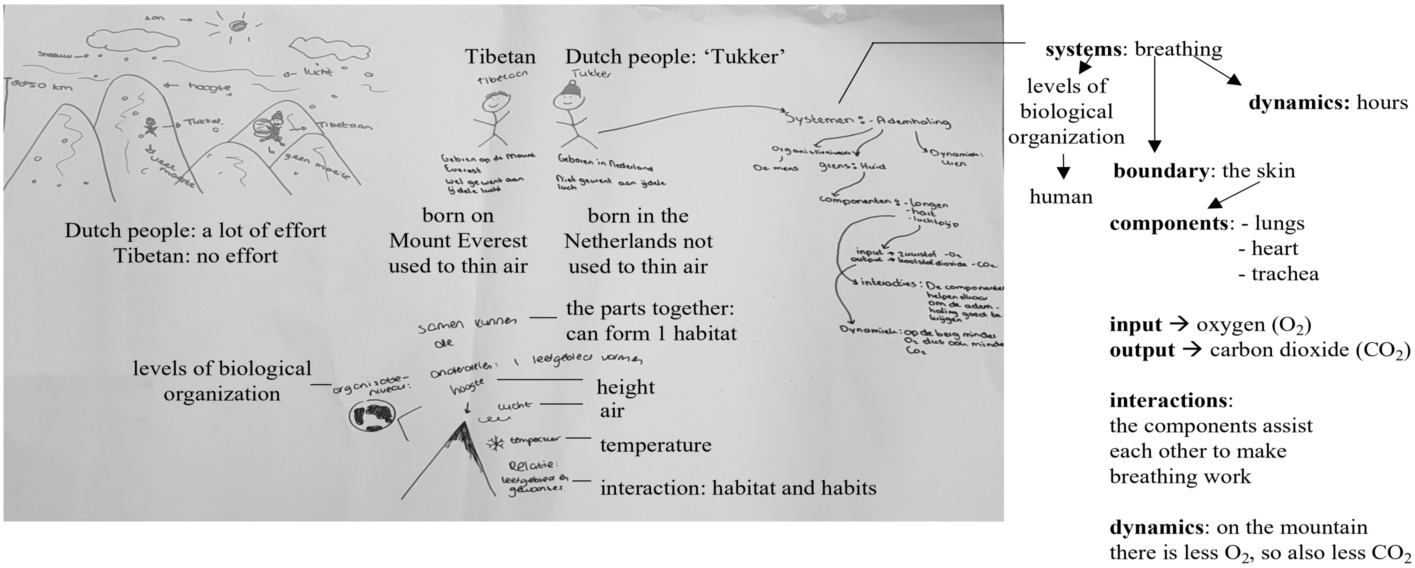

Figure 4.5. Example of students' visualizations of the Tibetan problem. Chris's group (Frans's class) visualized the problem in subsystems (type 1 model) and in terms of system characteristics (type 2 model).

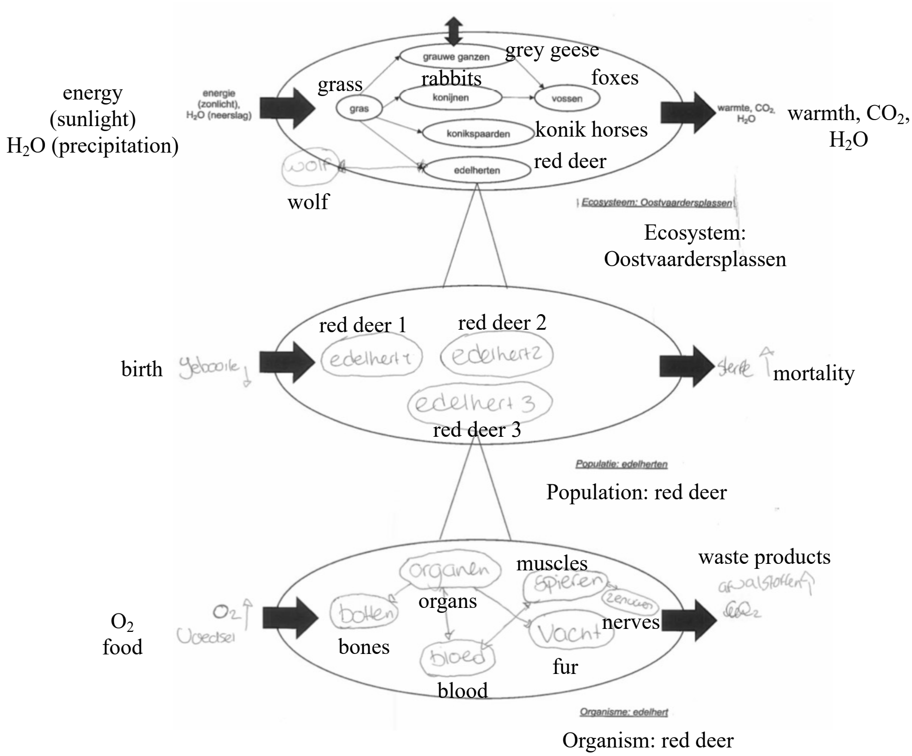

Figure 4.6. An example of students' systems models, completed by Caro's group (Julia's class).

effects (more red blood cells and thus more uptake of oxygen), but some steps are missing in his reasoning process, because he did not switch systematically between the different levels of biological organization.

- Caro thought that it had to do with '*habituation*': "It is in the genes of the Tibetan people." She described only an adaptation on the subcellular level (genes), but did not describe the effect on the other levels of organization.

The observers described in their observation notes that it seemed that the students already had some solutions in mind and did not approach the problem systematically by descending or ascending the different levels of organization.

For the revised lesson (1β), the LS team formulated scaffolding questions (which were provided in a worksheet) to assist students' cross-level reasoning (Table 4.2). This is in accordance with Knippels (2002) and Knippels and Waarlo (2018), who concluded that partial questions can serve as a motive to explore the different levels of biological organization. Based on student answers on the worksheets for KA3 and the observers' notes for Lesson 1β, it seems that the addition of scaffolding questions influenced students' reasoning. An illustration of this can be found in a discussion within Abel's group. The first researcher made almost verbatim observation notes on this discussion in her observation scheme. The students followed the format of the scaffolds carefully (see the words in bold):

> Abel: *Less O2 the higher you get* [which is an example of a **factor**]. **Consequences** *of O2 deficiency is that there is less O2 in your muscles, which can cause your heart to stop.* **An adjustment** *could be that you have more / larger lung vesicles or that you have more red blood cells so that you can transport more O2.*
>
> Student 2: *Larger lung capacity? Could that be possible? At which* **organizational level** *does this adjustment take place?*

Abel: *Cellular and organ level. The effect on a* **higher level** *is that all parts of the body get more O2. Larger lungs lead to more O2 uptake at a higher level. Extra red blood cells have an effect on a* **lower level.**

Student 3: *But then you also need more blood vessels.*

Abel: *Maybe they have a completely different physique.* [Students view a picture of a Tibetan.]

Abel: S*o thin and light, so maybe less energy is needed.*

Based on this discussion, it looks like the scaffolding questions (Table 4.2) assisted the students to reason about the problem across different levels of organization.

Britt's group described on their worksheet (KA3) that they thought the cause is the lower oxygen level in the ecosystem, and according to them, the organs and cells of Tibetan people can function with a smaller amount of oxygen, for example, "mitochondria are getting more out of the oxygen." While the students stayed on the organism level in their visualization (worksheet KA2), the students did descend to lower levels of organization during their reasoning (worksheet KA3 and the observer's notes). Perhaps the scaffolding questions assisted students in doing this. Chris's group thought that Tibetan people have greater muscle endurance. They thought that this is caused by larger uptake of air by the lungs, but, unfortunately, they did not gradually descend further to lower levels of organization. In summary, it seems that the scaffolding questions assisted some of the students to reason more systematically between the different levels of organization.

In Lesson 2 (Table 4.3), students had to think of possible measures to reduce red deer mortality due to starvation and reason about the effects of one of the measures on the system. In Lesson 2α, all case students could think of different types of measures to prevent starvation-related mortality of red deer, namely, additional feeding of the red deer, expansion of the nature reserve, introducing a red deer predator (the wolf), birth control, shooting of red deer, moving some red deer to other ecosystems. The observers noted that students already started reasoning during the visualization of the problem in the systems model. For example, Britt and her neighbor started to reason during completion of the systems model: “Drying out of grasses leads to more excess water and to a lower amount of food for red deer, which leads to a smaller population of red deer”. These reasoning steps are not directly related to the initial problem: mortality of red deer due to starvation, but apparently the visualization of the ecosystem encouraged the students to think of factors that influence the red deer habitat. The students explained on their worksheets how they think the introduction of the wolf will have an impact:

- Abel: “More deer will die and other herbivores ➔ less deer ➔ more grass.”
- Britt: “Fewer red deer, but more food for those who remain. Wolves also reproduce, so it remains balanced. More grass available means more food for the red deer.”
- Chris: “An increase in the number of wolves and a decrease in the number of red deer.”

These citations show that students' reasoning was quite brief and stayed primarily on the ecosystem level.

In the revised lesson (2β), the students received more time to reason about the effects of a specific measure on the system, and were asked more specifically to determine the effect of the measure on the different levels of biological organization (Table 4.3). Just as in Lesson 2α, the results showed that the students used the systems model as a tool to reason about the question; for example, students drew upward and downward pointing arrows to indicate an increase or decrease in components, input or output in the systems model. Different examples can be found in the observation notes that show students' cross-level reasoning skills:

Alec elaborated in his worksheet from KA7 on the measure, 'add more foxes':

> *Increase in the number of foxes leads to a decrease in geese and rabbits and an increase in the amount of grass for Konik horses and red deer* [effects on ecosystem level]. *This means that the individual red deer have more food* [effect on organism level], *which leads to more births and lower mortality of red deer* [effect on population level].

He also indicated that birth and mortality are interrelated with each other: "They always go in a circle."

Boaz focused on the isolation of weaker red deer. He described the effect on three levels of organization and visualized this in the systems model with arrows:

> *Ecosystem: number of red deer decreases and the amount of grass increases. Population: components 'weaker red deer' are removed, so the population number is decreased while the input (amount of grass) is increased, so this leads to the following output: less starvation. Organism level: the input (birth rate) increases, which leads to less starvation within the organism, so this leads to a lower output: mortality.*

Boaz and his partner did not recognize that their measure had a positive effect in the short term, but not in the long term, perhaps because they did not reason back from the organism level to the population level and then to the ecosystem level. The students also mixed up the input and output for the population and organism levels.

Caro described the effect of the introduction of the wolf on her worksheet for KA7 (Table 4.3):

> *There is an additional component in the ecosystem. The wolves hunt the red deer, which leads to fewer red deer. The birth rate decreases, and the death rate increases. This reduces the surplus in the number of red deer. This is done in a natural way. The population is getting smaller.*

These examples of students' reasoning show that the systems model encouraged students to reason within and between the different levels of biological organization (hierarchy) and to discuss interactions and processes over time (dynamics).

Systems language

In both lessons, explicit attention was paid to the eight system characteristics, because several studies have indicated that this encourages students to take a systems perspective (Gilissen, Knippels, & van Joolingen, 2020; Tripto et al., 2016; Verhoeff et al., 2008, 2018). For instance, students were asked to visualize the biological problem in terms of the system characteristics.

In Lesson 1 (α & β), case students Caro, Abel and Chris described the individual system characteristics explicitly in their visualizations for the context of the Tibetan problem (type 1 model). The remaining case students visualized different subsystems (type 2 model), which implicitly referred to the characteristic of hierarchy. Based on students' reasoning processes (reflected in students' worksheets and described in the observation notes) in Lesson 1, it seems that students did not often mention the system characteristics explicitly. The following (see words in bold) is an example of a conversation in which students made explicit use of systems language (Lesson 1β, KA2):

> Student 1: *What is the* **boundary***?*
>
> Student 2: *Human body.*
>
> Abel: *By* **boundary** *they mean the whole problem, so it also includes the environment and the atmosphere.*
>
> [continuing explicit discussion about the system characteristic of boundary, before they start discussing the system characteristic of components]
>
> Abel: *The respiratory system is a* **component***.*
>
> Student 1: *But also a system.*
>
> Abel: *Yes, but here it is also a* **component***.*

In Lesson 2 (α & β), none of the students explicitly mentioned the eight system characteristics on their systems model worksheet, but, as already mentioned, this systems model implicitly visualizes the system characteristics. Based on students' reasoning processes (reflected in students' worksheets and described in the observation notes) for Lesson 2, it seems that students often implicitly made use of the system characteristics, for example:

- In Lesson 2α, Britt addressed some of the characteristics implicitly on her worksheet for KA7: "After a certain time, a repeating line appears. Adding the wolf is the first cause of death and not the food shortage." In her reasoning, she talked implicitly about the interactions and balance (feedback) between the components of grass, red deer and wolves.

- In Lesson 2β, Alec gave an implicit example of a feedback loop (feedback): “the circle between birth and starvation.”
- Some of the possible measures that were mentioned in Lesson 2 (α & β) by the case students also implicitly refer to the system characteristics. The expansion of the nature reserve implicitly refers to the movement of the boundary of the system. Introduction of the wolf implicitly refers to the addition of a component to the ecosystem. Additional feeding refers implicitly to the input to the system: people have to put some extra food into the system. Birth control implicitly refers to feedback that can control the number of births and deaths within the system.

Analysis of student worksheets and student observations showed examples of implicit or explicit use of six out of the eight system characteristics. The characteristic of dynamics was less used by students and emergence was not used by students.

Do students experience systems thinking as a valuable approach?

In the post-lesson interviews for lessons 1 and 2, we asked the case students what they learned and to what extent they see the use of the system characteristics and the systems model as adding value. Two out of six case students indicated that they would not directly use systems thinking themselves.

- Abel: “I know better how to apply systems thinking in a certain situation and not only within a system itself.” Abel about his own use of systems thinking: “If I had to learn for a test, I would not use it [systems model]. I think it would make everything even more vague. Usually, for example, if I get a question on a test or something, I do not consciously think about it [the system characteristics]. Sometimes unconsciously, but then I am not going to write it out completely, because only more things will be added that will only make it more difficult.”
- Alec: “It [the systems model] makes it easier to visualize, how do you say that, a problem like this, that you have a bit of an overview. That is cool about a systems model. That you can divide those boxes. For example, like this up and down pointing arrow, so that you get a bit of an idea of what it will ultimately do. That helps with this systems model.” However, he also indicated that he would not use it himself, and when we asked him why, he said: “I have not really had moments when I really needed this.”

The remaining four case students were very positive about the use of the system characteristics and the systems model, and explained why.

- Britt indicated that she learned to apply the system characteristics more quickly in order to find solutions: “If you look at the system characteristics, you immediately see what you need to look at, so that's why it is useful." She also indicated that she could use more creativity because "it made you think." She learned: "That by removing or adding a component you can notice very small differences or very large differences that you do not expect immediately." She said also that the systems model was useful because it gives a good overview of everything that plays a part: "And it is easy because you already have something to think about. I guess it would be harder if you did not write anything down."

- Boaz said that he experienced that he unknowingly used the system characteristics more than he thought, and he found it useful to apply them in an actual daily life context. He indicated that the system characteristics ensure that you "delve deeper into the problem." He said: "It gives a different picture of how you can use the system characteristics and how you can learn and how you can work with it. [...] I now notice that I understand it better than when I only have to state the system characteristics one by one. I think this will help me a lot more. [...] It just really gives a better view, not because you only mention things, but you see it, you also get a real picture with all the arrows that are there. [...] It provides an overview".
- Chris explained: "I think it is more useful than just reading from the book and then trying to solve the questions for such a system. This will make you understand more." He indicated that

the system characteristics helped him to tackle the problem: “If you look at the system characteristics, you immediately see what you need to look at, so that’s why it is useful. [...] You see more quickly where to look at, therefore you know where to search faster.” He also learned: “That something, if you change it, leads to more changes. One change can have a major influence on an entire system.” He indicated why the systems model can be valuable: “It all affects each other, and has to do with each other and you can easily see that. [You can use it] for more difficult assignments, if you no longer know what to do, it gives you a little more overview.” However, he also had a more critical comment: “It is sometimes easier, because it gives more overview, but on the other hand you sometimes already have the answer on your own without the systems model. And then you have to think again about how you will put that in this [the systems model].”

- Caro concluded that she now better understands the system characteristics and their usefulness: “Because you look better at other perspectives or at other things. I would not look at it that way by myself.” According to her, this helped her to understand the problems: “That you might be able to see solutions faster or make connections, if you know all this [system characteristics].” In Lesson 2, she learned how you can fill in the systems model: “It looks like a mind map, which I use a lot, but this [the systems model] is clearer.”

Conclusion and discussion

RQ 1: How do modelling activities, cross-level reasoning and systems language change students' understanding of complex biological phenomena?

In this study, we investigated how modelling activities, cross-level reasoning and use of systems language changed students' understanding of complex biological systems (Appendix 4.1). Therefore, in Lesson 1 we first investigated students' initial capability for modelling and reasoning. The results for Lesson 1 (α & β) suggested that the eight system characteristics did not provide enough support for students to visualize a biological problem from a systems perspective and to reason between and within the different levels of biological organization. Students visualized ('modelling activity') the Tibetan problem as different subsystems or described the system characteristics without interrelating them. Moreover, students did not descend or ascend the different levels of organization systematically; for example, they switched between the ecosystem level and the cellular level, and then back to the population level. Therefore, in Lesson 2 the systems model (Figure 4.1) was introduced to students as a tool to visualize the problem in terms of the system characteristics. Moreover, the students received scaffolding questions to assist their cross-level reasoning.

The results for Lesson 2 (α & β) and the student interviews, suggested that the systems model assisted students to make a more meaningful overview of the problem in terms of the system characteristics. Moreover, it also seems that visualization of the problems in the systems model encouraged students' reasoning from a systems perspective. The systems model (Figure 4.1) used in this study is a static representation of the structure of a system (Verhoeff et al., 2008), but completion of the systems model seems to encourage students to reason about the system in a more dynamic way. For instance, by using arrows next to the components, input or output, an increase or decrease can be visualized in the model. Moreover, in the systems model different components and their interactions are visualized on different levels of organization (hierarchy), which enables students to realize that a change in one of the components has an effect on the system as a whole (e.g., Chris: "It all affects each other, and has to do with each other and you can easily see that."). So, for most students, the systems model gains meaning by reasoning about it. This is in line with Forbes et al. (2015) who claimed that models can act both as representations of biological systems and as tools to shape students' reasoning. Moreover, these results connect with work by K. J. Wilson et al. (2020), who suggested that modelling prompt students to build connections within and across biological systems and to reason about system dynamics, causality and emergence.

The scaffolding questions (Table 4.2) assisted students to reason back and forth between the different levels of biological organization, as represented in the systems model, more systematically. Scaffolding questions include partial questions that remind students of the biological level of organization they are thinking about and what consequence a change on this level has on the higher and lower biological levels of organization. During the two lessons enacted in this study, the students did not often make use of systems language, that is, explicit mentioning of one or more of the eight system characteristics. Although students did not explicitly use the characteristics themselves very often, many examples could be found of implicit use of the system characteristics (describing the system characteristic while not using the term itself), which indicates that students know what they mean. Perhaps it is more important that students are aware of the system characteristics and can use them when reasoning about biological systems than that they mention them explicitly. As shown by the example of the misunderstanding of input and output by some of the students given in the results section, it remains important to pay attention to the understanding of the individual system characteristics in classroom practice. Moreover, the characteristics of dynamics and emergence seem to need more specific attention, because the results indicate that these were less used by students.

RQ 2: To what extent do students experience systems thinking as a valuable approach to understanding biological phenomena?

In our previous study (Gilissen, Knippels, & van Joolingen, 2020), students were introduced to the concept of systems and the eight system characteristics. Most of the students involved indicated that they did not experience the value of applying the system characteristics to a specific biological system. In this current study, students made use of the system characteristics to visualize and reason about a complex biological problem. This study investigated to what extent students experienced systems thinking as a valuable approach to understanding biological phenomena. Based on the individual interviews (n = 6) after Lesson 2, the case students indicated that the systems model and the related system characteristics assisted them to make a clear overview of the problem and to reason in more detail about the problem, which was also in line with our observations (see answer to RQ 1). Interestingly, the two A type case students (who scored especially high on the insight and application test questions) indicated that they did not directly see the value of systems thinking. Alec indicated that he personally has not needed the systems model so far, while Abel indicated that the systems model confused him, especially the input and output for the different levels of biological organization. A possible explanation for this is that these students already are capable of thinking systematically about a complex problem. In that case, students can experience the explicit application of the system characteristics and the visualization in the systems model as unnecessary, perhaps because they already take these steps implicitly. For example, Abel said:

> *Usually, for example if I get a question on a test or something, I do not consciously think about this* [system characteristics]. *Sometimes unknowingly, but then I will not write it out completely, because then only more things will be added that will only make it more difficult.*

Nevertheless, it is interesting to see that the two type B case students (who scored especially well on the application questions) and the two type C students (who scored especially well on the factual questions) indicated that they did see the value of systems thinking. They stated that the systems model in combination with the system characteristics gives them more guidance to visualize a problem and to think in-depth about the corresponding subsystems. According to Boaz and Britt, the system characteristics helped them to delve deeper into the problem. Caro indicated that systems thinking invites you to take different perspectives on the problem (i.e., focusing on the different system characteristics), allowing you to see more connections, while Chris noticed that the systems model is particularly valuable for difficult problems, and not for simple questions: "[You can use it] for more difficult assignments, if you no longer know what to do, it gives you a little more overview.". Systems thinking is often mentioned as a metacognitive skill. So, recognizing what situations systems thinking can be applied to, which Chris seemed be capable of, is an important element of systems thinking ability. Although these are results for only a small group of students (n = 6), it seems that the average and low student achievers especially experienced the value of systems modelling. Other studies, interestingly, have also found positive relations between the learning of low-level performing students and the use of modelling activities. For example, Bennett, Gotwals, and Long. (2020) found that modelling activities led to greater learning for all types of students, but especially for the students who might be considered lower-achieving. Dauer et al. (2013) observed that students who entered the modelling course with a lower grade achieved greater learning in comparison to the highest performing students. Our study seems to confirm this trend, although further research is necessary.

Design guidelines

Based on the results of lessons 1 and 2, design guidelines are formulated for teachers to support students in visualizing and reasoning about complex biological problems from a systems thinking perspective:

1) **Start with a central complex problem/question that covers different levels of organization.**

2) **Let students visualize a complex biological problem in a systems model.** The value and applicability of the system characteristics becomes clear to students when applying them to a complex biological problem that covers different levels of biological organization. A systems model format seems to assist students to visualize a problem in terms of the system characteristics in a coherent way and encourages them to reason about it.

3) **Assist students in reasoning step-by-step within and between the levels of biological organization.** By visualizing the system in the systems model, the structure of the system (hierarchy) becomes visible for students. Students also need some scaffolds to reason systematically between the different levels of biological organization. According to Knippels and Waarlo (2002, 2018), partial questions (problems) can guide students to answer the central question by descending and ascending the different levels of biological organization (yo-yo strategy). This can be done by asking students explicitly what levels of organization should be included in their answer and on what level of organization they are starting their reasoning. Furthermore, they have to determine what effect a change in the system has on the different levels of biological organization. Students have to learn that causal explanations can be found by moving down to lower levels and functional explanations by moving up to higher levels of biological organization.

4) **Make students explicitly aware of the use of the system characteristics in various contexts.** The main aim of developing students' systems thinking is that students become aware of the eight universal system characteristics and that they are able to approach complex biological phenomena from a systems perspective. Explicit attention is needed to foster students' understanding of the individual system characteristics. Ways that seem effective to make students aware of the system characteristics include: making explicit connections with the system characteristics in the teaching and learning activities, and the teacher's regular use of systems language.

Putting the guidelines in context

The students in this study had already been **introduced to the concept of systems and system characteristics in a well-known biological context** in previous lessons (Gilissen, Knippels, & van Joolingen, 2020). With a new group of students, it is important to keep in mind getting students acquainted with the term system and the corresponding system characteristics. In-depth attention is needed to foster students' understanding of each of the system characteristics. Moreover, the students were introduced to the systems model for the first time in this study, and they only saw two elaborated versions of the systems model. The results showed that some students still found it difficult to complete the systems model by themselves. For example, during Lesson 2, the observers noted that Britt and her peers copied information from the example that was given by their teacher in another context. Therefore, it seems important that students need to practice more with the systems model in other biology contexts as well. Moreover, it would be interesting to determine whether students will use the systems model themselves when they are introduced to a new complex problem.

Externalization of systems thinking

In this study, we fostered and externalized students' systems thinking by having them make schematic drawings. Completion of the systems models in combination with the discussion between peers gave the teachers and observers insight into students' systems thinking in terms of the eight system characteristics: boundary, components, interactions, input and output, feedback, dynamics, hierarchy, and emergence. This allowed teachers to identify the difficulties that students encountered and let them provide scaffolds or extra instruction to students to overcome these difficulties. This can be of added value with regard to prior research that has reported about the difficulties of fostering students' reasoning about biological processes, such as the ability to trace matter in dynamic systems (C. D. Wilson et al., 2006). The systems model represents the structure of systems in terms of the system characteristics, and guides students to visualize biological phenomena from a systems perspective in a wide variety of contexts. Therefore, we think it is easier to use the systems model to identify the extent to which students can visualize a biological phenomenon from a systems perspective. For example, Van Geelen (2019) analysed student drawings in terms of the system characteristics to determine the students' systems thinking perspective with regard to the phenomena of respiration, photosynthesis and digestion. In the discussion, she mentioned the difficulty of coding the different system characteristics in the drawings, because it was not clear which elements of the drawings could be linked to the different system characteristics. A possible solution is to introduce the systems model to students, and then hand out the systems model and give the assignment to illustrate a biological problem or phenomenon in the systems model. In this way, it will be easier to code the extent to which the different system characteristics are represented correctly, because you already know where to look in the model to find the different system characteristics. For example, the circles illustrate the components of the system, the arrows between the circles represent the interactions, and so on (Figure 4.1).

Future

This study has shown that it is possible to encourage students' reasoning about dynamic features in a static representation such as the systems model, but computational models seem to be more suitable to represent systems' dynamic interactions, changes over time, and scales. With computational models, it is also possible to simulate experiments in which the effects of changed variables can be showed more easily (Yoon et al., 2013, 2016; Yoon & Hmelo-Silver, 2017). The qualitative modelling approach we introduced can serve as a first step towards quantitative modelling by schematically visualizing biological phenomena and identifying the components (the agents) and their interactions (actions). To narrow the gap between school biology and research biology, it would be good to start already at the high school level with the introduction of these types of models (Wilensky & Reisman, 2006). In a follow-up study, a way to add a quantitative aspect to the current qualitative systems model could be an interesting route to explore.

Chapter 5

From empirical research to daily practice: embedding systems thinking into pre- and in-service biology teacher education

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Abstract

Systems thinking is an approach to understand many different (biological) phenomena in terms of universal system characteristics. Several studies report on teaching and learning methods that have yet to find their way into daily classroom practice. The aim of this study was to determine the viability of the application of the five design guidelines, derived from earlier work involving classroom studies, by disseminating them to pre- (n = 39) and in-service teachers (n = 12) and teacher educators (n = 5) in the context of a professional development activity. Before and after, the teachers completed an online questionnaire, which was analysed in terms of the system characteristics to determine their systems thinking content knowledge. After the activity, 22 pre- and 8 in-service teachers developed educational materials on systems thinking which were analysed in terms of the design guidelines. In interviews, the teacher educators were asked to what extent they would like to change their teaching regarding systems thinking. Overall, the results showed that teachers developed a better understanding of systems thinking as a pedagogy. The involved teachers indicated that the design guidelines assisted them to embed systems thinking in their lesson designs, which suggests that the guidelines are applicable for educational practitioners. The teacher educators indicated that they became more aware of the importance of the explicit introduction of systems thinking in their curriculum and would like to pay attention to this in the future. This study showed the importance of involving practitioners to bridge the gap between empirical research and daily practice.

Introduction

Systems thinking or systems learning has been included in many educational standards and science curricula internationally. However, across curricula, different aspects of systems thinking are emphasized (York et al., 2019). We define systems thinking as an approach to understand how behaviour of complex systems is manifested at different scales and how patterns emerge from the interactions among system components. Systems thinking is a generic approach to understand many different phenomena in terms of universal system characteristics. These characteristics can be used as part of a metacognitive strategy to understand systems in different contexts (Verhoeff et al., 2018). System characteristics can be categorised to three different groups: *structures*, referring to the physical features of the system, *processes*, referring to the dynamics of complex systems and *states*, which describes how complex systems exist in the world as a result of shifts or due to existing structures and processes (Yoon et al., 2018, p. 302).

This study focuses on systems thinking in biology education. We base our work on eight biological system characteristics that have been indicated as important by current systems biologists and which refer to three systems theories, i.e., General Systems Theory, Cybernetics and Dynamical Systems Theories (Gilissen, Knippels, Verhoeff, & van Joolingen, 2020). In terms of these characteristics, each biological phenomenon can be identified as having a system boundary and consists of components which have interactions. Biological systems are open systems and therefore have an input and output of energy, information and matter. Feedback-loops can be identified to maintain the system as a whole, e.g., thermoregulation of the human body. Moreover, systems are dynamic, because (regular) changes can occur over time. The components of a biological system are partial systems of a higher-order system: they are hierarchic. Each (sub)system can be categorised to a level of biological organization, e.g., the cellular and the organism level. On each level of biological organization emergent properties can be identified; these properties emerge by the interactions of the underlying components. For example, muscles, neurons, lungs and blood vessels each have a function, each of which contributes to the emergent property of breathing, existing at a higher level of organization. These eight system characteristics can be used to give students more insight into the structure and functioning of biological systems. Thereby, taking a systems perspective can assist students in understanding and addressing complex and interdisciplinary real-world problems (York et al., 2019).

Many studies in science education have focused on the development and evaluation of teaching and learning methods to foster students' systems thinking. For example, Hmelo-Silver et al. (2017) focused on the development of a deeper systemic understanding by students in terms of structural, behavioural and functional relations by using conceptual representations and modelling activities. This approach seemed to assist students in deepening their system understanding, because it promotes more generic reasoning, which makes it easier to apply this to novel contexts. Tripto et al. (2018), followed students' systems thinking skills over time in the contexts of the human body and the earth system. They emphasize explicit usage of systems language including terms like interactions, patterns, dynamism, homeostasis and hierarchy. Mehren and colleagues (2018), empirically verified a system competence modelling instrument to diagnose and promote students' geographical system competence. Knippels, Verhoeff, and Gilissen (2005, 2013, 2020), developed different teaching and learning trajectories to develop students' systems thinking skills. Knippels, Waarlo, and Boersma (2005) showed in a study on genetics, that a teaching and learning strategy focusing on traversing levels of organization ('yoyo-ing') can assist students to cope with the complex and abstract nature of biological phenomena. Verhoeff, Boersma, and Waarlo (2013) showed in a study on the cell as a system the importance of systems thinking as a metacognitive tool for students. Moreover, this study introduced a hierarchical systems model as a tool to explicitly relate structures and processes of (sub)systems within and between different biological levels of organization. Gilissen, Knippels, & van Joolingen (2020, 2021a) combined the results of their predecessors and developed and tested four lessons, in close collaboration with two teachers, in upper-secondary biology education. The evaluation of these lessons resulted in five design guidelines for the implementation of systems thinking in biology education: (1) Get students acquainted with the term 'system' and the corresponding system characteristics; (2) Start with a central complex problem/question which covers different levels of biological organization; (3) Let students visualize a complex biological problem into a systems model (tool to visualize biological phenomena from a systems perspective); (4) Assist students to reason within and between the levels of biological organization step-by-step; (5) Make (students aware of the) use of the system characteristics.

The implementation process of systems thinking is challenging since different levels are involved, ranging from the supra (international level) to the macro (national level), meso (schools), micro (class and teacher), and nano level (individual student) (Van den Akker, 2006). To implement designed teaching methods at the micro and nano level, it is important to involve pre- and in-service teachers in the implementation process by providing professional development activities to support teachers and conduct research that determines their effectiveness (Krajcik, Codere, Dahsah, Bayer, & Mun, 2014). Practitioners have to get acquainted with systems thinking and learn how they can teach it. Therefore, it is important to investigate whether the developed teaching methods and described design guidelines are viable for teachers to use.

The importance of involving teachers also became clear in the study by Gilissen, Knippels, Verhoeff, & van Joolingen (2020). Although systems thinking is already part of the Dutch national biology curriculum (CTE, 2010) since 2010, Dutch biology teachers seem to be unfamiliar with systems thinking and therefore do not pay conscious attention to it in their education. Moreover, the teacher educators involved in the study of Gilissen, Knippels, Verhoeff, & van Joolingen (2020) indicated that they would like assistance on how to pay more explicit attention to teaching systems thinking in their university teacher training. Overall, it seems important to pay attention to (pre- and in-service) teacher professional development related to teaching systems thinking. After all, successful student learning strongly depends on the expertise of teachers (Hattie, 2009; Mahler, Grosschedl, & Harms, 2017).

The results of previous studies (Fanta, Braeutigam, & Riess, 2020; Yoon et al., 2017) point out that this professional development should not only focus on what systems thinking implies (content knowledge) or on the development of teachers' own systems thinking skills, but also should focus on the development of their pedagogical content knowledge: how can systems thinking be taught to students? Therefore, they recommend a mixed method in which there is attention for teachers' development of content knowledge and pedagogical content knowledge related to systems thinking. However, the reported teacher professional development trajectories are time consuming, for instance Yoon et al. (2017) enacted two weeklong workshops in combination with Saturday workshops (10h per year, for two years), and Fanta et al. (2020) enacted 14 sessions of 90 minutes (Fanta et al., 2020). From our view, university teacher training institutes most often only have a limited time to teach students about different pedagogical approaches, including systems thinking, and the same applies for in-service teachers who have only limited time for professional development next to their teaching job.

To bridge the gap between empirically tested teaching methods and daily classroom practice, the design guidelines of Gilissen, Knippels, & van Joolingen (2020, 2021a) were disseminated to pre-service teachers, in-service teachers and teacher educators in the context of a professional development activity. The aim of this study was to determine the viability of the application of the design guidelines, and therefore the following two research questions were addressed:

To what extent does a teacher professional development activity on systems thinking in biology education, based on the design guidelines, contribute to:

1. pre- and in-service biology teachers' systems thinking content knowledge and their efficacy for developing a lesson in which systems thinking is integrated?

2. biology teacher educators' content knowledge and pedagogical content knowledge related to teaching systems thinking in university-level biology teacher training?

Method

Overall research design

A teacher professional development activity in the form of a workshop was developed and enacted in order to foster teachers' and teacher educators' systems thinking content knowledge and their ability to integrate systems thinking in biology (teacher) education. The workshop was offered to all six university teacher training institutes in the Netherlands as a guest workshop embedded in the regular curriculum; only one institute could not participate due to time constrains. Moreover, we invited in-service teachers to participate voluntarily in two workshops on two locations: in the middle (Utrecht) and in the north (Groningen) of the Netherlands.

Participants

In total 39 pre-service teachers (27 females and 12 males, 21–50 years old) from five different Dutch university teacher training institutes participated in the guest workshop during their regular curriculum. They all are following a Master to achieve their upper-secondary biology education teachers' degree. Moreover, twelve in-service biology teachers (4 females and 8 males, 25–65 years old), all from different schools in the Netherlands, attended the in-service training workshop (Figure 5.1).

Questionnaires were used to determine pre- and in-service teachers' progress of their content knowledge, pedagogical content knowledge and self-efficacy regarding (teaching) systems thinking in biology education (Research Question 1). Additionally, they were asked to develop a lesson in which they incorporated systems thinking, so we could determine to what extent they were capable of this (Research Question 1). Completion of the questionnaires and development of educational material was on a voluntary basis. When teachers did not hand in material after three reminders in the two months after

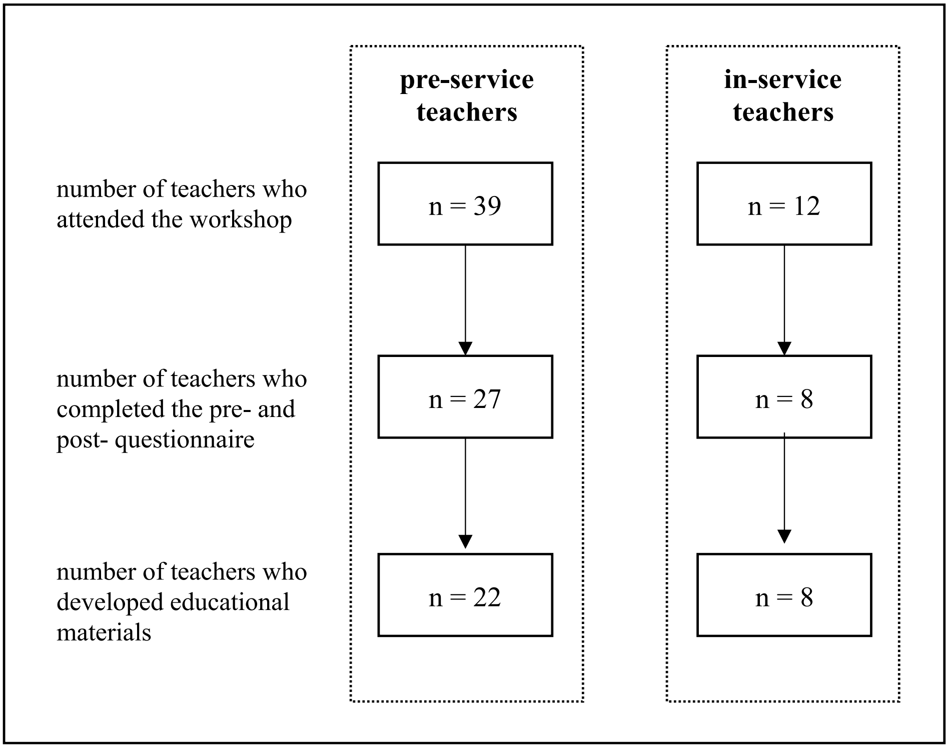

Figure 5.1. Overview of the number of pre- and in-service teachers who attended the workshop, completed the pre- and post-questionnaire and developed educational materials.

the workshop, they received an e-mail with a link to the post-questionnaire and they were asked to clarify why they did not develop any educational materials. Teachers gave the following reasons: not enough time in the next month to design a new lesson, the internship has ended, or reasons like illness or other unforeseen circumstances.

Teacher educators from the five university teacher training institutes (n = 5; 4 females and 1 male) also participated in the guest workshop. Semi-structured interviews (pre- and post) were used to determine their content knowledge and pedagogical content knowledge related to (teaching) systems thinking (Research Question 2).

Workshop

The workshop was developed by the three authors and enacted by the first author between September 2019 and March 2020. It comprises a PowerPoint presentation and activities for the participants. The workshop lasted approximately 2 – 3 hours and consisted of three different phases (Table 5.1).

Phase 1 and 2 focused on the development of participants' content knowledge and phase 3 on their pedagogical content knowledge related to systems thinking. In phase 1, the participants were introduced to systems thinking. The aim of this phase was to learn what systems thinking is and why it is important. In phase 2, the participants applied their obtained systems knowledge to two complex biological

Table 5.1. Overview of the different activities of the workshop that was offered to pre- and in-service teachers and teacher educators.

Phase	Aim	Activities
1	Introduction of systems thinking	1. Explanation of the definition and importance of systems thinking for secondary students in biology education. 2. Participants were asked to determine universal system characteristics by comparing four different biological objects, e.g., chloroplast, human body, animal cell and an ecosystem. 3. Explanation of the eight system characteristics and their visualization in a systems model.
2	Applying systems thinking	4. Participants apply systems thinking to two complex biological problems, i.e., Which measures can be taken to prevent high starvation mortality of red deer during the winter in the Oostvaardersplassen (a Dutch enclosed landscape nature reserve)? and Why are Tibetan people more capable of climbing Mount Everest than Dutch people? The participants have to visualize the corresponding systems in a systems model and reason between the different levels of biological organization to answer the main question.
3	Implementation of systems thinking in secondary biology education	5. Introduction of the design guidelines of Gilissen, Knippels, & van Joolingen (2020, 2021a) and some examples of educational materials where systems thinking is embedded. 6. Participants, individually or in pairs, think about and discuss ways to implement systems thinking in their own classroom practice. 7. Workshop closing and explanation of the homework assignment: (re)develop a lesson in which systems thinking is embedded.

problems. In phase 3, the participants got to know more about the implementation of systems thinking in biology education, i.e., the five design guidelines of Gilissen, Knippels, & van Joolingen (2020, 2021a) were introduced. Teaching examples were given to elaborate these guidelines into classroom practice, and the participants had to think about and discuss possible ways to introduce systems thinking in their own classes. At the end of the workshop, the teachers were asked to (re)develop (and perform) a lesson in the coming two months in which aspects of systems thinking are embedded. This 'homework' assignment was on a voluntarily basis. All workshops had the same content (Table 5.1), only small adjustments were made after performing a workshop, e.g., rearrangement of PowerPoint slides or adding some additional information to the slides.

Data collection and analysis

Online questionnaires (pre and post)

Before the workshop, the pre- and in-service teachers were asked to complete an online questionnaire. The pre-questionnaire consisted of some background questions (i.e., agreement to this study, name, e-mail address, age, and educational background) and two open-ended questions (Table 5.2). The aim of this questionnaire was to determine what the teachers already knew about systems thinking, and to what extent and in which way they already paid attention to systems

Table 5.2. Questions of the online pre- and post-questionnaire for the pre- and in-service teachers.

Questionnaire	Question
Pre-questionnaire	1. How would you define systems thinking (in biology)? 2. Have you ever paid attention to systems thinking in your teaching practice? If so, explain how you did this.
Post-questionnaire	1. What have you learned from the workshop? 2. How could the workshop be improved? 3. Try to describe systems thinking in your own words. 4. Has the original view you may have had on systems thinking changed? If so, how? 5. To what extent do you think it is important that students develop systems thinking on a scale from 1 (not important) to 6 (very important)? If necessary, provide an explanation. 6. To what extent do you think that after attending this workshop, you are able to incorporate systems thinking into your own lessons? Please indicate this on a scale from 1 (I am not capable) to 6 (I am certainly capable). 7. If applicable: what problems did you encounter when developing a lesson about systems thinking? and / or: what questions do you still have? 8. If applicable: how satisfied are you with your own developed system activity lesson on a scale from 1 (not satisfied) to 6 (very satisfied)? 9. Have you paid attention to systems thinking in the classroom in other contexts already? If so, explain in what context and how you did this. 10. Which biological topics / chapters do you think are suitable for paying attention to systems thinking? Please explain your answer. 11. Try to come up with a teaching and learning activity in which you can foster students' systems thinking and describe it briefly below.

thinking in their teaching practice. The post-questionnaire included 11 questions: 9 open-ended questions and 2 six-point Likert scale questions (Table 5.2).

The teachers received the post-questionnaire when they sent their developed educational materials to the first researcher, or when they did not hand in material after three reminders in the two months after the workshop. The aim of the post-questionnaire was to determine how the teachers' description of systems thinking changed, and to determine their self-efficacy regarding teaching systems thinking on a scale from 1 (not capable) to 6 (very capable). Moreover, we asked the teachers to try to come up with a new teaching and learning activity to foster students' systems thinking. Their ideas have been analysed in terms of the design guidelines to investigate teachers' pedagogical content knowledge related to teaching systems thinking.

Developed educational materials

At the end of the workshop, the pre- and in-service teachers were asked to (re)develop a lesson in which systems thinking aspects are embedded. The first researcher developed a codebook based on the design guidelines and general educational context, to analyse the developed educational materials on seven aspects (Appendix 5.1): (1) Biological topic of the lesson; (2) Target audience; (3) Involved system characteristics (design guideline 1); (4) Use of a starting question (design guideline 2); (5) Visualization in a systems model (design guideline 3); (6) Reasoning between and/or within different levels of organization (design guideline 4); (7) Explicit use of systems language (design guideline 5). The educational materials include a description of the lesson in a text document sometimes supplemented with a PowerPoint presentation or image(s). Developed educational materials of 30 teachers were coded by a second coder, i.e., the second author. Differences between the two coders were discussed to come to mutual agreement. Analysis of the developed educational materials gave insight into pre- and in-service teachers' ability to develop a systems thinking lesson, and it illustrates which design guidelines have (not) been used by the teachers in their design.

Interviews

The teacher educators involved were interviewed in a previous study by Gilissen, Knippels, Verhoeff, & van Joolingen (2020). This study aimed to give an overview of the perspectives of current experts on teaching systems thinking, including teacher educators. The aim of that interview was to determine their initial definition of systems thinking and to what extent they pay attention to systems thinking in their teacher training. In our current study these interviews are used as a baseline to analyse the post-interviews. Within one week after the workshop post-interviews were conducted which lasted between 15 and 30 minutes, and which were audio recorded and transcribed verbatim. The aim of the post-interview was to determine whether teacher educators' view on systems thinking had been changed after participating in the workshop, and whether they were going to change their education regarding systems thinking in practice. Moreover, we asked the educators feedback on the workshop. An overview of the questions of the pre- and post-interview can be found in Table 5.3. A summary of the interviews will be given to illustrate their systems thinking content knowledge and their ideas for the future implementation of systems thinking in their teacher training (pedagogical content knowledge).

Table 5.3. Questions of the pre- and post-interview with the teacher educators.

Interview	Question
Pre-interview	1. How would you define systems thinking (in biology)? 2. Have you ever paid attention to systems thinking in pre-service teacher training? If so, explain how you did this.
Post-interview	1. How did you experience the workshop? Can you give some tips and tops? 2. What did you learn from the workshop? 3. To what extent has your view on systems thinking changed after attending this workshop since our first interview? 4. Do you already have an idea how you want to pay attention to systems thinking in your teacher training in the future? 5. To what extent give the design guidelines, which are explained during the workshop, assistance to implement systems thinking in your own teaching practice and in that of the pre-service teachers?

Answering the research questions (RQ's)

The different data-sources have been used to answer the research questions (Table 5.4).

RQ 1: To determine pre- and in-service teachers' content knowledge related to systems thinking, we coded their systems thinking definitions, before and after the workshop, in terms of the system characteristics (Pre-question 1 and Post-question 3 & 4, Table 5.4). For example, the definition "Do not just look at the separate parts (components), but relate things together (interactions) to see it as one large system (boundary and hierarchy)." can be coded to four system characteristics. Teachers pre- and post-definitions, 35 in total, were coded by a second independent coder in three different rounds with the aid of a codebook (Appendix 5.2). Differences between the two coders were discussed to come to mutual agreement.

Note: pre- and in-service biology teachers' efficacy includes their pedagogical content knowledge and self-efficacy. To determine whether pre- and in-service teachers already paid attention to systems thinking in classroom practice, we categorised their answers on Pre-question 2 (Table 5.4) into different groups and counted how many teachers could give an example. To determine pre- and in-service teachers' developed pedagogical content knowledge related to systems thinking, we analysed how many and to what extent the teachers implemented the design guidelines in their developed educational material(s) and additional ideas they gave for practice in the questionnaire (Post-questions 9 & 11, Table 5.4). To determine their self-efficacy, we analysed to what extent on a scale from 1 to 6 teachers were satisfied with their own developed educational materials and to what extent on a scale from 1 (I am not capable) to 6 (I am certainly capable) they feel capable developing educational material on systems thinking (Post-questions 6 & 8, Table 5.4). Moreover, we have summarized the problems teachers identified themselves in relation to the development of educational materials to foster students' systems thinking (Post-question 7, Table 5.4) and the observations/opinions of the teacher educators (Post-interview question 5, Table 5.4).

Table 5.4. Overview of the various data-sources that have been used to answer the different research questions. The online pre- and post-questionnaires were completed by the pre- and in-service teachers and the interviews were conducted with the teacher educators.

RQ	Element	Data-source(s)	Question(s) (Tables 5.2 & 5.3)
1	Content knowledge	Online pre-questionnaire	1
		Online post-questionnaire	3 & 4
2	Pedagogical content knowledge	Online pre-questionnaire	2
		Developed educational material(s)	-
		Online post-questionnaire	9, 10 & 11
	Self-efficacy	Online post-questionnaire	6, 7 & 8
		Post-interview	5
3	Content knowledge	Pre-interview	1
		Post-interview	2 & 3
	Pedagogical content knowledge	Pre-interview	2
		Post-interview	2, 4 & 5

RQ 2: To determine teacher educators’ content knowledge, we coded their systems thinking definitions, given in the pre- and post-interviews, in terms of the system characteristics (Pre-question 1 and Post-questions 2 & 3, Table 5.4 and Appendix 5.2). To determine their pedagogical content knowledge, we determined which design guidelines can be found implicitly or explicitly in the current teacher training institute curriculum related to systems thinking, and their ideas to improve the curriculum in the future (Pre-question 2 and Post-questions 2, 4 & 5, Table 5.4). This is done with the method that is also used to analyse the teachers’ developed educational material (Appendix 5.1).

Results

RQ 1: Pre- and in-service teacher’ content knowledge

Before and after the workshop, in total 35 teachers (27 pre- and 8 in-service teachers) described their definition of systems thinking in the online questionnaire (Figure 5.1). Their definitions were coded in terms of the system characteristics (Table 5.5).

Thirty-four teachers were able to give a definition of systems thinking in the pre-questionnaire. One of the pre-service teachers described systems thinking in general terms, e.g., “Global thinking, [creating an] overview.” The remaining teachers described systems thinking in

Table 5.5. Analysis of participants (n = 35) definition of systems thinking in terms of the system characteristics before and after the workshop, i.e., analysis of pre-test question 1 vs. post-test question 3 of the online questionnaire. The post-results are presented in two columns. The first 'continued' column presents the number of participants that referred to this system characteristic in their pre-definition as well. The second column 'new' presents the number of participants that referred to this system characteristics only in their post-questionnaire.

System characteristics	Pre-service teachers n = 27			In-service teachers n = 8		
	Pre	Post		Pre	Post	
		Continued	New		Continued	New
Naming 'system characteristics' in general	1	1	6	0	0	3
Boundary	11	6	10	2	1	4
Components	24	16	3	5	3	1
Interactions	20	16	4	5	3	3
Input output	0	0	4	0	0	1
Feedback	0	0	1	0	0	0
Hierarchy/levels of organization	14	12	9	3	3	3
Dynamics	0	0	0	0	0	1
Emergence	3	0	2	1	1	0

terms of one or more system characteristics. One teacher implicitly mentioned the term system characteristics: "Thinking back and forth between the different levels of [biological] organization, and recognizing the same patterns, structures and processes on the different levels of organization." The characteristics boundary, components, interactions and hierarchy are represented most often in teachers' definitions, respectively by 13, 29, 25 and 17 out of 35 teachers (Table 5.5). An example of a definition in which four system characteristics (boundary, components, interactions and hierarchy) are represented is:

> *Individual 'parts' can be seen as part of a larger system. For example, organs and an organ system, or cells that together form an organism or different organisms that form an ecosystem together with the abiotic environment.*

The system characteristics input output, feedback, dynamics and emergence were mentioned by none or less than three out of 35 teachers (Table 5.5). In the post-definitions the same system characteristics as in the pre-definitions were presented most often, i.e., boundary, components, interactions and hierarchy, respectively by 21, 23, 26 and 27 teachers. Ten teachers also mentioned the term system characteristics or patterns in their post-definition, e.g.,

> *All (biological) processes can be described in terms of a system with system characteristics. By offering topics from a systems perspective, it is possible to make the connections clear between different topics and at which levels of organization these topics take place. This also provides insight into the bigger picture within which a biological process occurs.*

Moreover, the system characteristics boundary and input output are mentioned slightly more often than in the pre-definitions, respectively fourteen and five new teachers mentioned these characteristics (Table 5.5). The characteristics feedback, dynamics and emergence are not represented very often (by four teachers or less) in their pre- and post-definitions.

In the post-questionnaire, the teachers were asked to explain whether and, if so, how their original view on systems thinking had changed (Post-question 4, Table 5.2). From their answers, three different categories could be identified:

1) **Meaning and implementation of systems thinking in education**: Eleven pre- and six in-service teachers indicated that they developed a better meaning of systems thinking and/or that they know better how to implement systems thinking in classroom practice, e.g., "It has become clearer. Especially how I can apply it [systems thinking]."

2) **Yo-yo teaching and learning strategy versus systems thinking**: Four pre-service teachers indicated that they now know better that systems thinking encompasses more than yo-yo learning, e.g., "I first thought that it [systems thinking] only included the yo-yo strategy, i.e., thinking between and within the different [biological] levels of organization, but it is wider and more than that."

3) **Awareness of the system characteristics**: Three pre- and two in-service teachers indicate that they are now (more) aware of the system characteristics, e.g., "I now see that every system consists of the same components [system characteristics]." and "I know more about it [systems thinking] now. For example, I found the universal characteristics of biological systems a very welcome addition to what I already knew about systems thinking."

RQ 1: Pre- and in-service teachers' efficacy

In the online pre-questionnaire (Pre-question 2, Table 5.2), the pre- and in-service teachers described whether they already paid attention to systems thinking in classroom practice. Sixteen out of 27 pre- and three out of eight in-service teachers could think of an example in which they paid attention to systems thinking in their classroom practice. Three different types of examples could be identified:

1) **Connecting different biological topics** (mentioned by six pre- and two in-service teachers), e.g., pre-service teacher: "Mainly by linking chapters to each other and to relevant prior knowledge / students' daily life. In this way I hope to teach them that everything is connected, and I hope that they will see the mutual relationships / connections and that everything will fall more into place."

2) **Thinking between and within different levels of biological organization** (mentioned by five pre-service teachers), e.g.: "Each time I try to take students from the organism level, which they know well, to the level of organization we are dealing with."

3) **In a specific biological topic**, e.g., ecology (mentioned by seven pre-service teachers), hormone regulation with negative and positive feedback loops (mentioned by one pre-service teacher) and immunity (mentioned by one in-service teacher).

After participating in the workshop, 30 teachers (22 pre- and 8 in-service teachers) handed in developed educational materials in which they embedded systems thinking (Figure 5.1). Moreover, eighteen of these pre- and five in-service teachers have mentioned additional ideas to embed systems thinking in their education in the post-questionnaire (Post-question 9 & 11, Table 5.2). Most teachers developed educational materials for upper-secondary level, only three out of 30 were for a lower-secondary class. The topics of the educational materials were very diverse, e.g., reproduction, digestion, genetics, cells, photosynthesis, hormones, ecology, perception and behaviour, plants and evolution. We examined to what extent the five guidelines were implemented in teachers' developed educational materials or additional lesson ideas. The results that are mentioned can also be found in Table 5.6:

- **Guideline 1**: The results indicate that the teachers focused on various system characteristics in their educational materials, but all teachers embedded at least two system characteristics in their educational materials. Twenty pre-service teachers implemented the characteristics components, interactions, hierarchy and emergence in their educational material. Only five pre-service teachers implemented the characteristic feedback in their material. All in-service teachers implemented the characteristics boundary, components, interactions, input output, hierarchy, and emergence in their material. The remaining characteristics (feedback and dynamics) were implemented by respectively three and four in-service teachers.

- **Guideline 2:** All 22 pre- and eight in-service teachers used a complex question/problem, and in respectively seventeen and eight cases the question/problem was used as a starting point of the lesson.
- **Guideline 3:** Fourteen out of 22 pre- and eight out of eight in-service teachers made use of the systems model to visualize a system or more subsystems.
- **Guideline 4:** Except for one pre- and one in-service teacher, all teachers embedded reasoning between the different levels of biological organization in their educational materials.
- **Guideline 5:** All teachers have introduced the system concept in general or made use of a system characteristic in an explicit manner. Thirteen out of 22 pre- and six out of eight in-service teachers introduced the system concept and all system characteristics explicitly to students. The system characteristic hierarchy is explicitly mentioned most often, respectively by eighteen out of 22 pre-service teachers and seven out of eight in-service teachers, while the characteristics feedback, dynamics and emergence are mentioned less frequently by the teachers.

In total, 14 out of 22 pre- and 7 out of 8 in-service teachers have embedded all five design guidelines in their educational materials.

Table 5.6. Analysis of the developed educational materials and additional ideas for embedding systems thinking in classroom practice (Post-question 9 & 11, Table 5.2) of pre-service and in-service teachers in terms of the five design guidelines.

Design guidelines	**Pre-service teachers n = 22**	**In-service teachers n = 8**
(1) Involved system characteristics (implicit or explicit):		
Involvement of at least two characteristics	22 (100%)	8 (100%)
• Boundary	15	8
• Components	20	8
• Interactions	21	8
• Input output	14	8
• Feedback	5	3
• Hierarchy/levels of organization	21	8
• Dynamics	17	4
• Emergence	20	8
(2) Use of a question/complex problem	22 (100%)	8 (100%)
• Question/problem is used as a starting point of the lesson	17	8
(3) Visualization in a systems model	14 (63,6%)	8 (100%)
(4) Reasoning between different levels of biological organization or within one level	21 (95,5%)	7 (87,5%)
(5) Use of explicit systems language:		
Introduction of the system concept or use of at least one explicit characteristic	22 (100%)	8 (100%)
• General introduction of the system concept and all system characteristics	13	6
• Boundary	8	4
• Components	5	5
• Interactions	7	5
• Input output	8	3
• Feedback	3	1
• Hierarchy/levels of organization	18	7
• Dynamics	3	0
• Emergence	3	1
Embedment of all five design guidelines	14 (63,6%)	7 (87,5%)

In the online post-questionnaire, the teachers were asked to indicate their own capability to develop systems thinking oriented educational materials (Post-question 6, Table 5.2). Twelve pre- and seven in-service teachers scaled their capability positively, i.e., between 4 to 6 on the scale.

In the post-questionnaire (Post-question 7, Table 5.2), teachers were asked to describe possible problems they have encountered related to (developing educational materials for) teaching systems thinking. The challenge that was mentioned most often was time to implement systems thinking in the regular curriculum and to develop suitable educational materials, e.g., pre-service teacher: "Time. I think it [systems thinking] is quite a big and detailed item. To cover this in one lesson might be quite challenging." Systems thinking is not implemented in the regular textbook methods and therefore teachers should take into account some time to introduce students to systems thinking and the related system characteristics and systems model, e.g., from a pre-service teacher:

> *I ran into the problem that students are not familiar with the concept* [systems thinking]. *Therefore, it is not suitable for a one-off lesson.* [As a teacher] *you have to introduce a lot of terms and explain the whole concept of systems thinking. Once students are used to it, you may be able to apply it more often.*

To overcome this, regular attention can be given to systems thinking within different biological contexts, e.g., from an in-service teacher:

“They [the students] still thought it [systems thinking] was somewhat dry, but I just have to repeat it more often. It will be fine.”

Especially the pre-service teachers, ten of them, indicated they think it is difficult to find time in the regular curriculum to both foster students’ systems thinking and to develop students’ biological knowledge, e.g., from a pre-service teacher: “I did not have time (yet) to pay attention to all the characteristics and to let students think about them themselves when the topic (for example the topic genetics) is already difficult in itself.” While it seems that the in-service teachers did not indicate this as a problem, but see it as a necessity, e.g., an in-service teacher:

> *First, I have to encounter problem situations, which can serve as good examples. Initially I came up with a too complex example, where 17–18 years old students got stuck. So, I first have to gather more exercise material.*

The teachers were also asked to indicate how satisfied they were about the educational materials they have developed (Post-question 8, Table 5.2). Most teachers, fifteen out of 22 pre-service teachers and four out of eight in-service teachers, scored their satisfaction on a scale from 4 to 6.

In the post-interviews (Post-question 5, Table 5.3), the teacher educators were asked to what extent they think the pre-service teachers are capable of implementing systems thinking in classroom practice by themselves after the workshop. Teacher educator A mentioned that the systems thinking approach can be the first step for pre-service teachers to see the coherence between all the different biological topics they have to teach. In the workshop, various examples of systems in biology are presented, but the pre-service teachers now have to learn to recognize these systems themselves. She mentioned an example during the workshop in which a pre-service teacher did not recognize a system in the chapter 'introduction to biology' he was teaching at that moment:

> *They* [pre-service teachers] s*till struggled to recognize it [the system] themselves. Perhaps you could assist them to recognize it in their own topics.* [...] *Such as, what are you teaching at the moment? Which systems are present in this topic? Otherwise, they are going to see it as something really big.*

Teacher educator B mentioned that, during the workshop, most of the examples of teaching and learning activities that were presented were for upper-secondary education. Therefore, it could be that students do not see how they can implement systems thinking in lower-secondary education. Moreover, he indicated that the last assignment, in which the pre-service teachers had to elaborate a problem/question in a systems model by themselves, was quite challenging.

> *I can imagine that a lot of pre-service teachers think 'I do not see my students doing this'. I can see that this is at one end of the continuum.* [...] *I hope they see that there are all kinds of intermediate steps to start with to introduce systems thinking in a much more structured way.*

Teacher educator C indicated that some of the pre-service teachers experienced difficulties with completing a systems model in the context of a biological topic they have to teach in the near future. She thinks that is easier for pre-service teachers to develop systems thinking oriented lessons in the context of a biological topic which they already have taught: "Then they [pre-service teachers] already know a bit about how students will react and what they find difficult." Moreover, she mentioned that she noticed that the students in the last assignment focused especially on the elaboration of hierarchy and dynamic and not on the other characteristics. According to her, a reason for this could be that she already gave attention to those two characteristics in the context of the yo-yo teaching and learning strategy and by paying attention to visualization of dynamic processes in biological images. Another cause could be that the systems model invites pre-service teachers to focus on these two characteristics, because the different levels of biological organization are visualized explicitly in the systems model and the arrows visualize the dynamic processes.

Teacher educator D indicated that the workshop encouraged the pre-service teachers to think about interconnectedness in biology and how this can be visualized into a systems model. However, she wondered in how much detail the pre-service teachers would elaborate on systems thinking in their developed educational materials, i.e.,

> [...] *because I notice that when I give them things* [pedagogical approaches], *they are still caught up in the issues and fuss of the day and they are busy with class management, and*

therefore they get the feeling they do not have time for these things and just follow the textbook and nothing more.

Teacher educator E mentioned that discussing a complex problem in terms of the systems model promoted pre-service teachers' thinking and conversation between them. She also mentioned that she heard students say: "I do notice it is effective to think longer about a specific problem, but I do not think it will give a better overview [of biology]." She thought it would be interesting to have a discussion about this with the teachers, but "there was not a lot of time for that now, but it would be valuable to make time for it in the near future."

RQ 2: Teacher educators' content knowledge and pedagogical content knowledge

Teacher educator A indicated, in the pre-interview (Table 5.3), that she does not explicitly introduce the term systems thinking in her teacher training, e.g., "I am not paying attention to it [systems thinking] very explicitly, not like 'today we are going to talk about systems thinking', but I think it is interwoven in all my pedagogical lessons." She indicated that she pays explicit attention to the concept of emergence and reasoning between the different levels of biological organization, by giving the students a complex problem or question to investigate, e.g., "I think by offering them [students] a problem from practice, that they have to figure it out and that they therefore have to apply knowledge of different [biological] levels of organization to solve the problem."

In the post-interview, the teacher educator indicated that she would like to pay more in-depth and explicit attention to systems thinking by introducing the different system characteristics and making the pre-service teachers aware of the identification of systems around them. For example, she would like to let her students think of the different systems that could be identified in the biological topics they are teaching at the moment. She indicated that it would be nice to visualize one of these systems in the classroom.

Teacher educator B described systems thinking as:

> *A way to bring coherence to a whole lot of biology. Seeing all kinds of similarities between biological systems at all kinds of different levels of organization. In short, you see all kinds of systems, a living system, as a limited system.* [...] *You can consider it as a black box, but you can also zoom in and then recognize sub-systems in it and you will see that on all those different levels you can actually make the same well-known scheme* [systems model]. [...] *In my opinion systems thinking really provides horizontal coherence and the levels of* [biological] *organization provide vertical coherence.*

Systems thinking is introduced explicitly in his teacher training in series of lectures around 'coherence in biology'. Other pedagogies that are introduced in this workshop are the yo-yo teaching and learning strategy, concept mapping and molecular mechanistic reasoning. He expects from his students that they are able to pay attention to the different levels of biological organization and reasoning between them in their educational materials, and that they know about the concept of systems thinking. He thinks that the main concern for the pre-service teachers is to survive their first lessons and to plant seeds for pedagogical approaches, systems thinking among them. In the post-interview, teacher educator B indicated that his view on systems thinking and the application of it has become clearer, e.g.,

> *I found your distinction in those seven* [system] *characteristics very clear. It helps to recognize them each time. What I really liked was seeing the didactics* [of systems thinking]. *You have shown us a number of ways in which you can work with students with systems thinking.*

In the future, he would like to give the same workshop to his pre-service teachers. He thinks it is important to show his pre-service teachers that there is a range of different activities to foster students' systems thinking gradually.

Teacher educator C described systems thinking, similar to teacher educator B, as horizontal and vertical reasoning between the different levels of biological organization. In her teacher training, she teaches pedagogical strategies in relation to a specific biological topic. For example, she paid attention to the yo-yo teaching and learning strategy in the context of genetics, and to molecular mechanistic reasoning in the context of ecology. She indicated she only paid implicit attention to systems thinking in both strategies and by discussing different biological images, for example a food web. For example, by paying attention to the different interactions between the components (who eats who?), but also to dynamic processes (what happens if you introduce an invasive species to this ecosystem?). In the post interview, teacher educator C indicated that she preferred the eight system characteristics, because it is an easy starting point to develop educational materials. She also indicated that she already paid attention implicitly to the system characteristics hierarchy and dynamics and now became more aware of the importance of the system characteristics boundary and input output on the different levels of biological organization. In the future, she would like to pay more explicit attention to systems thinking in a specific biological context, just as she already did with the yo-yo strategy.

Teacher educator D described systems thinking as a way to see biological objects as self-organizing systems that are working together in a larger whole and in which “The sum of the whole is more than the sum of the parts.” She repeatedly pays attention to the yo-yo strategy, but she does not pay explicit attention to systems thinking in her teacher training. In the post interview, she indicated that she sees the added value of the systems model: “I have learned that with this simple scheme [systems model] you can actually make many things transparent.” Moreover, she also became more aware of the importance of the input and output of biological systems. In the future, she would like to use the workshop to introduce systems thinking to pre-service teachers, because it is a nice extension of the yo-yo strategy, e.g.,

> *The yo-yo strategy often remains a bit too superficial. That is how they* [the students] *pay attention to the levels of organization, but you do not really get to the core of systems thinking, I guess. This* [systems thinking approach] *is a very nice next step.*

Teacher educator E described systems thinking as a way to see overall patterns between the different biological topics in order to create a coherent view of biology and implemented it implicitly in the teacher training, e.g.,

> *I am afraid that I never mentioned that word* [systems thinking], *while of course I do pay attention to it. For example, when talking about regulation or all kinds of different core themes. Then we discuss about all kinds of possible strategies to tackle that in the classroom, but I think we do not use the word. We use the word yo-yo* [strategy], *horizontal and vertical thinking, but we do not use the word systems thinking.*

In the post interview, she indicated that her view on systems thinking has not changed, but that she would introduce the system characteristics more explicitly in teacher training in the future, e.g.,

> T*he idea that a system has certain characteristics and these are the characteristics, I did not say that at the time and I will probably just take over / use that from you. Because I think that it helps. There are just too many of them* [system characteristics] *to keep them flexible in your head and this is not necessarily because they* [students] *know that they have to pay attention to feedback loops after they have been working with it for a while even if you do not immediately mention them explicit.*

Conclusion and discussion

In the international literature and in current curricula in many countries there is consensus that systems thinking is an important thinking skill in the sciences, and in particular in biology. However, it seems that systems thinking did not find its way into daily biology classroom practice yet partly because teachers indicate a lack of professional skill to embed systems thinking in their regular lessons (Gilissen, Knippels, Verhoeff, & van Joolingen, 2020). Therefore, we developed a professional development activity (workshop) for pre- and in-service teachers concerning teaching systems thinking in biology education. This workshop was based on guidelines derived from earlier work involving classroom studies (Gilissen, Knippels, & van Joolingen, 2020, 2021a). We investigated to what extent this activity contributed to pre- and in-service teachers' systems thinking content knowledge, their efficacy to develop a lesson in which systems thinking is integrated (RQ

1), and biology teacher educators' (pedagogical) content knowledge towards the practice of systems thinking in university teacher training (RQ 2).

RQ 1: Teachers' content knowledge and efficacy

According to the teachers, the workshop led to an improvement of their content knowledge related to systems thinking. For instance, they already were familiar with the yo-yo learning and teaching strategy of Knippels et al. (2005, 2018), and they now have experienced that systems thinking is an extension to this strategy. The yo-yo strategy focuses on the horizontal and vertical coherence of different subsystems, whereas in our approach systems thinking also involves a more detailed breakdown in all eight system characteristics. Moreover, the teachers indicated they are now more aware of the universal system characteristics that apply to all biological systems. In the post-questionnaire, teachers define systems thinking mostly in terms of the following system characteristics boundary (60%), components (65,7%), interactions (74,2%) and hierarchy (77,1%) (Table 5.5). The remaining four characteristics (input output (14,3%), feedback (2,9%), dynamics (5,7%) and emergence (8,6%)), as can be seen from the percentages, are reflected less often in their definitions. A reason for this may be that the characteristics feedback, dynamics and emergence can be found more indirectly in the systems model which was central during the workshop. Another reason is that these four characteristics are more advanced characteristics, which is confirmed by Ben-Zvi Assaraf and Orion (2005) who described systems thinking in eight hierarchical abilities in an ascending order of difficulty, i.e., the Systems Thinking Hierarchical (STH) model. The first two abilities (1. identifying the components and processes of a system and 2. identifying simple relationships among a system's components') are in line with the characteristics boundary, components and interactions. The second, fifth and sixth 'higher' abilities are in line with the other four characteristics, e.g., 3. identifying dynamic relationships within a system (dynamics and feedback); 5. identifying matter and energy cycles within a system (input output); 6. recognizing hidden dimensions of a system (emergence).

The results of the analysis of the developed educational materials (Table 5.6) shows that a majority of the teachers, 14 out of 22 pre- and 7 out of 8 in-service teachers, translated all five design guidelines into their lesson. All teachers embedded at least one system characteristic (**design guideline 1**) in their educational materials. Moreover, they all centre their material around a central complex problem/question (**design guideline 2**). The systems model was used by 14 of the pre- and by all eight in-service teachers to visualize a complex biological problem (**design guideline 3**). Except the educational material of one pre-service teacher, all developed educational materials include ways to assist students to reason step-by-step within and between the levels of biological organization (**design guideline 4**). Moreover, all teachers gave a general introduction of the system concept or made use of at least one explicit system characteristic (**design guideline 5**). Notably, while the teachers did not often mention the characteristics input output, feedback, dynamics and emergence in their definition of systems thinking (Table 5.5), they did give attention (implicitly or explicitly) to most of these characteristics in their developed educational materials (Table 5.6). Only the characteristic feedback was embedded less often in the materials, i.e., by five of the pre- and three of the in-service teachers.

Overall, a small difference can be found between the pre- and in-service teachers' developed lessons. As the results show in Table 5.6, the in-service teachers embedded more system characteristics and used the problem/question more often as a starting point of the lesson compared to the pre-service teachers. This is probably due to the fact that pre-service teachers are developing their PCK in terms of subject knowledge *and* pedagogical strategies, in this case systems thinking. For the in-service teachers, only systems thinking as pedagogical strategy is new. A majority of the teachers (fifteen of the pre-and four of the in-service teachers) indicated that they are satisfied with their developed material and more than half of the teachers (twelve of the pre- and seven of the in-service teachers) indicated that they feel capable to develop systems thinking oriented educational materials. Probably this is partly due because the workshop has put the teachers in the perspective of students which can have assisted them to develop more effective lesson plans (Richman, Haines, & Fello, 2019).

Teachers indicated they struggled to find time to introduce the system concept and the system characteristics and to think of a way to gradually embed systems thinking in the regular biology curriculum, which is indeed a big challenge. Here also lies a responsibility for textbook writers who might embed systems thinking in the biology textbooks to ensure its sustainable implementation into biology education. However, just as teacher educator B indicated, the teachers are now for the first time introduced to the concept of systems thinking in a 2 to 3 hours workshop, in other words: a seed has been planted. Given the available time for the workshop, the results can be seen as very satisfactory. The next step is to encourage the seed to grow in follow-up professional development activities in which attention could be paid to the gradual development of students' systems thinking within the biology curriculum.

Ninety percent of the developed educational materials focused on upper-secondary biology education. This can be due to the fact that the involved pre-service teachers are following the university teacher training and thus often teach upper-secondary biology classes during their internship, and the involved in-service teachers are, except one, upper-secondary biology teachers. Another reason can be that the workshop especially showed examples of teaching and learning activities for upper-secondary students. In a follow-up activity, examples can also be shown of teaching and learning activities for lower-secondary education.

RQ 2: Teacher educators' (pedagogical) content knowledge

Most teacher educators stated that they only implicitly paid attention to systems thinking in their university teacher training, i.e., they did not mention the term systems thinking. They especially valued the overview of the eight system characteristics of biological systems and the systems model in which these characteristics can be made visual. In the future, the teacher educators would like to introduce systems thinking explicitly, similar to we did in the workshop.

Final note

The results of this study can be categorised as a qualitative explorative study, because of the relatively low number of participants and detailed description of the results. Therefore, it is important to scale-up this research in the future and to compare these results with other countries. Moreover, while the response rate on the questionnaire was fine (69% of the pre- and 67% of the in-service teachers), the response rate for the educational materials was lower (56% of the pre- and 67% for the in-service teachers). The teachers did not develop educational materials due to time constrains or other unforeseen circumstances. Nevertheless, in this study, a first step is made to bridge the gap between empirical research and daily classroom practice. The empirically tested design guidelines of Gilissen, Knippels, & van Joolingen (2020, 2021a) are transferred to pre- and in-service teachers in a workshop, and the results showed that teachers are able to translate these guidelines into educational materials, which suggest that the guidelines are viable for use by educational practitioners. Further research could focus on the effect of the developed educational materials on students' systems thinking (Fischer et al., 2005), i.e., the nano level (Van den

Akker, 2006), but this was not within the scope of this study. The teacher educators of the Dutch university teacher training institutes declared that they would like to pursue the workshop on systems thinking in their curriculum. In this way, pre-service teachers already get familiar with systems thinking as a pedagogical teaching strategy during their teacher training (Fanta et al., 2020). To sustain and extend this, professional development activities concerning teaching systems thinking in biology education can be offered to in-service teachers in the future as well, so systems thinking becomes more and more entangled within the biology curriculum. Thus, systems thinking can become one of the 'regular' embedded pedagogical strategies in the curriculum, just as for example the yo-yo teaching and learning strategy of Knippels (2005) and the concept-context approach of Ummels, Kamp, de Kroon, and Boersma (2015) already seem to be. Of course, this not only applies for biology education, but also for geography and chemistry education, in which systems thinking also is evident. By paying attention to systems thinking in both pre-service and in-service professional development, systems thinking will eventually find its way into daily classroom practice.

Chapter 6

General conclusion and discussion

The main aim of this dissertation was to describe how systems thinking can be fostered in secondary biology education. We first identified what systems thinking entails according to systems biologists, teacher educators and teachers in the light of three systems theories (i.e., GST, cybernetics and DST) and to what extent systems thinking has found its way into Dutch secondary biology education since the introduction of systems thinking into the curriculum in 2010 (Chapter 2). We then carried out four lesson study (LS) cycles to identify design guidelines for embedding systems thinking in secondary biology education (Chapter 3 and 4). Finally, we validated the applicability of the guidelines for (re) designing biology lessons to embed systems thinking by disseminating the guidelines to pre- and in-service teachers and teacher educators from university-level teacher training institutes in the context of a workshop (Chapter 5).

Definition of systems thinking

By combining the perspectives of current systems biologists, teacher educators and biology teachers on systems thinking and three systems theories, a usable working definition of systems thinking was developed for secondary biology education. The results of the study presented in Chapter 2 (Gilissen, Knippels, Verhoeff, & van Joolingen, 2020), showed that the systems concepts from three systems theories, from which systems thinking was originally derived, should be the focus of students' conceptual development. According to the systems biologists involved, secondary biology education should address students' exploration of universal characteristics of biological systems through modelling. This led to the following definition of systems thinking for secondary biology education:

> *Systems thinking is a way of thinking in which biological phenomena are seen as systems and can be understood by modelling them in terms of seven system characteristics: boundary, components, interactions, input and output, feedback, hierarchy, dynamics, and thereby developing knowledge about the remaining eighth overarching characteristic: emergence.*

Although systems thinking is part of the Dutch secondary biology curriculum, the results suggest that limited attention is paid to systems thinking in current secondary biology education and university-level teacher training courses. When attention is paid to systems thinking, it is done mostly in an implicit manner: the individual system characteristics are not mentioned by name. It appears that teachers and teacher educators mainly pay attention to the yo-yo teaching and learning strategy of Knippels (2002), which shows an implicit relation to the system characteristics of components, interactions and hierarchy. As a consequence, students do not become aware of the system characteristics. Although not much attention is paid to systems thinking in teaching practice in the Netherlands, teachers and educators do emphasize the importance of developing students' systems thinking in biology education and are willing to develop pedagogical content knowledge related to teaching systems thinking.

Design guidelines to foster students' systems thinking

Systems thinking focuses on part-whole relationships and therefore it is inevitable that an integrative teaching and learning approach is needed to foster students' systems thinking. Students must learn to interrelate and place the different biology topics, the parts, within a bigger picture. The results of the studies presented in Chapter 3 (Gilissen, Knippels, & van Joolingen, 2020) and 4 (Gilissen et al., 2021a), led to guidelines for implementing systems thinking in secondary biology education, the applicability of which has been validated by educational practitioners (Chapter 5).

First get students acquainted with the term 'system' and the corresponding system characteristics. This can be done by showing students different examples of systems and introducing the eight system characteristics. The results of the study presented in Chapter 3 showed the importance of doing this in a well-known biology context, due to the twofold meaning of the characteristics of hierarchy and feedback. This is in line with Dauer, Dauer, Lucas, Helikar, & Long (2021), who indicated that it is important "to relate the complexity to a clear example content". Hierarchy in biology has to do with the organization of systems, and not with a certain ranking. Feedback has to do with changes that occur in systems, and not with giving feedback to someone. While this is clear for biologists, it seems to be not so clear for students, and therefore it is important to discuss this twofold meaning with students.

After introduction of the system characteristics, students have to learn how they can apply the different system characteristics. The results of the study presented in Chapter 4 showed that the value and applicability of the system characteristics becomes especially clear to students when applying them to a complex biological problem that covers different levels of biological organization. So, **a complex problem can be used as a starting point to encourage students to apply the system characteristics**. The first step is to identify the system of interest. Modelling can support students to organize and visualize their understanding, specifically to identify and describe the system of interest: the boundaries of the system, the elements comprising the system and how those elements interact (K. J. Wilson et al., 2020). **The systems model** (a tool to visualize biological phenomena from a systems perspective, see Figure 4.1) **assists students to create an overview of the system of interest in terms of the system characteristics.** The results of the study presented in Chapter 4 (Gilissen et al., 2021a), showed that the process of visualization encouraged students to reason about the complex problem, which shows that the systems model gains meaning for students by their reasoning about it. This is in line with Forbes et al. (2015), who claimed that models can act both as representations of biological systems and as tools to shape students' reasoning. Perhaps this is because of the offloading function of externalizing students' mental representations (Ainsworth, 2006; Dunlosky, Rawson, Marsh, Nathan, & Willingham, 2013; Leopold & Mayer, 2014; Schmidgall, Eitel, & Scheiter, 2019). **It is important to assist students in reasoning step-by-step within and between the levels of biological organization** represented in the systems model. Partial questions (problems) can guide students to answer the central question by descending and ascending the different levels of biological organization (without skipping intermediate levels), which is also known as the yo-yo teaching and learning approach (Knippels, 2002). This can be done by asking students explicitly what levels of organization should be included in their reasoning steps and with what purpose: students have to learn that causal explanations can be found by moving down to lower levels and functional explanations by moving to higher levels of biological organization. Furthermore, students must determine what effect a change in the system has on the different levels of biological organization.

Make students aware of the broad applicability of the system characteristics. To assist students in remembering the system characteristics, a tangram figure with the icons of the system characteristics can be used as a metaphor (Figure 3.2 and cover of this dissertation). Moreover, it is important for teachers to pay attention to systems thinking in a wide variety of contexts during the school year, ranging from the cellular to the biosphere level, and to make explicit connections with the system characteristics (and the tangram figure used as a metaphor) in the teaching and learning activities. This is in line with Verhoeff et al., (2008) and Tripto et al., (2016), and with Dauer et al. (2021), who recommended "to de-compartmentalize concepts by explicitly connecting them across a curriculum". In this way, students become aware of the wide applicability of the system characteristics.

A systems perspective can be used to design a variety of lessons to foster students' systems thinking. Systems thinking includes zooming in and out on parts and wholes. Therefore, it is possible to **focus a lesson on a specific system characteristic (zooming in) and also to deepen students' understanding of this characteristic in relation to the others (zooming out)**. Another possibility is to model a complex system (zooming in) and to compare this system with other complex systems (zooming out).

Considerations when applying guidelines

The results (described in Chapter 3 and 4) showed that the system characteristics of feedback, dynamics, hierarchy and emergence are considered more difficult by students. This is in line with Ben-Zvi Assaraf and Orion (2005), who suggested that systems thinking can be categorised as eight hierarchical characteristics or abilities that students should develop in an ascending order. According to their model, feedback, dynamics and hierarchy fall within the most advanced levels of systems thinking. Therefore, we recommend paying specific attention to deepening students' understanding of these system characteristics as well. For example, the characteristic of feedback is of a different nature in physiological systems and in ecosystems. Many physiological systems within an organism's cells, tissues and organs, tend to reduce fluctuations to maintain a stable state called homeostasis (Freeman et al., 2017; Wellmanns & Schmiemann, 2020). In contrast, ecological systems have a certain resilience to perturbations, but there is no such thing as a 'balance of nature' (Ampatzidis & Ergazaki, 2018). It is better to talk about a 'flux of nature': natural systems have no need to be in (dis)balance and are ever-changing (Ladle & Gillson, 2009).

The results (presented in Chapter 3 and 4) also showed that the average and low student achievers especially valued the use of the system characteristics in combination with the systems model. These students indicated that systems thinking assisted them to delve deeper into the problem and invited them to take different perspectives on complex problems, allowing them to see more connections. This in line with other studies that also found positive relations between the learning of low-level performing students and the use of modelling activities (Bennett et al., 2020; Dauer et al., 2013).

Validation of applicability of the guidelines by educational practitioners

The workshop, which was based on the design guidelines for fostering systems thinking, led to improvement of teachers' and teacher educators' content and pedagogical content knowledge related to teaching systems thinking (Chapter 5). The participants indicated that they were now more aware of the universal characteristics that apply to all biological systems and had experienced that systems thinking is an extension of the yo-yo teaching and learning strategy. The yo-yo strategy focuses on the horizontal and vertical coherence of different subsystems, without involving a more detailed breakdown into all eight system characteristics. The teachers involved indicated that the design guidelines assisted them to embed systems thinking in their lesson designs. They especially valued the overview of the eight system characteristics and the use of the systems model to visualize the system in terms of the system characteristics. The 'difficulty' most often mentioned by the teachers involved was finding time to (re) develop their lessons to embed systems thinking and finding time in the regular curriculum to pay attention to systems thinking regularly. Embedment of systems thinking indeed takes time, but when attention is paid to the overarching principles of biology, it can save time in the end, because when you are able to take a systems perspective, you can apply it to a wide range of (biology) contexts.

Considerations for textbook writers

Textbook writers have an important role in supporting teachers in embedding systems thinking in secondary biology education. For example, Campbell et al. (2011), a textbook that is often used by first year biology undergraduate students, has a chapter about the unifying principles of biology. For secondary biology textbooks, a chapter introducing students to systems in biology, the corresponding system characteristics and the systems model would be very welcome. Recurring assignments in the textbook can assist students to become aware of the wide applicability of the system characteristics and to practice application of the system characteristics and the systems model.

Contributions to the research field

Systems thinking

Several frameworks can be found in science education literature for fostering students' systems thinking, for example, the Systems Thinking Hierarchical (STH) model (Ben-Zvi Assaraf & Orion, 2005), the Structure-Behaviour-Function (SBF) model (Hmelo-Silver et al., 2007) and the Phenomenon-Mechanisms-Components (PMC) model (Hmelo-Silver et al., 2017). While all of these models share some similarities, their differences can be attributed to references, explicit or implicit, to the key concepts of different systems theories, that is, General Systems Theory (GST), Dynamical Systems Theories (DST) and Cybernetics (Boersma et al., 2011). While most science education studies reporting about systems thinking have focused only on some systems concepts in their definition of systems thinking, Boersma et al. (2011) and Verhoeff et al. (2018) recommended focusing on the systems concepts from all three systems theories. We have built on these considerations and defined eight system characteristics that are based on the theoretical systems concepts of all three systems theories and also on insights from systems biologists.

Another point in which our approach differs from the other frameworks for systems thinking is that we recommend introducing students to all eight system characteristics at once, after which students can explore specific characteristics in more detail. For instance, the STH model (Ben-Zvi Assaraf & Orion, 2005) describes systems thinking as four abilities that should mastered by students in an ascending order. In our view, for a holistic view on systems, students should be introduced to all system characteristics simultaneously. Of course, some system characteristics are more difficult than others; our results showed that hierarchy, feedback, dynamics and emergence were perceived as especially difficult by students. Therefore, we also recommend paying specific attention to students' understanding of the individual system characteristics. In this dissertation, various recommendations have been given for assisting students to approach a complex biological problem from a systems perspective. Guiding questions related to the system characteristics assist students to investigate the system of interest in terms of the system characteristics. Moreover, the systems model assists students to visualize the system of interest in terms of the system characteristics and encourages students to reason about it, because the model gives insight into the interactions between the different components on the different levels of biological organization (hierarchy). This illustrates how a change in one component has an effect on the system as a whole, that is, emergence.

While systems thinking is a generic approach to understanding many different (biological) phenomena in terms of system characteristics, many educational studies on systems thinking have focused on fostering students' systems thinking with regard to a specific biology topic, such as the cell (Verhoeff, 2003), the human body (Ben-Zvi Assaraf et al., 2013; Snapir et al., 2017) and ecosystems (Jordan et al., 2014). The advantage of our guidelines is that they are not topic specific but are applicable to a wide range of (biology) topics. The system characteristics can be used as part of a metacognitive strategy to understand systems in different contexts.

In summary, this dissertation led to a working definition of systems thinking for secondary biology education and guidelines to foster students' systems thinking in secondary biology education.

Lesson study

Besides the contributions to the literature on systems thinking, the results of this dissertation also contribute to the existing literature about the use of LS as a professional development approach (e.g., Lewis et al., 2006) and as a research method (e.g., Bakker, 2018). With LS, teachers' knowledge of student capabilities, didactic knowledge and practical applicability can be integrated with theoretical knowledge from the educational research community (Gilissen et al., 2021c), which can also lead to the construction of new theoretical knowledge and thereby bridge the gap between educational practice and research.

Limitations

Qualitative study

Due to the qualitative nature of our research, the different studies compromise a relatively small sample size.

In the study presented in Chapter 2, we ensured that data saturation (Glaser & Strauss, 2017) was achieved. After conducting three interviews with participants from each group (systems biologists, teacher educators, teachers), the corresponding transcripts were analysed before a second round of interviews was performed. During this round no new codes were originated, which suggests that there was data saturation. This was confirmed in a third round.

In the studies presented in Chapters 3 and 4, we chose to perform four LS cycles with the same LS team in the same two classes during one school year. In this way the teachers continued their development of knowledge related to teaching systems thinking in each cycle and students' learning could be followed over time. So, although we made use of a relatively small sample size, it gave us in-depth insight into the key teaching and learning activities that foster students' systems thinking. Another possibility was to disseminate the designed lessons to other schools and to determine effects on students' systems thinking, but this was not within the scope of our study. In this study, we aimed to identify design guidelines that can be used by practitioners to embed systems thinking in secondary biology education, and not to design perfect ready-to-use lessons and to determine their effect-size. These guidelines give opportunities for embedding systems thinking in lessons covering a diverse range of (biology) topics and levels. Therefore, we chose to perform our final study (Gilissen et al., 2021b), presented in Chapter 5, in which we verified whether the guidelines were viable for use by in- and pre-service teachers and by teacher educators. In this study, we analysed the extent to which the guidelines were embedded in the developed educational materials, but we did not study the use of the lessons in classroom practice.

Externalization and assessment of students' systems thinking

While this dissertation does not explicitly report about a tool to assess students' systems thinking, we did attempt to develop an assessment tool. In a related study by Van Geelen (2019), supervised by our research team (Gilissen, Knippels, & van Joolingen), we investigated whether students' drawings of different biological phenomena and some additional questions could give an indication of students' systems thinking. Development of a suitable code book was very challenging. Even when we coded a specific element in a drawing as a system characteristic, the question still remained whether students drew this specific element on purpose, so it was difficult to determine whether the test was reliable and valid for assessing students' systems thinking. The only conclusion we could draw was that students in our case studies made more explicit use of the system characteristics in the tests during the school year in comparison to the control group (Van Geelen, 2019).

In retrospect, the systems model is a way to encourage, but also to visualize, students' systems thinking in terms of the system characteristics. This is in line with Long et al. (2014), who stated that modelling is simultaneously a tool that fosters reasoning about complex systems for students, and one that makes students' reasoning visible to instructors. Models allow instructors to provide rapid, individual and specific feedback to improve modelling and foster better conceptual understanding (K. J. Wilson et al., 2020). So, the systems model could be used as a formative and summative assessment tool.

Directions for future research

A good direction for a follow-up study could be to ask a group of teachers to (re)design their lessons to embed systems thinking in their classrooms. It would be interesting to follow teachers and students over a longer period to see what this way of thinking and teaching yields in terms of understanding complex biological problems and development of a coherent view on biology.

This dissertation reports specifically about students in upper secondary biology education, but in our opinion, it is preferable to introduce systems thinking earlier, in lower-secondary biology education. In this way, students learn to take a systems perspective on biology from the outset and could benefit from it longer. Moreover, in this way teachers have more time to foster students' systems thinking in secondary education. The results (presented in Chapter 3 and 4) showed that some systems characteristics are more difficult than others, namely feedback, dynamics, hierarchy and emergence. Our hypothesis is that it is possible to embed systems thinking in lower-secondary education by starting with: recognizing systems in biology, introducing the eight system characteristics, defining systems in terms of their components, interactions, input and output, and visualizing these characteristics in the systems model. Moreover, it is important to pay attention to part-whole relations and name the corresponding levels of biological organization, which is a step towards understanding the hierarchy of systems. In a follow-up study, attention could be paid to fostering students' systems thinking in lower-secondary education.

Moreover, it would be interesting to investigate whether the design guidelines described in this dissertation are applicable to embedding systems thinking in other secondary education subjects.

Final note

This dissertation provides guidelines for paying attention to systems thinking in secondary biology education. As systems come in all types of shapes and forms, systems thinking is valuable not only for secondary biology education but also for other contexts. For instance, systems thinking can be valuable to solve complex problems within a professional organization or on a personal level. Systems thinking is the ability to create an overview of a complex problem and to think of outside-the-box answers by approaching a phenomenon from different angles. With a systems thinking perspective, you are trying to understand systems' emergent behaviour by focusing on the interrelated whole instead of the separate components. Development of systems thinking in secondary biology education is of great importance for a coherent and interdisciplinary view in, and on, the rest of your life!

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Appendices

Appendix 2.1.

I would like to ask you to fill in the questionnaire below as honestly as possible so that I get a complete and reliable picture of the meaning of systems thinking according to systems biologists, teacher educators and biology teachers.

1. Indicate for each aspect whether you consider this as an important aspect of systems thinking or not.

Aspect	Important	
	yes	no
IDENTIFY THE SYSTEM - If you are interested in a biological phenomenon, you can characterise the corresponding system. You have to determine the system boundary: which parts and processes belong to the system and which ones to the environment. The parts in a system interact with each other.		
INPUT AND OUTPUT - Biological systems are open systems; they interact with their environment. Matter, energy and/or information enter the system (input), then the system itself can be seen as a black box where all sorts of processes take place and after that, matter, energy and/or information comes out (output). Open systems are also self-regulating and dynamic. With the aid of feedback mechanisms / control circuits, the system ensures that a deviating value is brought back to the set point. At the level of the cell and the organism, this process is called homeostasis.		
EMERGENCE - The components of a system work together to achieve a certain goal or function at a higher organizational level. This is called emergence. To be able to explain this phenomenon, you have to descend to the underlying levels or from the parts to the top. This is also called yo-yo strategy or vertical coherence.		
DEVELOPMENT - A system can be approached from the perspective of development, e.g., in terms of developmental biology (how does an individual develop during his life) or in terms of evolution.		
MODELS - Models can be used for every aspect, for example to visualize / simulate the system or to make predictions.		

2. Are you missing important aspects of systems thinking in the list above? Yes? Which one?

This second part of the questionnaire is ONLY for teacher educators and teachers.

3. State for each aspect to what extent you pay attention to this your teaching practice from never to often. Fill this in as honestly as possible.

	never	**almost never**	**occasionally**	**regularly**	**often**
Identify the system					
Input and output					
Emergence					
Development					
Models					

4. Give an example to illustrate how you pay attention to the different aspects of systems thinking in teaching practice. If you do not pay attention to this aspect, you can leave the text box blank.

Aspect	**Example**
Identify the system	
Input and output	
Emergence	
Development	
Models	

End of the questionnaire. Thank you for answering.

Appendix 3.1.

Part 1 of the assignment

Name: ……………………………………..
Teacher: ……………………………………

1. Try to give at least three examples of a system.

2. Try to describe a system in your own words.

3. Name the seven system characteristics.

    1) ………………………………….
    2) ………………………………….
    3) ………………………………….
    4) ………………………………….
    5) ………………………………….
    6) ………………………………….
    7) ………………………………….

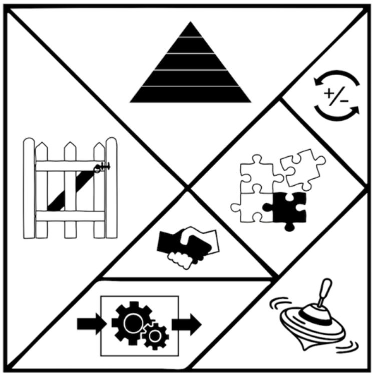


Image 1. Tangram with the system characteristics

4. Explain what the system characteristics have to do with biology.

5. To what extent do you find the system characteristics useful / valuable on a scale from 1 (not at all useful) to 6 (very useful)? Explain your choice.

1 – 2 – 3 – 4 – 5 – 6

Explanation:

6. Have you ever used the system characteristics yourself without your teacher telling you to do that? In what situation was this?

7. How often does your teacher pay attention to the system characteristics on a scale from 1 (never) to 6 (very often). Also indicate how your teacher pays attention to this, for example: refers to tangram (Image 1), names the characteristics, has assignments with questions that refer to the characteristics, and so on.

1 – 2 – 3 – 4 – 5 – 6

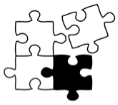
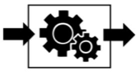
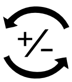
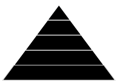
Explanation:

If you have answered questions 1 to 7, you can submit part 1 and you will receive part 2 of the questionnaire.

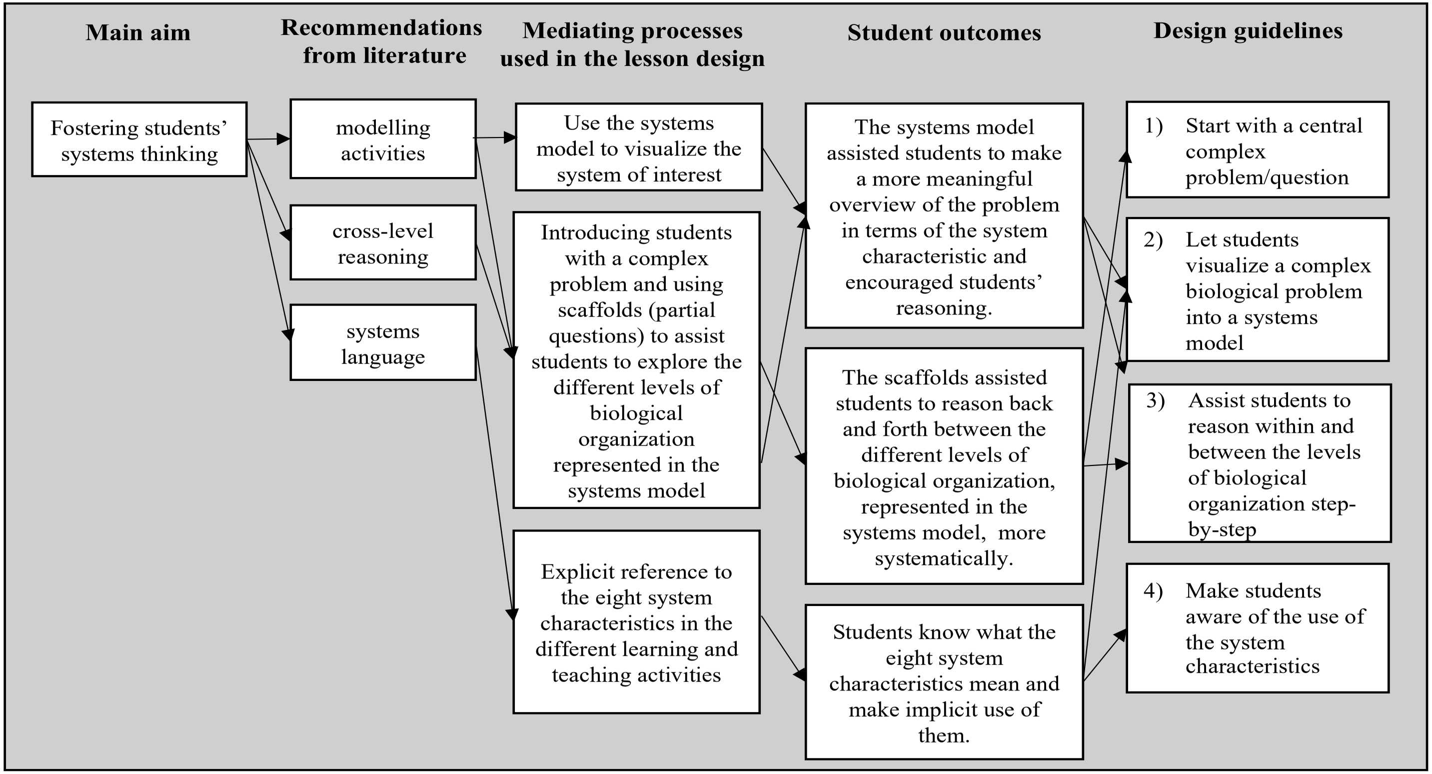
Part 2 of the assignment

Name: ……………………………………..
Teacher: ……………………………………

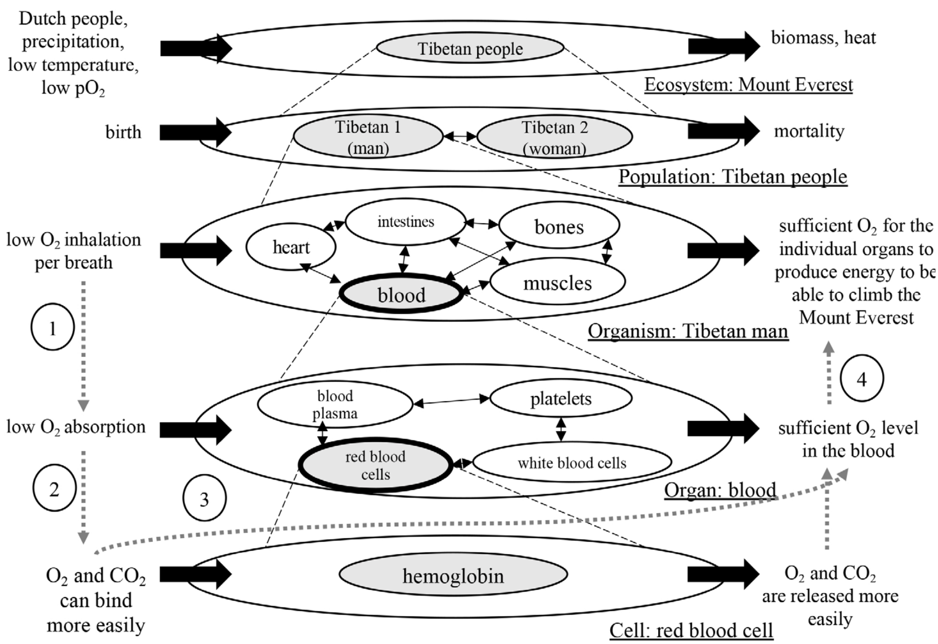
Assignment 'applying the system characteristics'
In addition to this worksheet, you also received a picture of an ecosystem of a pond. Try to apply the seven system characteristics to this system.

Icon + system characteristic	Answers
 **Boundary**	
Components 	
Interactions 	
Input output 	
Feedback 	
Dynamics 	
Hierarchy 	

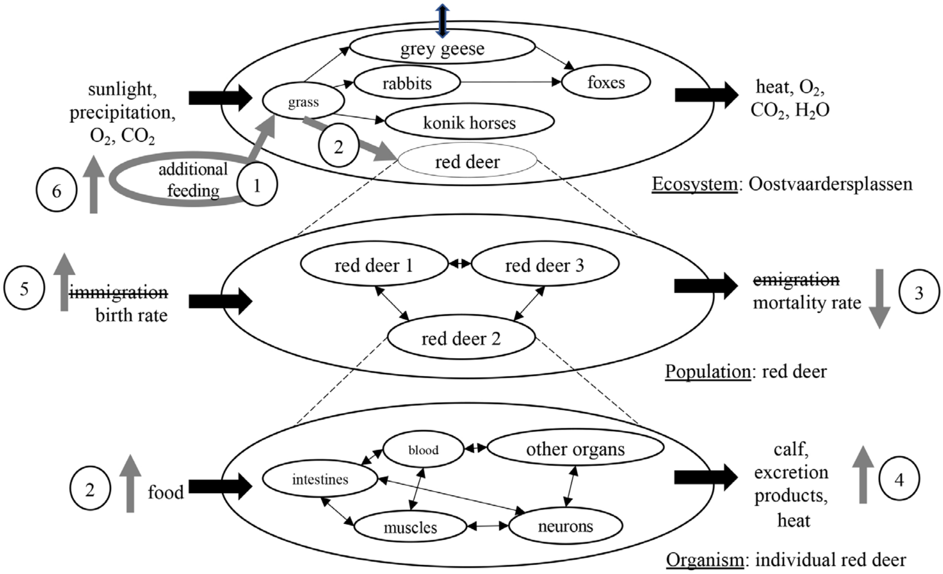
Appendix 4.1. A conjecture map (Sandoval, 2014) of this research which shows how the recommendations from literature are translated into mediating processes in the lesson design and which design guidelines could be formulated based on the student outcomes.



Appendix 4.2. Visualization of the Tibetan problem into the systems model. This model represents is the hierarchy of the problem. We zoom in step by step from the ecosystem level to the cellular level. Each level is visualized in terms of an input and output (exchange of matter, energy or information with the environment), components of the subsystem, and their interactions (visualized with arrows, but in this case not described). The numbers 1 to 4 illustrate the reasoning steps from the organism level to the cellular level back to the organism level. It declares how Tibetan people are able to live in an environment with a low pO2. In this figure we zoomed in on the component blood, but it is also possible to zoom in on the muscles, because these also have an adjustment on cellular level (Huerta-Sánchez et al., 2014).



Appendix 4.3. Visualization of the Oostvaardersplassen problem into the systems model. The numbers 1 to 6 illustrate the effects of the measure 'additional feeding' on the ecosystem, population and organism level. In the short term, additional feeding leads to less starvation mortality of red deer, but to prevent this in the longer term, more additional feeding must take place to feed all the red deer.



Appendix 5.1. Codebook for analysing the developed educational materials in terms of the five design guidelines of Gilissen, Knippels, & van Joolingen (2020, 2021a).

Aspect	Description
Biological topic(s) of the lesson	Determine to which biological topic(s) this lesson belongs
Target audience	Determine for which target audience this lesson is developed
Involved system characteristics (**design guideline 1**)	Determine on which system characteristics the lesson focuses implicitly or explicitly. Does the lesson pay attention to the:
Boundary	… definition of the system(s) involved? / visualization of the boundary in the systems model?
Components	… identification of the components of the different (sub)systems?
Interactions/relations	… interactions between the components?
Input output	… input and output of information, energy or matter into (sub)systems?
Feedback	… regulation of (sub)systems with feedback loops?
Hierarchy/levels of biological organization	… identification of the different (sub)systems to the different levels of biological organization?
Dynamics	… changes that take place within the system over time (hours, days, months, years), for example in the input and output?
Emergence	… interactions of the different components that together result in emergent behaviour (explicit)? Description of emergent phenomena (implicit)?
Use of a starting question / complex problem (**design guideline 2**)	Has a complex problem/question been used in the lesson? Has the problem/question been used as starting point of the lesson?
Visualization in a systems model (**design guideline 3**)	Has the systems model been used in the lesson design to visualize (sub)systems?

Aspect	Description
Reasoning between and/or within different levels of biological organization (**design guideline 4**)	Has attention be paid to reasoning between or within different levels of biological organization?
Use of systems language (**design guideline 5**)	Determine to what extent the different system characteristics and the concept of 'systems' is mentioned in general and on which system characteristics the lesson focuses explicitly: General introduction of the system concept and all system characteristics Boundary Components Interactions/relations Input output Feedback Hierarchy/levels of biological organization Dynamics Emergence

Appendix 5.2. Codebook for analysing pre- and in-service teachers' systems thinking definitions.

Characteristic	Description
System characteristics	when a teacher explicitly included 'system characteristics' in his / her definition or shows that he / she is implicitly talking about the 7 or 8 system features, for example by mentioning 'patterns' or 'similarities' between systems.
Boundary	when a teacher described systems thinking as 'thinking in systems.' He / she is then aware that you can consider a biological object as a system. Or when a teacher described (implicitly) how a system can be identified by drawing the boundary of a system.
Components	when a teacher included 'individual components, parts, subsystems, topics or themes' in his or her definition.
Interactions	when a teacher included 'interactions, relationships, coherence, connections' or 'consider something as a whole' in his or her definition.
Input output	when a teacher described the interaction between a system and its environment, i.e., the flow or input/output of information, energy or matter. Effects from one system to another are not coded as input output.
Feedback	when a teacher described feedback mechanisms or loops that maintain the system.
Hierarchy/levels of biological organization	when a teacher described different biological levels of organization or when he / she talks about part / whole relationships: one large system consists of several parts / subsystems (zooming in and zooming out must be mentioned).
Dynamics	when a teacher described changes that can take place over time (and it is possible to make predictions about systems dynamic behaviour).
Emergence	when a teacher included 'more than the sum of the parts' or explained a property or a whole explained from the underlying components or subsystems. Or from the definition it should be clear that something specifically influences the functioning of the larger whole. For example: "the subsystems together enable the system to function as a whole." "Reasoning about complex problems", is not coded as emergence.

Summary in English

Chapter 1 – General introduction

A muscle cell, a bicycle, a forest, a company, the solar system, are all examples of systems. At first glance, these systems are very different, but they still have a number of things in common. They all consist of interconnected components. A change in one of the components has an effect on the whole system. In addition, systems have what are called *emergent* properties. These are properties that arise through interactions between the underlying components and that only come to light at the level of the system. For example, by connecting a frame, wheels, pedals, a seat, a chain and a handlebar, a bicycle is created with which you can move yourself, while you cannot do that with the separate underlying components. So, a new emergent property has emerged here. The ability to understand systems is called *systems thinking*. It is a way of thinking in which you consider a complex phenomenon as a system and approach it by considering characteristics that all systems have in common.

Systems thinking can be applied in many disciplines and is increasingly used in school subjects (National Research Council, 2010). In the Netherlands, systems thinking has been part of the examination requirements for secondary biology education since 2010 (Boersma et al., 2010). Systems thinking involves reasoning in part-whole relationships and seeing overarching patterns. This provides insight into the construction of living systems and their underlying coherence (Verhoeff et al., 2018), which is necessary to be able to reason about complex problems and to better understand the world as a whole.

Although the importance of systems thinking is internationally recognized, many different definitions of it can be found in the literature (Boersma et al., 2011). This is partly because researchers refer in their definition implicitly or explicitly to one or more systems theories from which systems thinking originally emerged: General Systems Theory, Cybernetics and Dynamical Systems Theories (Boersma et al., 2011). Each of these systems theories has a different focus. General Systems Theory (Von Bertalanffy, 1968) focuses on the nested structure of systems, also called hierarchy. Cybernetics (Wiener, 1948) focuses on the regulation of systems with feedback loops. Dynamical Systems Theories (Prigogine & Stengers, 1984) emphasizes the open and changing character of living systems: there is a continuous exchange of matter, energy and information between a biological system and its environment, causing changes within the system.

In the literature, indications can be found regarding how attention can be paid to systems thinking within a specific biological theme, for example, around homeostasis (Ben-Zvi Assaraf et al., 2013). However, systems thinking can be applied in multiple contexts. The aim of this research is therefore to describe how systems thinking can be implemented in an integral way in secondary biology education.

Chapter 2 – What does systems thinking entail?

This chapter describes a study in which systems biologists (n = 7), university-level biology teacher educators (n = 9) and upper-secondary biology teachers (n = 8) were interviewed to determine what they understand by systems thinking and to what extent they pay attention to systems thinking in their teaching practice. Similarities with concepts from all three systems theories were found in the definitions of systems biologists and teacher educators. This is in agreement with Boersma et al. (2011) and Verhoeff et al. (2018), who indicated that systems thinking should focus on the concepts from all three systems theories. In the definitions of teachers, similarities were only been found with the concepts from General Systems Theory and Cybernetics. Online questionnaires were used to determine what elements of systems thinking were most important to the participants. These results showed that it is important to pay attention to identifying and modelling systems based on eight universal system characteristics: each system has a *boundary*, consists of *components* that *interact* with each other, has an *input* and an *output*, consists of *feedback* loops, shows *dynamic* behaviour, has a *hierarchical* structure and shows *emergent* properties. Moreover, it became clear that both teachers and teacher educators still pay little attention to systems thinking in their educational practice.

Chapters 3 and 4 – Fostering students' systems thinking in biology education

These two chapters describe how four lessons were developed and evaluated using lesson study (LS) with the aim of fostering students' (15- to 16-year-olds in senior general secondary education, in Dutch: 4 havo) systems thinking in biology. LS has been used as a professional development method (Lewis et al., 2006), but due to its cyclical design character, LS can also be used as a research method (Bakker, 2018). In this research, the different steps of LS were followed: 1) determining the learning goal of the lesson; 2) developing the lesson; 3) teaching the lesson while observing 'case students'; 4) evaluating the lesson and adjusting the lesson; 5) performing the lesson again, but now by the other teacher; 6) evaluation of the whole cycle. The LS team consisted of the three researchers and two biology teachers (pseudonyms: Frans and Julia) from the same school. Colleagues of the teachers assisted in observing the case students. The four lessons were designed, tested and evaluated during the 2018-2019 school year. Each lesson was conducted twice, once in Julia's 4 havo class and once in Frans's 4 havo class.

Systems thinking requires a holistic approach, which is why the LS team chose to introduce the eight system characteristics to students all at once in Lesson 1. Since the literature (Verhoeff et al., 2008; Tripto et al., 2016) provides indications of the importance of using system language, the system characteristics were given explicit attention in the lesson.

The introduction of the characteristics was done with the use of the tangram figure (see cover of this dissertation) as a metaphor. Each piece of the tangram represents a system characteristic and the seven pieces together form a whole - a certain figure - and thus demonstrates the system characteristic of emergence. Subsequently, the characteristics were explained in the context of 'the school as a system' and students were asked to apply them to a known biology context, 'the cell as a system'. The description of the characteristics in the latter context showed that the students were still not sufficiently able to describe the characteristics of hierarchy, feedback and dynamics. This was partly because these concepts have a different meaning in everyday language than in biology, which was reinforced by using the example of the school as a system, in which, for example, feedback was associated with being told what to improve.

In Lesson 2, specific attention was paid to two of these system characteristics. At that time, the chapter on homeostasis was scheduled for the students and according to the LS team, this chapter was ideally suited for paying specific attention to feedback and dynamics. Due to the abstract nature of these two system characteristics and recommendations from the literature (e.g., Hmelo-Silver et al., 2007), the LS team chose to use a modelling assignment. In class, students played a role-playing game in groups, in which changes in glucose concentration during a day in the life of Glucia (a metaphorical personification of a glucose molecule) were depicted using a balance and visualized in a graph. The case student in each group had to draw the fluctuating glucose level on a graph and the other students had to visualize and regulate the glucose concentration on the balance using insulin and glucagon (hormones) weights. Next, the students were asked about other examples from biology in which feedback and dynamics can be found and to describe the two characteristics in their own words. Students were able to come up with different examples and were now also able to describe the two concepts (in terms of their biological meaning).

After Lessons 1 and 2, the case students were interviewed with the aim of determining to what extent they appreciated the lessons and to what extent they perceived systems thinking as helpful. The results showed that most students did not yet see the added value of using the system characteristics.

Since systems thinking can help with tackling complex problems, the LS team decided to present the students in Lessons 3 and 4 with a complex biological problem. In addition, this could possibly also show students the need for systems thinking.

In Lesson 3, the following complex problem was presented to students: Why are Tibetan people more capable of climbing Mount Everest than Dutch people are? The students were asked to visualize the problem using the system characteristics before reasoning about possible hypotheses. The results showed that the students did not know how to visualize the (sub)systems involved in terms of the system characteristics. For example, many students made a kind of mind map in which they described the different system characteristics or drew separate sub-systems, but it was not clear how these were related. Moreover, the results showed that students skipped some levels of biological organization in their reasoning steps. In a complex problem, the answer can often be found by thinking back and forth between the different organizational levels. This requires insight into the hierarchical structure of the system and the interactions that take place between the components, or in other words: systems thinking. Students often unconsciously skip different biological organizational levels in their reasoning. By explicitly asking students what organizational level they are at in their reasoning and what organizational levels should be involved in their answer, they can be assisted to complete their reasoning. This is also known as *the yo-yo teaching and learning strategy* of Knippels (2002). That is why the LS team gave the students scaffolding questions during the second version of Lesson 3 (3β), such as: At what biological level of organization does your reasoning start? What effect does a change in the system have on the different levels of biological organization? From the student observations and interviews it seems that the questions helped students to reason more systematically between the different organizational levels.

In Lesson 4, the LS team chose to offer students, in addition to the scaffolding questions, a tool to visualize the problem: *a systems model* (an abstract representation of a system). According to Forbes et al. (2015), models can assist students to visualize and reason about biological phenomena. In addition, Verhoeff et al. (2008) reported positively on the use of a systems model to visualize a biological phenomenon in terms of the system characteristics. In Lesson 4, the students were presented with the following problem: What measures can be taken to prevent high starvation-related mortality of red deer during the winter in the Oostvaardersplassen (a Dutch enclosed landscape nature reserve)? The results showed that the systems model in combination with the scaffolding questions assisted students to visualize and reason about the problem.

In the interviews with students after Lesson 4, it appeared that the less performing students especially saw the added value of using the systems model and the system characteristics. The case students indicated that the systems model and the system characteristics assisted them to make a clear overview of the problem and to reason in more detail about the problem. However, the students who already showed a lot of biological insight in advance reported that they (unconsciously) already approached the problem in such a way and that they experienced the completion of the systems model as an extra activity.

The four LS rounds led to the following design guidelines for promoting systems thinking among students in biology education: (1) Get students acquainted with the term 'system' and the corresponding eight system characteristics in a well-known biology context; (2) A complex biological problem, including different levels of biological organization, can be used as a starting point to encourage students to apply the system characteristics; (3) Let students visualize the system of interest in terms of the system characteristics in the systems model; (4) Use scaffolding questions to assist students to reason step-by-step within and between the different biological levels of organization; (5) Make students explicitly aware of the applicability of system characteristics in a wide range of contexts.

Chapter 5 – Validation of the applicability of the design guidelines

This chapter describes to what extent the five design guidelines from Chapters 3 and 4 can be used in practice. Based on the design guidelines, a workshop was developed and offered to the six Dutch biology university-level teacher trainers and to pre- and in-service biology teachers. The workshop was implemented as a guest workshop in the regular curriculum at five university teacher training institutes, with five teacher educators and 39 pre-service teachers. In addition, two workshops were performed for biology teachers, in which a total of 12 teachers participated.

The 2- to 3-hour workshop consisted of 3 phases. In phase 1, an explanation was given of what systems thinking entails and why it matters. In this phase, participants were introduced to the eight system characteristics in a well-known biology context, using the tangram figure. In phase 2, the participants visualized and reasoned about two complex biological problems using the system characteristics and the systems model. In phase 3, participants received an overview of the design guidelines and example activities to implement systems thinking in their own biology instruction. The participants worked in groups on (re)designing lessons on systems thinking. This last phase concerned the development of didactic knowledge among participants with regard to the teaching of systems thinking.

Before and after the workshop, the teachers completed an online questionnaire to determine what they already knew and what they had learned about teaching systems thinking. Afterwards, the teachers received a voluntary final assignment: developing a lesson themselves in which systems thinking is embedded. A total of 30 teachers submitted their own developed educational materials.

The results of the questionnaire showed that all participants involved now had a better understanding of systems thinking and had become more aware of the eight system characteristics that apply to biological systems. The analysis of the educational materials that were developed showed that all participants explicitly focused on one or more system characteristics, made use of a complex problem, and a large part of them also used the systems model and guided students to reason step-by-step between the biological levels of organization. In the post-questionnaire, 19 of the 30 teachers indicated that they were satisfied with their developed educational materials and the same number of teachers indicated that they felt capable of developing educational materials around systems thinking. On the other hand, some teachers indicated that they found it a challenge to find time in the curriculum and to develop educational materials to offer systems thinking to students in different contexts during the school year. In our view, there is a responsibility here for textbook writers, who could help teachers with this by paying attention to the system characteristics in their textbooks.

The teacher educators were interviewed after the workshop with the aim of determining to what extent their perception of systems thinking had changed since the first study (Chapter 2), in which they had already been involved. They mentioned that they had now become more aware of the importance of paying explicit attention to systems thinking in teacher education and said that they want to do this in the future. In addition, they found the overview of the eight system characteristics in combination with the systems model very clear and easy to apply.

Overall, the results suggest that the design guidelines offer teachers and teacher educators enough tools to implement systems thinking in their educational practice.

Chapter 6 - General conclusion and discussion

Fostering students' systems thinking

The main aim of this dissertation was to describe how systems thinking can be fostered in secondary biology education. The research has shown that biological phenomena can be seen as systems and understood by modelling them according to the eight system characteristics: boundary, components, interactions, input and output, feedback, hierarchy, dynamics and emergence.

In order to promote students' systems thinking, it is first important to introduce them to the term 'system' and the eight system characteristics. The results have shown that it is important to do this in a well-known biology context. This is in line with Dauer et al. (2021), who indicated that it is important to link complexity to a concrete and well-known example. After the system characteristics are introduced, it is important that the students learn to apply them. **A complex biological problem can be used as a starting point to motivate students to apply a systems perspective.** Students first have to determine what system is involved, what components the system consists of and how they relate to each other (K. J. Wilson et al., 2020). **The systems model assists students to develop an overview of a system in terms of the system characteristics** (Figure 4.1). A complex problem concerns different biological levels of organization, and students appear to encounter difficulties with reasoning step-by-step between these levels. **That is why it is important to help students to think back and forth between the different organizational levels.** This can be done by explicitly asking students what organizational levels should be involved in their reasoning steps and for what purpose. A step to a higher organizational level provides a functional explanation and a step to a lower organizational level provides a causal explanation. This is also known as the yo-yo educational learning strategy of Knippels (2002). Moreover, **students must become aware of the broad applicability of the system characteristics.** Since students' systems thinking cannot be developed within one lesson, it is important that teachers pay attention to systems in different biology contexts at various times during the school year and explicitly refer to the system characteristics. The metaphor of the tangram figure (see cover of this dissertation) can be used to remind students of the broad applicability of the characteristics. This is in line with Verhoeff et al. (2008), Tripto et al. (2016) and Dauer et al. (2021), who recommended making explicit connections between concepts and the curriculum. Systems thinking involves zooming in and out on parts and wholes. Therefore, **it is important to occasionally zoom in and give a lesson focusing on understanding a specific system characteristic and then zoom out again and position the characteristic in relation to the other characteristics.**

Student perspective

In particular, the students who did not score well on the insight questions on a biology test appeared to find it valuable to use the systems model in combination with the system characteristics (Chapters 3 and 4). These students indicated that systems thinking assists them to make a complete and clear overview of the problem, which helps them to think about the problem. This is also consistent with results from other studies in which they found a positive relationship between the use of modelling activities and benefits for underperforming students (Bennett et al., 2020; Dauer et al., 2013).

Usability of the design guidelines

The study described in Chapter 5 showed that the design guidelines offer teachers tools to (re)design lessons around systems thinking. The teachers particularly appreciated the overview of the eight system characteristics and the use of the systems model to visualize systems in terms of the system characteristics. Nevertheless, a number of teachers indicated that they would find it difficult to find time in the regular curriculum to regularly pay attention to systems thinking in their teaching practice. In order to foster students' systems thinking, it is indeed important to pay attention to the system characteristics regularly and in different contexts, but it can ultimately also save time. When students have learned to use a systems perspective, they can apply this to a wide range of contexts within and outside biology.

Consideration for textbook writers

In order to implement systems thinking sustainably in biology education, it is important that textbook writers pay attention to the understanding, recognizing and modelling of systems in biology education. In an introductory chapter, attention can be paid to different biological systems, a general description of the eight system characteristics and a concrete example of application of the system characteristics to a concrete and well-known biology context. In the following chapters, reference can then be made to the system characteristics and application of the systems model.

Contributions of this research

Various frameworks can be found in the literature for promoting students' systems thinking, such as the Systems Thinking Hierarchical (STH) model (Ben-Zvi Assaraf & Orion, 2005), the Structure-Behaviour-Function (SBF) model (Hmelo-Silver et al., 2007) and the Phenomenon-Mechanisms-Components (PMC) model (Hmelo-Silver et al., 2017). Although all of these frameworks share similarities, the differences can be attributed to their implicit or explicit references to the theoretical concepts from three systems theories: General Systems Theory, Cybernetics and Dynamical Systems Theories (Boersma et al., 2011). Some frameworks only refer to some of the concepts, while Boersma et al. (2011) and Verhoeff et al. (2018) indicated that it is important to pay attention to the concepts from all three systems theories. Hence, in this study we focus on eight system characteristics that are based on the concepts from all three systems theories.

Another difference from the other frameworks is that we recommend introducing students directly to all eight system characteristics. The STH model of Ben-Zvi Assaraf and Orion (2005), for example, indicates that students should develop skills in order of increasing difficulty. Some system characteristics are indeed (perceived) to be more difficult than others, for example, hierarchy, feedback, dynamics and emergence, but because systems thinking calls for a holistic approach, it is important that all eight system characteristics are introduced at the same time. Later, more attention can be paid to understanding of the individual system characteristics, but it is also important to continue to relate the individual system characteristics to the other system characteristics. This dissertation provides various tools to support students in approaching a complex biological problem from a systems perspective: the questions related to the system characteristics, the systems model, the scaffolding questions to assist with reasoning step-by-step between the different biological levels of organization, and the tangram figure.

While systems thinking is a way to understand different (biological) phenomena from a systems perspective, many studies have focused on developing systems thinking for a specific biology topic, for example, cells (Verhoeff, 2003), the human body (Snapir et al., 2017) and ecosystems (Jordan et al., 2014). The added value of our study is that the tools we provide can be applied to a wide range of (biology) subjects.

This dissertation has led to: (1) a definition of systems thinking that was established by combining the perspectives of stakeholders (systems biologists, teacher educators and biology teachers) with insights from the three systems theories; (2) useful design guidelines for educational practice to implement systems thinking in a wide variety of biology contexts; (3) a contribution to the existing literature on the use of LS as a research method, bridging the gap between research and educational practice.

Limitations

In this study, we decided to work with the same LS team to develop and carry out four lessons in two classes during one school year. This allowed the teachers to build on their didactic insights and we could continue to follow the students over time. The aim was not to develop perfect lessons, but to develop knowledge about how systems thinking can be promoted in students. Because of this choice and the qualitative nature of the data, the various sub-studies were therefore carried out on a small scale.

In addition, this dissertation does not report on a tool for assessing students' systems thinking. An attempt was made to this in the context of a related study by Van Geelen (2019). That study aimed to investigate to what extent it is possible to determine students' systems thinking by analysing their drawings of biological phenomena. However, it turned out to be very difficult to code the drawings in terms of the system characteristics. On the other hand, the systems model itself can also be used as an assessment tool, since it is a visualization of the system as perceived by students. This is also in line with Long et al. (2014), who indicated that modelling can be used as a tool to (1) promote students' systems thinking and (2) provide teachers with insight into student reasoning.

Follow-up research

A good next step is to ask a group of teachers to regularly incorporate systems thinking into their lessons for a year and determine what it will do for students in terms of approaching complex biological problems and developing a coherent view on biology.

Since this dissertation focuses on students in upper secondary education, it would also be interesting to focus in future research on the development of systems thinking in the lower grades. The results of this dissertation show that some characteristics, in particular, feedback, dynamics and hierarchy, are more difficult. In lower secondary education, for example, it would be possible to start with recognizing systems in biology, and briefly introduce the eight system characteristics and the visualization of a system in terms of its components, interactions and input and output. Moreover, attention could already be paid to part-whole relations and the naming of the different biological levels of organization, which is already a start towards the understanding of the characteristic of hierarchy.

It would also be interesting to determine to what extent the design guidelines can be applied to implementing systems thinking in other subjects.

Final note

Ultimately, it is not about the students being able to name the eight system characteristics. The point is that they can think in parts and wholes and understand that a small change can affect the system as a whole. As a result, they see that it is important to have an overview of the system of interest. Development of students' systems thinking is not only useful for understanding the complexity of biology, but is also very valuable in other contexts.

Nederlandse samenvatting (summary in Dutch)

Hoofdstuk 1 – Algemene introductie

Een spiercel, een fiets, een bos, een bedrijf, het zonnestelsel, het zijn allemaal voorbeelden van systemen. Op het eerste gezicht zijn deze systemen heel verschillend, maar toch hebben ze een aantal dingen gemeen. Zo bestaan ze allemaal uit componenten die onderling met elkaar verbonden zijn. Een verandering in een van de componenten kan een effect hebben op het hele systeem. Daarnaast vertonen systemen zogenaamde *emergente* eigenschappen. Dat zijn eigenschappen die ontstaan door interactie tussen de onderliggende componenten en die alleen op het niveau van het systeem aan het licht komen. Door bijvoorbeeld een frame, wielen, trappers, een zadel, een ketting en een stuur aan elkaar te verbinden ontstaat er een fiets waarmee je jezelf kunt voortbewegen, terwijl je dat met de losse onderliggende componenten niet kan. Hier is dus een nieuwe, emergente eigenschap ontstaan. Het vermogen om systemen te begrijpen wordt *systeemdenken* genoemd. Het is een manier van denken waarbij je een complex verschijnsel als systeem beschouwt en de kenmerken daarvan systematisch beschrijft en onderzoekt.

Systeemdenken is een denkwijze die toepasbaar is in tal van disciplines en wordt steeds vaker in schoolvakken toegepast (National Research Council, 2010). In Nederland is systeemdenken sinds 2010 opgenomen in de exameneisen van het voortgezet biologieonderwijs (Boersma et al., 2010). Systeemdenken omvat het redeneren in deel-geheel relaties en het zien van overkoepelende patronen. Dit geeft inzicht in de bouw van levende systemen en hun onderliggende samenhang (Verhoeff et al., 2018) wat noodzakelijk is om over complexe problemen te kunnen redeneren en de wereld als geheel beter te kunnen begrijpen.

Alhoewel het belang van systeemdenken internationaal onderkend wordt, zijn er veel verschillende definities in de literatuur te vinden (Boersma et al., 2011). Dat komt mede omdat onderzoekers in hun definitie impliciet of expliciet refereren aan één of meerdere systeemtheorieën waar systeemdenken oorspronkelijk uit voortgekomen is: de Algemene Systeemtheorie, de Cybernetica en de Dynamische Systeemtheorie (Boersma et al., 2011). Elk van deze systeemtheorieën heeft een andere focus. De Algemene Systeemtheorie (Von Bertalanffy, 1968) focust op de geneste structuur van systemen, ook wel hiërarchie genoemd. De Cybernetica (Wiener, 1948) concentreert zich op de regulatie van systemen met behulp van feedbackloops. De Dynamische Systeemtheorie (Prigogine & Stengers, 1984) benadrukt het open en veranderende karakter van levende systemen: er vindt continu uitwisseling plaats van materie, energie en informatie tussen een biologisch systeem en haar omgeving waardoor er veranderingen binnen het systeem plaatsvinden.

In de literatuur zijn aanwijzingen te vinden hoe aandacht geschonken kan worden aan systeemdenken binnen één bepaald biologisch thema, bijvoorbeeld rondom homeostase (Ben-Zvi Assaraf et al., 2013). Systeemdenken is echter een generieke benadering die op veel situaties toepasbaar is. Het doel van dit onderzoek is daarom om te beschrijven hoe systeemdenken integraal kan worden vormgegeven in het voortgezet biologieonderwijs.

Hoofdstuk 2 – Wat houdt systeemdenken in?

Dit hoofdstuk beschrijft een studie waarin systeembiologen (n = 7), universitaire lerarenopleiders biologie (n = 9) en eerstegraads biologiedocenten (n = 8) geïnterviewd zijn om te bepalen wat zij onder systeemdenken verstaan en in hoeverre zij aandacht schenken aan systeemdenken in hun onderwijs. In de definities van systeembiologen en lerarenopleiders zijn overeenkomsten te vinden met concepten van alle drie de systeemtheorieën. Dit is in overeenstemming met Boersma et al. (2011) en Verhoeff et al. (2018) die aangeven dat systeemdenken zich zou moeten richten op de concepten van alle drie de systeemtheorieën. In de definities van docenten zijn alleen overeenkomsten gevonden met de concepten van de Algemene Systeemtheorie en de Cybernetica. Met behulp van online vragenlijsten is bepaald welke elementen van systeemdenken de deelnemers het belangrijkste vinden. Uit deze resultaten is naar voren gekomen dat het van belang is om aandacht te schenken aan het identificeren en modelleren van systemen op basis van acht universele systeemkenmerken: ieder systeem heeft een *grens*, bestaat uit *componenten* die *interacties* met elkaar hebben, heeft een *input* en een *output*, bestaat uit *feedbackloops*, vertoont *dynamisch* gedrag, heeft een *hiërarchische* structuur en vertoont *emergentie*. Daarnaast kwam naar voren dat zowel docenten als opleiders nog nauwelijks aandacht schenken aan systeemdenken in hun onderwijspraktijk.

Hoofdstuk 3 en 4 – Bevorderen van systeemdenken bij leerlingen in het biologieonderwijs

Deze twee hoofdstukken beschrijven hoe met behulp van lesson study (LS) vier lessen zijn ontwikkeld en geëvalueerd met als doel het bevorderen van systeemdenken bij 4-havoleerlingen. LS is eerder als docentprofessionaliseringsmethode gebruikt (Lewis et al., 2006), maar vanwege het cyclische ontwerpkarakter kan LS ook als onderzoeksmethode worden ingezet (Bakker, 2018). In dit onderzoek zijn de verschillende stappen van LS doorlopen: 1) bepalen van het onderzoeksdoel van de les; 2) het ontwikkelen van de les; 3) doceren van de les terwijl zogenoemde 'caseleerlingen' worden geobserveerd; 4) evalueren van de les en aanpassen van de les; 5) de les nogmaals doceren maar nu door de andere docent; 6) evaluatie van de hele cyclus. Het LS-team bestond uit de drie onderzoekers en twee biologiedocenten (pseudoniemen: Frans en Julia) van dezelfde school. Collega's van de docenten hielpen bij het observeren van de caseleerlingen. De vier lessen zijn ontworpen, getest en geëvalueerd tijdens schooljaar 2018-2019. Iedere les is twee keer uitgevoerd, één keer in de 4-havo klas van Julia en één keer in de 4-havo klas van Frans.

Systeemdenken vraagt om een holistische aanpak en daarom heeft het LS-team ervoor gekozen om de acht systeemkenmerken allemaal tegelijk te introduceren bij leerlingen in les 1. Aangezien de literatuur (Tripto et al., 2016; Verhoeff et al., 2008) aanwijzingen geeft voor het belang van het gebruik van systeemtaal werd er expliciet aandacht geschonken aan de systeemkenmerken in de les. De introductie van de kenmerken is gedaan aan de hand van het tangramfiguur (zie omslag van dit proefschrift) als metafoor. Ieder stukje van het tangram representeert een systeemkenmerk en de zeven stukjes samen vormen een geheel – een bepaald figuur – en demonstreert daarmee het systeemkenmerk emergentie. Vervolgens zijn de kenmerken toegelicht in de context 'de school als een systeem' en werd leerlingen gevraagd deze toe te passen op een bekende biologische context 'de cel als een systeem'. Uit de beschrijving van de kenmerken in deze laatste context bleek dat de leerlingen nog onvoldoende in staat waren om de kenmerken hiërarchie, feedback en dynamiek te beschrijven, mede doordat deze begrippen een andere betekenis hebben in het dagelijkse taalgebruik dan in de biologie. Dit effect werd versterkt door het voorbeeld van de school als systeem te gebruiken, waarin bijvoorbeeld feedback geassocieerd werd met het te horen krijgen wat je moet verbeteren.

In les 2 werd specifiek aandacht geschonken aan twee van deze systeemkenmerken. Op dat moment stond het hoofdstuk 'homeostase' op de planning voor de leerlingen en volgens het LS-team was dit hoofdstuk uitermate geschikt om specifiek aandacht te schenken aan feedback en dynamiek. Vanwege de abstracte aard van deze twee systeemkenmerken en aanbevelingen uit de literatuur (e.g., Hmelo-Silver et al., 2007) koos het LS-team ervoor om gebruik te maken van een modeleeropdracht. In de les speelden leerlingen in groepjes een rollenspel waarin de glucose huishouding van een dag uit het leven van Glucia (een metaforische verpersoonlijking van een glucosemolecuul) werd uitgebeeld met behulp van een balans en gevisualiseerd in een grafiek. De caseleerling kreeg de taak om in een grafiek het fluctuerende glucosegehalte te tekenen. De overige groepsleden hadden de taak om de glucoseconcentratie te visualiseren op de balans en te reguleren met behulp van insuline en glucagon (hormonen) gewichtjes.

Vervolgens werd de leerlingen gevraagd naar andere voorbeelden uit de biologie waarin feedback en dynamiek terug zijn te vinden en de twee kenmerken te beschrijven in eigen woorden. Leerlingen bleken in staat om verschillende voorbeelden te bedenken en waren nu ook in staat de twee begrippen (vanuit de biologische betekenis) te beschrijven.

Na les 1 en 2 zijn de caseleerlingen geïnterviewd met als doel om te bepalen in hoeverre ze de lessen waardeerden en in hoeverre ze systeemdenken als behulpzaam ervaarden. Daaruit kwam naar voren dat de meeste leerlingen de meerwaarde nog niet voelden om de systeemkenmerken te gebruiken.

Aangezien systeemdenken kan helpen bij het aanvliegen van complexe problemen, besloot het LS-team de leerlingen in les 3 en 4 een complex biologisch vraagstuk voor te leggen. Daarnaast zou dit leerlingen mogelijk ook de meerwaarde van systeemdenken kunnen laten inzien.

In les 3 werd het volgende complexe probleem aan leerlingen voorgelegd: Waarom kunnen Tibetanen veel makkelijker de Mount Everest beklimmen dan bijvoorbeeld Nederlanders? De leerlingen werd gevraagd om het probleem te visualiseren aan de hand van de systeemkenmerken voordat ze over mogelijke hypothesen gingen redeneren. Uit de resultaten bleek dat de leerlingen niet goed wisten hoe ze de betrokken (deel)systemen konden visualiseren in termen van de systeemkenmerken. Zo maakten veel leerlingen een soort mindmap waarin ze de verschillende systeemkenmerken beschreven of tekenden zij aparte deelsystemen, maar werd niet duidelijk hoe deze samenhingen. Daarnaast bleek ook dat leerlingen in hun redeneerstappen de organisatieniveaus oversloegen. Bij een complex probleem is het antwoord vaak te vinden door “heen-en-weer” te denken tussen de verschillende organisatieniveaus. Dit vergt inzicht in de hiërarchische structuur van het systeem en de interacties die plaatsvinden tussen de componenten, of met andere woorden: systeemdenken. Leerlingen slaan onbewust vaak verschillende organisatieniveaus over in hun redenering. Door leerlingen expliciet te vragen op welk organisatieniveau ze zich bevinden in hun redenering en welke organisatieniveaus betrokken moeten worden in hun antwoord kunnen ze geholpen worden om hun redenering volledig te maken. Dit is ook wel bekend als *de jojo-onderwijsleerstrategie* van Knippels (2002). Daarom heeft het LS-team bij de tweede uitvoering van les 3, de leerlingen hulpvragen gegeven, zoals: Op welk organisatieniveau start je je redenering? Welk effect heeft een verandering in het systeem op de verschillende organisatieniveaus? Uit de leerlingobservaties en interviews kwam naar voren dat de vragen leerlingen hielpen om meer stapsgewijs te redeneren tussen de verschillende organisatieniveaus.

In les 4 heeft het LS-team ervoor gekozen om de leerlingen naast de hulpvragen voor het redeneren ook een hulpmiddel aan te bieden om het probleem te visualiseren: *een systeemmodel* (een abstracte weergave van een systeem). Volgens Forbes et al. (2015) kunnen modellen gebruikt worden om systemen te visualiseren, maar ook als hulpmiddel bij het redeneren. Daarnaast rapporteert Verhoeff et al. (2008) positief over het gebruik van een systeemmodel om een biologisch verschijnsel in termen van de systeemkenmerken te visualiseren. In les 4 kregen de leerlingen het volgende probleem voorgelegd: Welke maatregel kunnen we nemen in de Oostvaardersplassen om sterfte van edelherten door voedseltekort te voorkomen? De resultaten laten zien dat het systeemmodel in combinatie met de hulpvragen leerlingen hielp om het probleem te visualiseren en er over te redeneren.

In de interviews met caseleerlingen na les 4, bleek dat vooral de wat minder presterende leerlingen de meerwaarde inzagen van het gebruik van het systeemmodel en de systeemkenmerken. De leerlingen gaven aan dat ze met behulp van het systeemmodel en de systeemkenmerken een duidelijk overzicht konden maken van het probleem en dat het ze hielp om meer in-detail te redeneren over het probleem. De leerlingen die van tevoren al blijk gaven van veel biologisch inzicht, meldden dat zij (onbewust) al op deze manier over het probleem nadachten en dat het invullen van het systeemmodel voor hen juist als een extra activiteit werd ervaren.

De vier LS rondes hebben tot de volgende ontwerprichtlijnen geleid met betrekking tot het bevorderen van systeemdenken bij leerlingen in het biologieonderwijs: (1) Introduceer de term ‘systeem’ en de acht systeemkenmerken bij leerlingen met behulp van een concreet en voor de leerlingen bekend biologisch voorbeeld; (2) Leg leerlingen een complexe vraag of probleem voor die meerdere organisatieniveaus omvat; (3) Laat leerlingen het probleem visualiseren in een systeemmodel; (4) Help leerlingen stapsgewijs met het redeneren binnen en tussen de verschillende organisatieniveaus; (5) Maak leerlingen expliciet bewust van de toepasbaarheid van systeemkenmerken in verschillende contexten.

Hoofdstuk 5 – Verifiëren van de ontwerprichtlijnen

Dit hoofdstuk beschrijft in hoeverre de vijf ontwerprichtlijnen uit hoofdstuk 3 en 4 bruikbaar zijn voor de praktijk. Aan de hand van de ontwerprichtlijnen is een workshop ontwikkeld en aangeboden aan de zes Nederlandse universitaire lerarenopleidingen biologie en biologiedocenten. In totaal is de workshop bij vijf lerarenopleidingen in het reguliere vakdidactiek curriculum als gastworkshop geïmplementeerd. Daarbij namen 5 lerarenopleiders en 39 eerstegraadsdocenten in opleiding deel. Daarnaast is er twee keer een nascholingsworkshop georganiseerd voor biologiedocenten waar in totaal 12 docenten aan hebben deelgenomen.

De 2 tot 3 uur durende workshop bestond uit 3 fasen. In fase 1, werd uitgelegd wat systeemdenken inhoudt en waarom het van belang is. In deze fase werden de deelnemers geïntroduceerd met de acht systeemkenmerken, aan de hand van het tangram figuur, in een bekende biologische context. In fase 2, hebben de deelnemers met behulp van de systeemkenmerken en het systeemmodel twee complexe biologische vraagstukken gevisualiseerd en hier over geredeneerd. In fase 3, kregen de deelnemers een overzicht van de ontwerprichtlijnen en voorbeeldactiviteiten om systeemdenken te implementeren in hun eigen biologieonderwijs. Vervolgens moesten zij in groepjes aan de slag met het (her)ontwerpen van lessen rondom systeemdenken. Deze laatste fase had betrekking op het ontwikkelen van didactische kennis bij deelnemers met betrekking tot het onderwijzen van systeemdenken.

Voor en na de workshop kregen de docenten een online vragenlijst om te bepalen wat ze reeds wisten en wat ze hadden geleerd over het onderwijzen van systeemdenken. Na afloop kregen de docenten een vrijwillige eindopdracht: zelf een les ontwikkelen waarin systeemdenken is verwerkt. In totaal hebben 30 docenten lesmateriaal ingeleverd.

Uit de resultaten van de vragenlijst bleek dat alle betrokken deelnemers nu beter weten wat systeemdenken inhoudt en bewuster zijn geworden van de acht systeemkenmerken die van toepassing zijn op biologische systemen. Uit de analyse van het ontwikkelde lesmateriaal kwam naar voren dat alle deelnemers in het door hun ontwikkelde lesmateriaal expliciet focussen op een of meerdere systeemkenmerken, een complex vraagstuk introduceren, een groot deel van hen het systeemmodel gebruikt en leerlingen begeleidt bij het stapsgewijs redeneren tussen de organisatieniveaus. In de post-vragenlijst gaven 19 van de 30 docenten aan dat ze tevreden waren met hun lesmateriaal en hetzelfde aantal docenten gaf aan zich vaardig te voelen om lesmateriaal te ontwikkelen rondom systeemdenken. Daarentegen gaven sommige docenten wel aan dat ze het een uitdaging vinden om tijd te vinden in het curriculum en om lesmateriaal te ontwikkelen om systeemdenken gedurende het schooljaar in verschillende contexten aan te bieden aan leerlingen. Hier ligt in onze ogen dan ook een verantwoordelijkheid voor tekstboekschrijvers die docenten hierbij zouden kunnen helpen door aandacht te schenken aan de systeemkenmerken in de tekstboeken.

De universitaire lerarenopleiders biologie zijn na de workshop geïnterviewd met als doel te bepalen in hoeverre hun beeld van systeemdenken sinds de eerste studie (Hoofdstuk 2), waar zij al bij betrokken waren, is veranderd. Zij vermeldden dat ze zich nu bewuster zijn geworden van het belang om expliciet aandacht te schenken aan systeemdenken in de lerarenopleiding en zeggen dit ook te willen gaan doen in de toekomst. Daarnaast vonden ze het overzicht van de acht systeemkenmerken in combinatie met het systeemmodel heel overzichtelijk en goed toepasbaar.

Kortom, de resultaten suggereren dat de ontwerprichtlijnen genoeg handvatten bieden aan docenten en opleiders om systeemdenken te implementeren in hun onderwijspraktijk.

Hoofdstuk 6 – Algemene conclusie

Bevorderen van systeemdenken bij leerlingen

Het doel van dit proefschrift is om te beschrijven hoe systeemdenken kan worden bevorderd bij leerlingen in het voortgezet biologieonderwijs. Het onderzoek heeft laten zien dat systeemdenken een manier van denken is waarin biologische verschijnselen kunnen worden gezien als systemen en kunnen worden begrepen door ze te modelleren aan de hand van de acht systeemkenmerken: grens, componenten, interacties, input en output, feedback, hiërarchie, dynamiek en emergentie.

Om systeemdenken te bevorderen bij leerlingen is het eerst van belang om ze te introduceren met het begrip 'systeem' en de acht systeemkenmerken. De resultaten hebben laten zien dat het van belang is om dit in een voor de leerlingen bekende biologische context te doen en dit komt overeen met Dauer et al. (2021), die aangeeft dat het van belang is om complexiteit te koppelen aan een concreet en bekend voorbeeld. Na het introduceren van de systeemkenmerken is het van belang dat de leerlingen leren om de systeemkenmerken toe te passen. **Een complex biologisch vraagstuk kan als startpunt**

worden gebruikt om leerlingen te motiveren om een systeemperspectief toe te passen. Leerlingen moeten dan eerst bepalen om welk systeem het gaat en uit welke componenten het systeem bestaat en hoe deze in verhouding met elkaar staan (K. J. Wilson et al., 2020). **Het systeemmodel helpt leerlingen om een overzicht te krijgen van een systeem in termen van de systeemkenmerken** (zie Figuur 4.1). Een complex vraagstuk heeft betrekking op verschillende organisatieniveaus en leerlingen blijken moeite te hebben om stapsgewijs te redeneren tussen deze niveaus. **Daarom is het van belang om leerlingen te helpen met het heen-en-weer denken tussen de verschillende organisatieniveaus.** Dit kan gedaan worden door leerlingen expliciet te vragen welke organisatieniveaus betrokken zouden moeten worden in hun redeneerstappen en met welk doel. Een stap naar een hoger organisatieniveau geeft een functionele verklaring en een stap naar een lager organisatieniveau geeft een oorzakelijke verklaring. Dit is ook wel bekend als de jojo-onderwijsleerstrategie van Knippels (2002). **Daarnaast moeten leerlingen bewust worden van de brede toepasbaarheid van de systeemkarakteristieken.** Aangezien systeemdenken niet binnen één les ontwikkeld kan worden bij leerlingen is het van belang dat docenten gedurende het schooljaar op meerdere momenten bij verschillende biologische contexten aandacht schenken aan systemen en expliciet verwijzen naar de systeemkenmerken. De metafoor van het tangram (zie omslag proefschrift) kan gebruikt worden om leerlingen te herinneren aan de brede toepasbaarheid van de kenmerken. Dit komt overeen met Verhoeff et al. (2008), Tripto et al. (2016) en Dauer et al. (2021) die aanbevelen om expliciete verbanden aan te brengen tussen concepten en het curriculum. Systeemdenken omvat het in- en uitzoomen op delen en gehelen. **Daarom is het van belang om af en toe in te zoomen en een les aandacht te schenken aan het begrip van een specifiek systeemkenmerk om vervolgens weer uit te zoomen en het kenmerk te plaatsen in relatie tot de andere kenmerken.**

Leerlingperspectief

Met name de leerlingen die nog niet goed scoren op de inzicht vragen van een biologietoets blijken het gebruik van het systeemmodel in combinatie met de systeemkenmerken waardevol te vinden (Hoofdstuk 3 en 4). De leerlingen geven aan dat met behulp van systeemdenken een volledig en duidelijk overzicht kunnen maken van het probleem wat hen helpt om over het probleem na te denken. Dit komt ook overeen met resultaten van andere studies waarbij ze een positieve relatie vonden tussen de minder presterende leerlingen en modelleeractiviteiten (Bennett et al., 2020; Dauer et al., 2013).

Bruikbaarheid van de ontwerprichtlijnen

De studie beschreven in Hoofdstuk 5 heeft laten zien dat de ontwerprichtlijnen docenten handvatten bieden om lessen te (her)ontwerpen rondom systeemdenken. De docenten waardeerden vooral het overzicht van de acht systeemkenmerken en het systeemmodel om systemen in termen van de systeemkenmerken te visualiseren. Toch gaf een aantal docenten aan dat ze het lastig vinden om tijd te vinden in het reguliere curriculum om regelmatig aandacht te schenken aan systeemdenken. Om systeemdenken bij leerlingen te bevorderen is het inderdaad van belang om regelmatig en in verschillende contexten aandacht te besteden aan de systeemkenmerken, maar het kan uiteindelijk ook tijd besparen. Wanneer leerlingen namelijk hebben geleerd om een systeemperspectief te gebruiken kunnen ze dit toepassen op een breed scala aan (biologische) contexten.

Overweging voor tekstboekschrijvers

Om systeemdenken duurzaam te implementeren in het biologieonderwijs is het van belang dat tekstboekschrijvers aandacht besteden aan het begrijpen, herkennen en modelleren van systemen in de biologie. In een eerste hoofdstuk kan dan aandacht worden geschonken aan verschillende biologische systemen, een algemene beschrijving van de acht systeemkenmerken en concrete toepassing van de systeemkenmerken op een eenvoudig en bekend biologisch voorbeeld. In de volgende hoofdstukken kan dan worden terugverwezen naar de systeemkenmerken en kan het systeemmodel toegepast worden.

Bijdragen van dit onderzoek

In de literatuur zijn verschillende raamwerken te vinden om systeemdenken bij leerlingen te bevorderen, zoals the Systems Thinking Hierarchical (STH) model (Ben-Zvi Assaraf & Orion, 2005), the Structure-Behaviour-Function (SBF) model (Hmelo-Silver et al., 2007) en the

Phenomenon-Mechanisms-Components (PMC) model (Hmelo-Silver et al., 2017). Hoewel al deze raamwerken overeenkomsten vertonen, kunnen de verschillen toegewezen worden aan de impliciete of expliciete verwijzingen naar de theoretische concepten van drie systeemtheorieën: de Algemene Systeemtheorie, Cybernetica en Dynamische Systeem Theorieën (Boersma et al., 2011). Sommige raamwerken bevatten alleen verwijzing naar sommige concepten, terwijl Boersma et al. (2011) en Verhoeff et al. (2018) aangeven dat het van belang is om aandacht te schenken aan de concepten van alle drie de systeemtheorieën. Vandaar dat wij in deze studie ook focussen op acht systeemkenmerken die gebaseerd zijn op de concepten van alle drie de systeemtheorieën.

Nog een verschil met de andere raamwerken is dat wij aanbevelen om leerlingen direct kennis te laten maken met alle acht systeemkenmerken. Het STH model van Ben-Zvi Assaraf en Orion (2005) bijvoorbeeld geeft juist aan dat leerlingen vaardigheden in oplopende moeilijkheidsgraad moeten ontwikkelen. Sommige systeemkenmerken zijn inderdaad lastiger dan andere, bijvoorbeeld hiërarchie, feedback, dynamiek en emergentie, maar aangezien systeemdenken een holistische benadering omvat, is het juist belangrijk dat alle acht de systeemkenmerken tegelijk werden geïntroduceerd. Later kan dan meer aandacht worden geschonken aan het begrip van de individuele systeemkenmerken, maar daarbij is het ook weer van belang om de individuele systeemkenmerken te blijven relateren aan de andere systeemkenmerken. Dit proefschrift geeft verschillende handvatten om leerlingen te ondersteunen bij het benaderen van een complex biologisch vraagstuk vanuit een systeemperspectief: de hulpvragen gerelateerd aan de systeemkenmerken, het systeemmodel, het stapsgewijs redeneren tussen de organisatieniveaus, en het tangram figuur.

Terwijl systeemdenken een denkwijze is om verschillende (biologische) verschijnselen te begrijpen vanuit een systeemperspectief, focussen veel studies zich op het ontwikkelen van systeemdenken in een specifiek biologisch onderwerp, bijvoorbeeld cellen (Verhoeff, 2003), het menselijk lichaam (Snapir et al., 2017) en ecosystemen (Jordan et al., 2014). De meerwaarde van onze studie is dat de handvatten toepasbaar zijn op een breed scala aan (biologische) onderwerpen.

Dit proefschrift heeft geleid tot: (1) een definitie van systeemdenken die tot stand is gekomen door perspectieven van belanghebbenden (systeembiologen, lerarenopleiders en biologie-docenten) te combineren met inzichten uit de drie systeemtheorieën; (2) bruikbare ontwerprichtlijnen voor de onderwijspraktijk om systeemdenken te implementeren in een grote variëteit van biologische contexten; (3) een bijdrage aan de bestaande literatuur over het gebruik van LS als onderzoeksmethode waarbij een brug wordt geslagen tussen het onderzoek en de onderwijspraktijk.

Begrenzing van het onderzoek

In deze studie is ervoor gekozen om met hetzelfde LS-team te werken waarmee gedurende één schooljaar in twee klassen vier lessen zijn ontwikkeld en uitgevoerd. Hierdoor konden de docenten voortbouwen op hun didactische inzichten en konden we de leerlingen door de tijd heen blijven volgen. Het doel was niet om perfecte lessen te ontwikkelen, maar om kennis te ontwikkelen over hoe systeemdenken kan worden bevorderd bij leerlingen. Vanwege deze keuze en de kwalitatieve aard van de data zijn de verschillende deelstudies daarom op kleine schaal uitgevoerd.

Daarnaast rapporteert dit proefschrift niet over een toetsingsmiddel voor het beoordelen of leerlingen in staat zijn systeemdenken toe te passen. Hiertoe is wel een poging gedaan in de context van een masterafstudeeronderzoek (Van Geelen, 2019). Daarin is onderzocht in hoeverre het laten tekenen van biologische verschijnselen door leerlingen laat zien in hoeverre zij systeemdenken. Het bleek alleen heel lastig om de tekeningen te coderen in termen van de systeem-kenmerken. Aan de andere kant kan het systeemmodel op zichzelf ook als toetsingsmiddel gebruikt worden, aangezien het een visualisatie is van het systeembeeld van leerlingen. Dit komt ook overeen met Long et al. (2014) die aangeven dat modelleren zowel gebruikt kan worden als middel om (1) systeemdenken te bevorderen bij leerlingen en (2) docenten inzicht te geven in het redeneren van leerlingen.

Vervolgonderzoek

Een mooie volgende stap is om een groep docenten te vragen om gedurende een jaar lang systeemdenken regelmatig in hun lessen te laten verwerken en te bepalen wat dit oplevert voor leerlingen wat betreft het aanpakken van complexe biologische problemen en het ontwikkelen van een samenhangend beeld van de biologie.

Aangezien dit proefschrift zich focust op de bovenbouw, zou het ook interessant zijn om in toekomstig onderzoek aandacht te richten op het ontwikkelen van systeemdenken in de onderbouw. De resultaten uit dit proefschrift laten zien dat sommige kenmerken, met name feedback, dynamiek en hiërarchie, meer geavanceerd zijn. In de onderbouw is het bijvoorbeeld al mogelijk om te starten met het herkennen van systemen in de biologie, de acht systeemkenmerken kort te introduceren en ze een systeem te laten visualiseren in termen van hun componenten, interacties en input en output. Daarnaast kan er al aandacht worden geschonken aan deel-geheel relaties en het benoemen van de verschillende biologische organisatieniveaus, wat al een begin is richting het ontwikkelen van het begrip hiërarchie.

Ook zou het interessant zijn om te bepalen in hoeverre de ontwerprichtlijnen toegepast kunnen worden om systeemdenken te implementeren in andere vakken.

Slotopmerking

Uiteindelijk gaat het er niet om dat de leerlingen de acht systeemkenmerken kunnen benoemen. Het gaat erom dat ze kunnen denken in delen en gehelen, en begrijpen dat een kleine verandering invloed kan hebben op het systeem als geheel. Daardoor zien ze in dat het van belang is om het systeem goed in kaart te brengen. Het bevorderen van systeemdenken bij leerlingen is niet alleen nuttig om de complexiteit van de biologie te begrijpen, maar is ook zeer waardevol in andere contexten omdat systeemdenken helpt om inzicht te krijgen in complexe problemen vanuit het grotere geheel.

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Curriculum Vitae

Melde Gilissen was born on March 23, 1991 in Heerlen, the Netherlands. She completed her secondary education at the Montessori Lyceum Rotterdam in 2009. After a visit to a virus laboratory, she became interested in the physiological and molecular mechanisms that cause diseases. Therefore, she has chosen to study the bachelor Biomedical Sciences at Utrecht University (completed in 2012). During an elective she became enthusiastic about teaching biology to secondary students. After a gap year, in which she worked and travelled to New Zealand, Australia, Taiwan and Thailand, she attended the Master's Science Education and Communication at Utrecht University. During this master she completed the 1-year teaching program to become a teacher for upper-secondary biology education.

Since 2015 she is working as a biology teacher at the Bonhoeffer College in Enschede. In 2016 she started with the DUDOC Bèta program at Utrecht University, funded by the Ministry of Education, Culture and Science, as PhD student (3 days), and combined this with her job as teacher (2 days a week).

Melde lives in Apeldoorn together with her friend Tiemen and their daughter Filou. In her free time, Melde enjoys cooking, walking or doing one of her many creative DIY projects.

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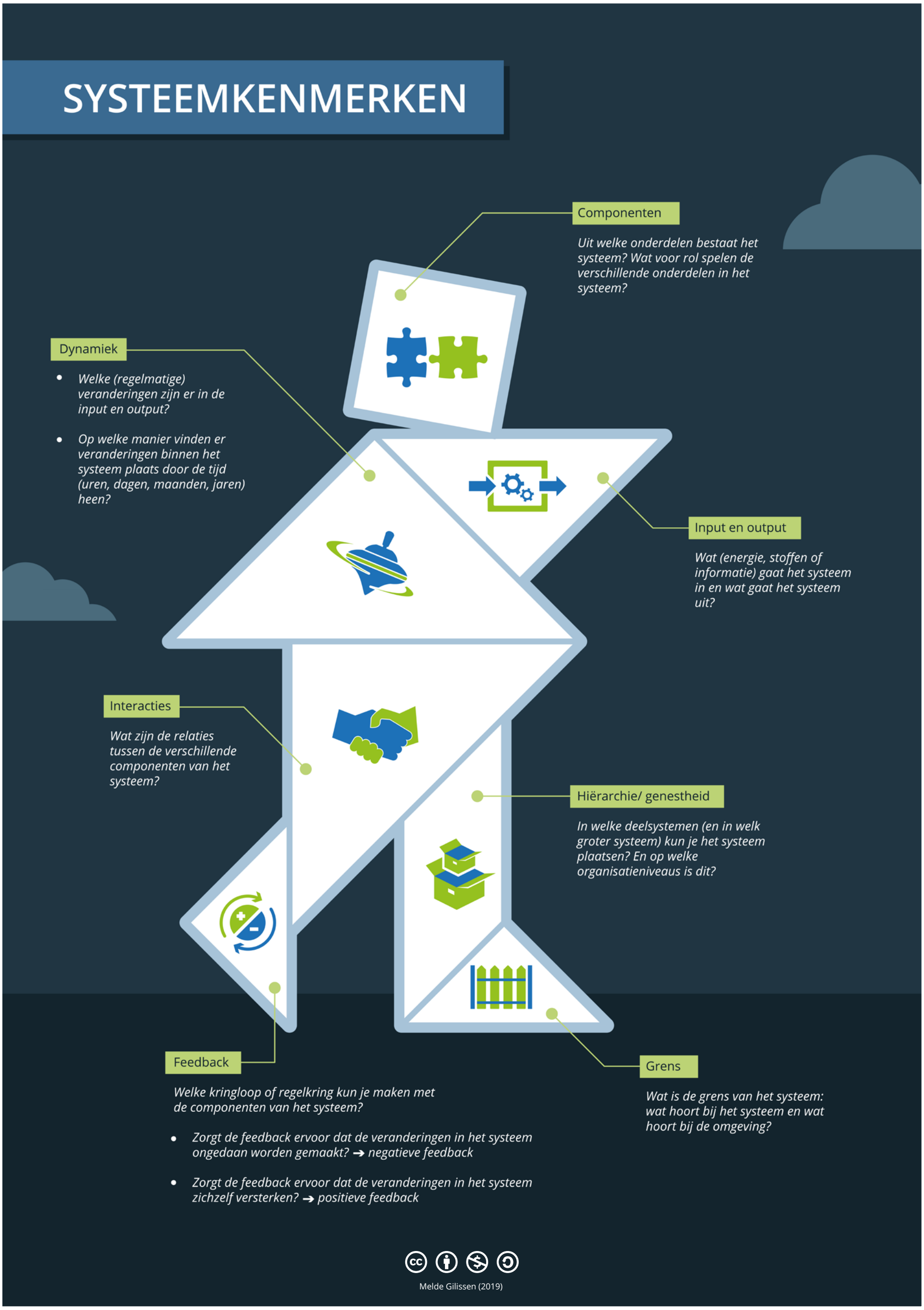
"The system characteristics ensure that you delve deeper into the problem."

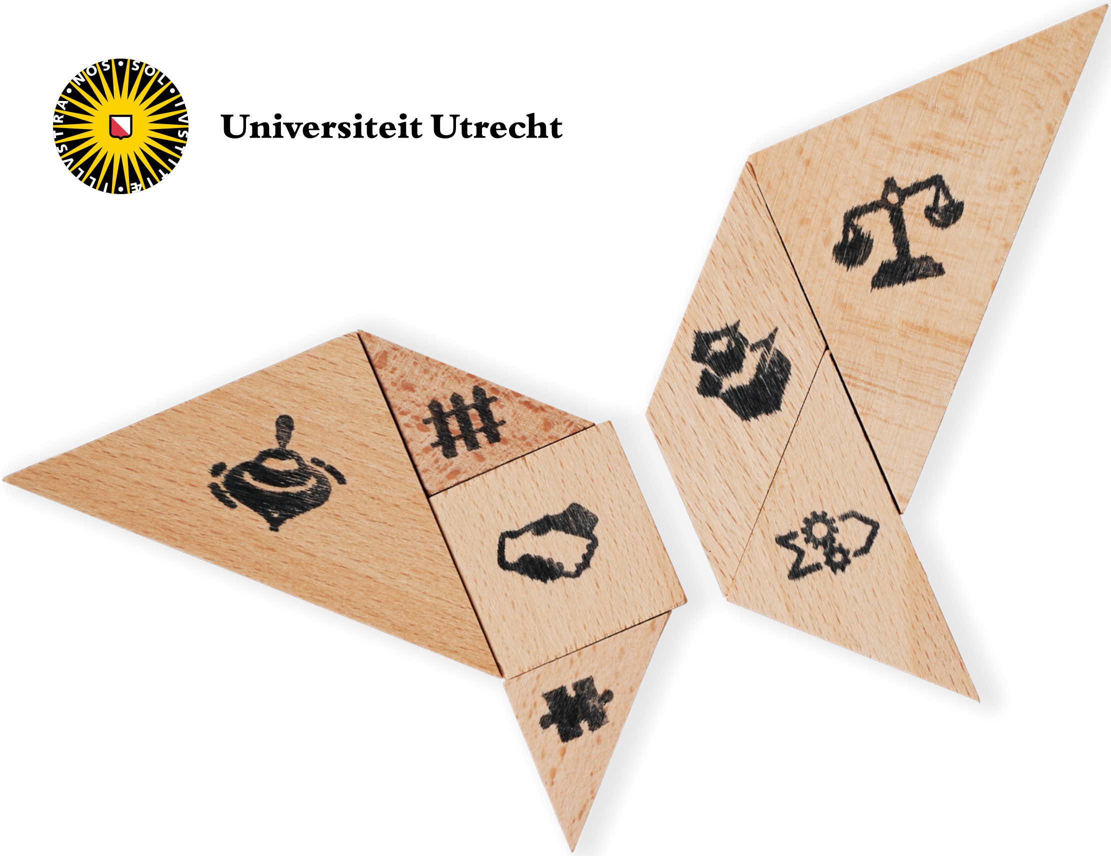
"If you look at the system characteristics, you immediately see what you need to look at, so that's why it is useful. […] You see more quickly where to look, therefore you know where to search faster."

"These things [system characteristics] are logical themselves. You know them, but you have to remember that they are really there. I really learned that. Recognize that these system characteristics are always present in systems."

Quotes of three different students who reacted on the value of the system characteristics presented on the poster on the next page


SYSTEEMKENMERKEN
Componenten
Uit welke onderdelen bestaat het systeem? Wat voor rol spelen de verschillende onderdelen in het systeem?
Dynamiek
• Welke (regelmatige) veranderingen zijn er in de input en output?
• Op welke manier vinden er veranderingen binnen het systeem plaats door de tijd (uren, dagen, maanden, jaren) heen?
Input en output
Wat (energie, stoffen of informatie) gaat het systeem in en wat gaat het systeem uit?
Interacties
Wat zijn de relaties tussen de verschillende componenten van het systeem?
Hiërarchie/ genestheid
In welke deelsystemen (en in welk groter systeem) kun je het systeem plaatsen? En op welke organisatieniveaus is dit?
Feedback
Welke kringloop of regelkring kun je maken met de componenten van het systeem?
• Zorgt de feedback ervoor dat de veranderingen in het systeem ongedaan worden gemaakt? → negatieve feedback
• Zorgt de feedback ervoor dat de veranderingen in het systeem zichzelf versterken? → positieve feedback
Grens
Wat is de grens van het systeem: wat hoort bij het systeem en wat hoort bij de omgeving?
Melde Gilissen (2019)

Universiteit Utrecht



Systems thinking is important to make sense of the increasingly complex world around us, because complex problems cannot be solved by linear thinking. In science education systems thinking is important to help students make sense of complexity in (biological) systems, e.g., a muscle cell, the human body, an ecosystem. This higher-order thinking skill can assist students to create a more coherent understanding of biology by seeing the universal principles that apply to biological systems on different biological levels of organization. The question is: How can students' systems thinking be fostered within secondary biology education? This dissertation answers this question and provides: (1) a definition of systems thinking that has been established by combining the perspective of systems biologists, teacher educators and biology teachers with insights from three systems theories; (2) useful design guidelines for educational practice to implement systems thinking in secondary biology education; (3) an example of the use of lesson study as a research method to bridge the gap between research and educational practice.