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Science of complex systems and future-scaffolding skills: a pilot study with secondary school students

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Abstract

The present work is situated within *I SEE* (Inclusive STEM Education to Enhance the capacity to aspire and imagine future careers), a three-year Erasmus+ project started in November 2016, coordinated by the University of Bologna and involving further six partners (http://www.iseeproject.eu).

The *I SEE* project aims to design innovative approaches and teaching modules to enhance students' capabilities to imagine the future and aspire to STEM careers. The goal is not only to develop professional skills but also to foster students' identities as capable persons and citizens in a global, fragile and changing world. For this purpose, have been recognized specific skills that should be developed through science education in school and out-of-school contexts: we call them *future-scaffolding skills* and their aim is to construct visions of the future that support possible ways of acting in the present with one's eye on the horizon.

The work I developed for this Master Thesis intends to contribute to examine how scientific knowledge, particularly the science of complex systems, can foster the development of future-scaffolding skills. For this purpose, three sets of activities have been designed and implemented in a teaching laboratory-course about the topic of climate change, targeted to secondary school students (17-18 years old, grade 12-13).

In the thesis, I provide the theoretical framework within which my work intends to place, then I describe the activities, their learning outcomes and the context of the pilot study; finally, I report the data analysis and the results that show criticalities and strengths of the work, opening at new research perspectives.

Sommario

Il presente lavoro si colloca nell'ambito di *I SEE* (Inclusive STEM Education to Enhance the capacity to aspire and imagine future careers), un progetto Erasmus+ triennale, iniziato nel novembre 2016, che, coordinato dall'Università di Bologna, coinvolge altri sei partner (http://www.iseeproject.eu).

Il progetto *I SEE* mira a progettare approcci e moduli di insegnamento innovativi per migliorare la capacità degli studenti di immaginare il futuro e di aspirare a carriere in ambito STEM. L'obiettivo non è solo quello di sviluppare competenze professionali, ma anche di incoraggiare l'identità degli studenti come persone e cittadini competenti in un mondo globale, fragile e in mutamento. A questo scopo, sono state rintracciate particolari competenze che dovrebbero essere sviluppate tramite l'educazione scientifica a scuola e in contesti extra-scolastici: diamo loro il nome di *competenze di future-scaffolding* e il loro obiettivo è di costruire visioni del futuro che supportino possibili modi di agire nel presente, con uno sguardo sull'orizzonte.

Il lavoro che ho sviluppato per questa tesi di laurea intende contribuire ad esaminare come la conoscenza scientifica, in particolare la scienza dei sistemi complessi, può incoraggiare lo sviluppo di competenze di future-scaffolding. A tal fine, sono stati progettati tre set di attività per un target di studenti di scuola secondaria (17-18 anni).

Nella tesi, fornisco il quadro di riferimento entro il quale il mio lavoro intende collocarsi, quindi descrivo le attività, i loro risultati di apprendimento e il contesto dello studio pilota; infine, riporto l'analisi dei dati ed i risultati che mostrano criticità e punti di forza del lavoro che aprono a nuove prospettive di ricerca.

Introduction

The theme of future is crucial for our lives. Everything we do, every day, is, in some way, a future thing, since we always make plans, projecting ourselves into the future. The future can be near or far, it can be perceived as certain or uncertain, it can be a hope or a fear. But why a master thesis in Physics about the theme of the future?

This issue touches the heart of the sense of science and physics, since future is intrinsic to these disciplines, that have been historically developed also to manage rationally and emotionally the fear of the unknown and to make predictions. Reducing the uncertainties about the future has been the goal of a large part of the physics since, for a long time, there has been the belief that a rationality that embraced all the knowledge of all the physical phenomena would have hold the future in its mind and would have had the capability of taming all the uncertainties. But this magnificent rationality cannot simply exist and also physics had to adapt itself by producing new concepts, new knowledge, new models with the goal not to neutralize but to manage the uncertainty about the future. However, while the scientific discipline has developed theories (like the probability theory, the statistical mechanics, the quantum physics, the science of complex systems) that with their specific methods, languages, analytical tools try to rationally deal with the future, the emotional component of fear toward the future is very common, in particular among the young generations, with specific regard to some crucial issues.

Issues of climate, global warming, weather, nanotechnologies, big data are becoming pressing questions in society and in making decisions in future. The alarmist, brusque and confusing communication about these themes often impact on people, so that the worries arisen by the environmental and technological changes, together with other global problems like economic and political crises, have a strong influence on the perception about the future of the young generations which is considered no longer as a promise but as a threat (Benasayag & Schmit, 2005). In particular, in our contemporary society of global uncertainties and social acceleration (Rosa, 2013), the young generations have difficulty in projecting themselves into the future, and in developing scope as responsible and active persons, citizens and future professionals (Sjøberg & Schreiner, 2010). This evidence challenges physics education through demanding research questions such as: *How can the contents of physics be reconstructed so as to make disciplinary learning a place to develop competencies to deal with the future?*

This Master Thesis intends to contribute to answer this question, in the context of *I SEE* (Inclusive STEM Education to Enhance the capacity to aspire and imagine future careers), a three-year Erasmus+ project started in November 2016, coordinated by the University of Bologna and involving further six partners (http://www.iseeproject.eu). The *I SEE* project aims to design innovative approaches and teaching modules to enhance students' capabilities to imagine the future and aspire to STEM careers. The goal is not only to develop professional skills but also to foster students' identities as capable persons and citizens in a global, fragile and changing world. For this purpose, have been recognized specific skills that should be developed through science education in school and out-of-school contexts: we call them future-scaffolding skills and their aim is to construct visions of the future that support possible ways of acting in the present with one's eye on the horizon.

The work I developed for this Master Thesis intends to contribute to examine how scientific knowledge, particularly the science of complex systems, can foster the development of future-scaffolding skills. For this purpose, three sets of activities have been designed and implemented in a teaching laboratory-course about the topic of climate change, targeted to secondary school students (17-18 years old, grade 12-13).

The first set of activities has the main goal to develop hard-scientific knowledge about the science of complex systems, by introducing the concepts of non-linearity, feedback, sensitivity to initial conditions, emergent property, self-organization, as well as the tool of computer simulation.

The second set aims to develop transversal skills of text analysis. It consists of two activities: one is the reading of a synthesis of an IPCC report, related to the issue of global warming, and the elaboration of a global causal map; the second one is based on the reading of a scientific text about the use and the production of biodiesel and includes sub-activities that require, respectively, to build a further global causal map and to identify possible feedback loops that enrich the map itself.
The third set of activities has the main goal to develop specific future-scaffolding skills through the analysis of a problem of urban planning. The activity has been inspired by the future studies and is focused on: i) the concepts of scenarios, forecast, foresight, backcasting, anticipation; ii) the distinction between probable, possible and preferable futures.

The present work is divided into three chapters.

In Chapter 1, I provide the theoretical framework of the whole thesis. I describe the context of the ISEE Erasmus+ Project, its general objectives and specific goals; then, I discuss my choice of considering the science of complex systems for a future-oriented science education, specifying which concepts and methods I found appropriate; in a section I explain the framework I used for distinguishing between scientific knowledge and scientific skills, hence explaining why these scientific skills can contribute to the so-called scientific citizenship; the chapter continues with a discussion of the main concepts of the discipline of futures studies and their disciplines of forecast, foresight and anticipation; finally, all the theoretical framework converges into the definition of future-scaffolding skills and the distinction between future-scaffolding scientific skills and future-scaffolding transversal ones.

In Chapter 2, I describe the three sets of activities, stressing the main common features that characterize each set; a considerable importance will be given to the design aspects of these completely innovative materials (that are available in the Annexes).

In Chapter 3, I explain the context of the pilot study I have carried out, together with Dr. Giulia Tasquier, within a laboratory-course about the topic of climate change organized by the Department of Physics and Astronomy of the University of Bologna within the *Piano Lauree Scientifiche* project; then, I show the research questions and the methods that have guided the data analysis; finally I present the results of the data analysis in three sections (scientific knowledge, scientific skills, transversal skills) and I provide, at the end, an overall discussion of the results.

Chapter 1
Theoretical framework

1.1 The *I SEE* Erasmus+ Project

This work is situated within the framework of *I SEE* (Inclusive STEM Education to Enhance the capacity to aspire and imagine future careers), a three-year Erasmus+ project started in November 2016 (www.iseeproject.eu). The project is coordinated by the University of Bologna, particularly the Department of Physics and Astronomy, and involves further six partners: the Scientific Lyceum 'Albert Einstein' of Rimini, Fondazione Golinelli of Bologna, the University and Normal Lyceum of Helsinki, the English Association for Science Education (ASE), the Icelandic Environment Association (IEA) 'Landvernd' and the upper secondary educational institution 'Hamrahlid College' of Reykjavik.

The idea at the basis of *I SEE* arises from the recognition of the fact that in our contemporary society of global uncertainties and social acceleration (Rosa, 2013), our imagination of the future becomes problematic and source of anxiety: also because of global problems like climate change, ecosystem degradation and economical and political crises, the future, instead of a promise, is often perceived as a threat (Benasayag & Schmid, 2006). Many young people feel marginalised or excluded from economic and social life by the crises, and in many countries, especially those with high youth unemployment rates, young people perceive their country's education and training system as not well adapted to the world of work (EP(EB395), 2014). In such a context, the young generation have difficulty in projecting themselves into the future, and in developing their potential as responsible and active persons, citizens and future professionals (Sjøberg & Schreiner, 2010).

This social need is accompanied with the worldwide crisis, denounced from European reports and research, in STEM (Science, Technology, Engineering and Mathematics) education, since students perceive school science as 'irrelevant' in the individual, societal and vocational sense (Stuckey et al., 2013). The cause of this perception has been found in the fact that what students learn in school is often not authentic science but school science, a construct detached from the nature, processes and results of real scientific enterprise. A consequence of the lack of relevance of school science is that Europe is suffering from an alarming decrease in student interest in pursuing STEM careers (EC/EACEA/Eurydice, 2012) – a phenomenon also known as 'STEM shortage' – while, on the other side, STEM-based industry leaders complain about the so called 'skill gap', because schools do not support the formation of the skills that the labour market needs. More generally, it is acknowledged in society a common scientific illiteracy.

The path toward a more widespread scientific literacy has however to deal with a third issue: the dramatic social change in Europe caused by unprecedented flows of migrants to the region (OECD, 2016). In the field of education this issue has been transformed in the need of an inclusive education that acknowledges diversity and supports students' capacity to aspire towards the future also, and especially, in young people coming from difficult, sometimes traumatic, experiences. Though, this individual and cultural diversity is not only a need to be met, but also an invaluable resource for deepening student engagement and increasing personal and societal relevance of disciplines and, particularly, STEM ones.

From these three issues – the difficulty in imagination of futures, the widespread scientific illiteracy and the challenge of cultural diversity in education – the project has identified its priorities that lead to the three general objectives:

- GO1: Contribute to innovating science teaching at the level of upper secondary school students (grades 11-13, 16-19 years old) in order to facilitate scientific literacy and employability in a changing, multicultural and fragile world.
- GO2: Contribute to addressing the societal issues represented by the STEM skill gap and professional shortage.

- GO3: Contribute to innovating teaching methods to make science teaching inclusive and supportive of cultural diversity.

Therefore, in accordance with the general objectives the strategic partnership of *I SEE* is committed to designing innovative approaches and teaching modules aimed to foster students' capacities to imagine the future and aspire to STEM careers. The goal is not only to develop professional skills but also to foster students' identities as capable persons and citizens in a global, fragile and changing world: persons who can learn, from STEM education, a way to cope rationally and emotionally with the present and future, developing authentic conceptual, epistemological and professional competencies.

Both the general objectives and the more specific goals of the project can be translated into the need to reconsider science education – in terms of contents, skills, competencies that should be promoted as well as in terms of teaching methods – in order to make science school teaching closer to students' and societal requirements. In this sense, the strategic partnership has selected special skills to develop through science education, named 'future-scaffolding skills': they refer to the ability to construct visions of the future that empower action in the present with an eye on the horizon.

The development of these skills is expected both to make science learning relevant (scientifically, personally, socially and professionally) and to enhance students' capacity to aspire, envisage themselves as agents of change and push their imagination towards future careers in STEM.

It is aim of the project to define more and more precisely and operationally the future-scaffolding skills so as to provide researchers and teachers evaluation tools to understand how they develop and monitor them.

My thesis is situated in the context of this project and aims to:

a) design teaching/learning activities for an *I SEE* module, where the potential of physics learning to develop futures thinking is exploited and valued;
b) contribute to select and operationally define *future-scaffolding skills*.

1.2 What physics for future-oriented education?

The problem of the young generation with the future deeply challenges physics education and poses demanding research questions such as: *How can the contents of physics be* *reconstructed so as to make disciplinary learning a place to develop competencies to deal with the future?*

The question touches the heart of the sense of science and physics, since future is intrinsic to these disciplines, that have been historically developed also to manage rationally and emotionally the fear of the unknown and to make predictions.

The theme of future is indeed strictly woven with the issue of causal explanations: the ways in which we talk about the future – predicting, forecasting or anticipating it – mirror the idea of causal relationship at their basis. Science and more specifically physics, during its historical development, has produced various models of causal explanation.

At school, students learn almost exclusively about one of these models: the causal determinism. It can be defined by the following assertion (Hoefer, 2016):

The world is governed by (or is under the sway of) determinism if and only if, given a specified way things are at a time t, the way things go thereafter is fixed as a matter of natural law.

This is the main assumption of classical physics and its roots lie in the very common philosophical idea that everything can, in principle, be explained. The determinism is often commingled with the idea of prediction, as the famous Pierre-Simone Laplace's claim (Laplace, 1820) shows:

We ought to regard the present state of the universe as the effect of its antecedent state and as the cause of the state that is to follow. An intelligence knowing all the forces acting in nature at a given instant, as well as the momentary positions of all things in the universe, would be able to comprehend in one single formula the motions of the largest bodies as well as the lightest atoms in the world, provided that its intellect were sufficiently powerful to subject all data to analysis; to it nothing would be uncertain, the future as well as the past would be present to its eyes. The perfection that the human mind has been able to give to astronomy affords but a feeble outline of such an intelligence.

The determinism has its roots in one of the fundamental properties of the classical physics that is the linearity, displayed overall in the formal linearity of most of the differential equations typical of the classical physics (Feynman, 1963). We can consider, for example, the harmonic oscillator

$$m\ddot{x} + kx = 0,$$

or the equation for the radiative decay

$$\dot{N} + kN = 0,$$

or the heat equation

$$\frac{\partial u}{\partial t} = k\frac{\partial^2 u}{\partial x^2},$$

where the first two examples are ordinary linear differential equations (ODE) and the third one is a partial linear differential equation (PDE).

Their structure is linear because they display the properties of additivity and homogeneity with respect to the multiplication for a constant: considered together, can be proved that these properties imply that if two functions f and g are solutions of the linear equation, then any linear combination of them af + bg is a solution too. This is called the principle of superposition for linear systems.

We can consider again the first example cited above, the harmonic oscillator. It is a particular example of the more general Newton's second law that can be written in the differential form that follows:

$$F = m\ddot{x}.$$

We have to note that in general the second law of dynamic is not a linear differential equation because this property depends on the form of the force F. In order to be linear, the differential equation has to equate 0 to a polynomial that is linear in the value and various derivatives of a variable: this means that each term in the polynomial has degree either 0 or 1. For linear ODEs and PDEs, the solutions can be found explicitly in analytical form, but there are problems, also in classical physics, that can only be modelled by nonlinear systems. One of the most famous examples is the three-body problem. For studying analytically these problems, the procedure followed is the linearization around the equilibrium points, which consists in considering just the linear part of F, under the hypothesis that it is of class C^1: once linearized, the property of linear combination of the solutions is still valid.

The principle of superposition means that, in a mechanical system, if we have a complicated force *F*, but that can be decomposed into a sum of separate forces, then the effect of the vector sum of all the forces on the system is equal to the effect of force *F*, this effect being the acceleration of the body.
The classical principle of linear superposition of causes is at the basis of an epistemological belief named reductionism. Reductionism leads also to argue that the cause is always seen to flow from the lower levels to the higher levels and, according to this assumption, the higher level biological and behavioural phenomena are derived from lower level physical, specifically mechanical, causes.

Coming back to Laplace's claim, we can interpret it referring to the Cauchy problem or to the boundary value problem: if one knew the initial or the boundary conditions, given a system of partial differential equations, he could find the unique solution of the problem. One of the main aspects of this deterministic perspective is the distinction between past (from which the equations and laws of nature come), present (that is used to determine the initial conditions) and future (for which we investigate the evolution of the system) that refers to one of the linear pattern of causality. Linear causality can be interpreted in terms of three basic rules (DeLanda, 2002):

- unidirectionality: if the event A causes the effect B, B has no demonstrable effect on A (see Figure 1.1 for a visual representation);
- uniqueness and necessity: the same cause leads always to the same effect;
- proportionality: small causes always produce small effects and large causes produce large effects.

Figure 1.1. Visual representation of a chain of causes and effects according to a linear pattern of causality.

The linear, deterministic and reductionist paradigm is the most taught in school physics but is not the only one that authentic physics has provided. For example, the science of complex systems laid the foundations of a completely new paradigm of causal explanation.

The most fundamental concept, at the basis of the difference between complexity and ordinary physical models, is the renounce at linear causality in favour of the recognition of the existence of a circular pattern of causality. According to this pattern, the mentioned characteristic of unidirectionality fails: if an event A makes B happen, in circular causality B is also a cause itself and can modulate or perpetuate A (see Figure 1.2 for a visual representation).

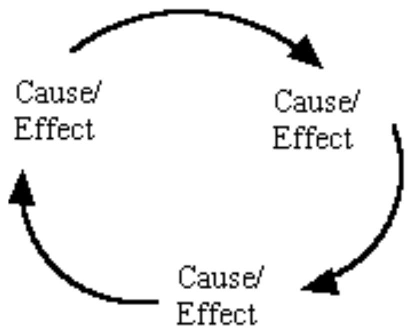


Figure 1.2. Visual representation of a loop of causes and effects according to a circular pattern of causality.

The circular causality brings about the concept of feedback as one of the most fundamental in the study of complex systems: it can be defined as an element of the cause-effect relationship intended as a circular loop in which the last effect of the chain acts back on the cause from which the loop has started, amplifying it further (positive feedback) or softening it (negative feedback).
The non-linearity is also a property of the systems of differential equations that characterize complex systems, in the sense that linearization around equilibrium points has a limited usefulness: this implies that the solutions of these systems cannot be written in an analytical form but their study is possible through the application of numerical methods.

The renounce at linearity involves also a renounce at the characteristic of proportionality between causes and effects: because of the existence of feedback phenomena, together with a non-linear mathematical description, complex systems can show a high sensitivity to initial conditions, since at small variations in causes can correspond big modifications in effects. Sensitivity to initial conditions is popularly known as the 'butterfly effect', so-called because of the title of a paper given by Edward Lorenz in 1972 to the American Association for the Advancement of Science in Washington, entitled ‘Predictability: Does the Flap of a Butterfly's Wings in Brazil set off a Tornado in Texas?’. The flapping wing represents a small change in the initial condition of the system, which can cause a chain of events leading to large-scale phenomena: had the butterfly not flapped its wings, the trajectory of the system might have been vastly different.

The new approach at causality forces, in some sense, the vocabulary and the mental schemas to change when talking about the future evolutions of systems. The existence of feedback phenomena requires to reason both in terms of mutual increases and balances, while the non-proportional relationship between causes and effect leads to a new meaning of determinist conception itself. The high sensitivity of systems to initial conditions weakens the possibility to obtain a determinist prediction about the future because the non-linear equations, rather than conserving the unavoidable experimental errors on initial conditions, can progressively amplify them. In this way, every error, even if apparently negligible, produces consequences that are relevant for the evolution of the system: the result is a loss of predictability that is not reparable with scientific and technological progresses, since, firstly, every measure has a related uncertainty and, secondly, during the computational running of the model there will always be approximations of some irrational number. It is important to notice that the causal paradigm remains determinist, since the models elaborated for complex systems have no noise, randomness or probabilities built in: anyway, the apparent result that we see, looking at the evolutions of such systems, is chaos. This is the so-called deterministic chaos and it emerges from the modelling description of numerous natural phenomena. As a consequence of this reasoning, the term ‘prediction’ itself – referring to the univocal result of the application of a model – loses significance beyond a little time horizon. Therefore, instead of ‘prediction’, a more used term is ‘projection’ because it indicates the range of possibilities which is as wide as many and various are the future scenarios obtained from the application of a model. A crucial word for the study of complex systems is properly the term ‘scenario’ and it means not a specific prediction about future but a plausible description of what could happen, based on trends and events obtained from the past and from the present.

Another characteristic that is no more valid in many complex systems is the additivity of causes in leading to an effect. The loss of validity of this concept is due to the fact that there is an even more basic change in the equations that describe systems themselves: while classical physics considers systems equipped with linear equations, the complexity science considers a system as the overall result of many concurrent factors that interact each other in non-linear ways. The interaction between the components of a system leads to the impossibility of assuming the hypothesis of independence of causes and then to the invalidity of the property of additivity. One of the main proofs of this is the existence of phenomena of self-organization, spontaneous processes where some form of overall order arises from local interactions between parts of the system. Differently from the procedure always followed in classical physics, for complex systems, the forces F that act on them are not separated into linear and independent components, since, otherwise, the emergent properties would disappear from the model.

Within this perspective the reductionist paradigm fails too: in complex systems, understanding the individual components is crucial but the knowledge of the parts is not sufficient in order to explain the behaviour of the whole system; the complex interactions between parts create new processes, principles and structures that, although having their material basis on the underlying components, are conceptually independent from those. The sharp distinction between holism and reductionism loses significance in complexity science: the reductionist approach is not substituted for the holistic one because both the perspectives are needed. It is the model of explanation that has to be modified in a dynamic way: the understanding of a phenomenon is possible only by moving from the perspective of the whole to that of the individual parts and vice versa. In this sense, the aim of complex thinking is the multidimensionality, the integration of different levels of order that maintain their identity at the same time. Instead of an opposition between reductionism and holism, the new perspective is the 'unitas multiplex' (Morin, 2003), the capability of maintaining a distinction among what is joined together and linking without reducing.

1.3 What science of complex systems for secondary school students?

Despite the acknowledged intellectual relevance of the conceptual and epistemological contents that come from the science of complex systems, its teaching and learning is not considered in the official national programmes for secondary schools. Therefore, since complexity science is rarely studied and taught at school level, there is an evident gap between the hyper-specialized language and the language used for popularization: there is a lack of complete educational proposals about this issue (Amaldi, 2011).

In order to contribute to meet this need, I have designed activities targeted for upper secondary school students in order to build a knowledge about the science of complex systems exploring different contexts of application and different teaching methods, with the ultimate goal of translating the knowledge acquired into proper skills that allow students to interpret the complexity of the real world. The activities I designed include formal, methodological and cultural dimensions and, in the following, I am going to explain briefly the main choices that stay behind the activities.

The first choice is to use the formalism as much as possible and to base on it the discussion about non-linearity. This choice implied me to find a way to present it to 17-18 years old students, at their penultimate year of secondary school. The introduction to differential equation was simply made by explaining the derivative in terms of variation of a certain quantity in a time interval. The goal of such an explanation was not to completely clarify the precise mathematical meaning of the formal tools (this can be done with students who have already studied mathematical analysis during school courses) but to give an idea of what those formulas, used in the modelling process, mean. This approach allows a non-neutral involvement of students in the discussion of the mathematical models, since they can be guided to manage the concepts of increment and variation in a correct way, even if the exact analytical formulation is not within their range. To reinforce this objective, a high importance was given to the different graphical representations: showing various kinds of graphs, the meaning of the equations of the model can be explored from many perspectives.

The second choice regards the emphasis put on the tool of simulations and to their methodological role and epistemological meaning in contemporary physics. I decided to use a simulation in almost all the activities and they are used to stress that reality can be known not only through direct observation, through our senses, but also through simulation, that means reproducing it on a computer. Simulation can be considered the third of the tools of science beyond the two traditional ones, namely laboratory experiments and theories (Parisi, 2001). It does not use normal words or symbols of mathematics but uses a particular language that incorporates into a computer program. When the simulation runs on the computer, it gives rise to empirical predictions that derive from the theory, and it works as a virtual laboratory in which, as in the real laboratory, the researcher monitors the phenomena under controlled conditions, manipulates the conditions themselves and discovers the consequences of such manipulations. The wide use of simulations in the activities I designed reflects the wide use of this tools in the authentic scientific research about complex systems.

The last, but obviously not the least, choice is cultural. I tried to stress the interdisciplinary and transversal nature of the conceptual issues of science of complex systems. The epistemological contents are underlined in order to allow the students to consider the activities as particular examples of a wider phenomenology that goes beyond the merely scientific discipline and can be extended at other contexts like social and economic phenomena. This aspect is what can transform knowledge about complex systems to competencies. We named these competencies scientific skills because they allow to interpret the reality (including complex social and economic phenomena) using categories, vocabulary, concepts, methods, tools and epistemological perspectives learnt and borrowed from science.

1.4 From scientific knowledge to scientific skills

In this thesis, one of the most fundamental issues, that leaded also to the formulation of research questions, is the distinction between knowledge and skills (or competencies). Various definitions can be given for these two words. For example, we could consider the KSAs (Knowledge, Skills, Abilities) framework, the method used to evaluate the applicants to United States Federal government job openings. The specific knowledge, skills, and abilities necessary for the successful performance of a specific position are contained on each job vacancy announcement but there are also general definitions of the three that we report in the followings:

- knowledge: an organized body of information, usually factual or procedural in nature, applied directly to the performance of a function;
- skill: an observable competence to perform a learned psychomotor act, since it involves the proficient manual, verbal, or mental manipulation of things;
- ability: a competence to perform an observable behaviour or a behaviour that results in an observable product as an activity or task.

The necessity of providing skills, and not only knowledge, has been highly perceived not only within the labour market but also in the context of science education, pursuing the goal of building a scientific literacy. The most recent report of PISA defines (PISA, 2015) three skills that characterize scientific literacy:

- explain phenomena scientifically: it means recognize, offer and evaluate explanations for a range of natural and technological phenomena demonstrating the ability to recall and apply appropriate scientific knowledge, identify, use and generate explanatory models and representations, make and justify appropriate predictions, offer explanatory hypotheses, explain the potential implications of scientific knowledge for society;
- evaluate and design scientific inquiry: it means describe and appraise scientific investigations and propose ways of addressing questions scientifically demonstrating the ability to identify the question explored in a given scientific study, distinguish questions that are possible to investigate scientifically, propose a way of exploring a given question scientifically, evaluate ways of exploring a given question scientifically, describe and evaluate a range of ways that scientists use to ensure the reliability of data and the objectivity and generalisability of explanations;
- interpret data and evidence scientifically: it means analyse and evaluate scientific data, claims and arguments in a variety of representations and draw appropriate conclusions demonstrating the ability to transform data from one representation to another, analyse and interpret data and draw appropriate conclusions, identify the assumptions, evidence and reasoning in science-related texts, distinguish

between arguments which are based on scientific evidence and theory and those based on other considerations, evaluate scientific arguments and evidence from different sources (e.g. newspaper, internet, journals).

All these competencies require knowledge but, according to the PISA framework, the scientific knowledge can be considered as consisting of three distinguishable but related elements. The first of these and the most familiar is knowledge of the facts, concepts, ideas and theories about the natural world that science has established; this kind of knowledge is referred to as 'content knowledge'. Knowledge of the procedures that scientists use to establish scientific knowledge is referred to as 'procedural knowledge' and is knowledge of the practices and concepts on which empirical inquiry is based. Furthermore, understanding science as a practice also requires 'epistemic knowledge' which refers to an understanding of the role of specific constructs and defining features essential to the process of knowledge building in science; it includes an understanding of the functions that questions, observations, theories, hypotheses, models, and arguments play in science, a recognition of the variety of forms of scientific inquiry, and the role peer review plays in establishing knowledge that can be trusted.

People need all three forms of scientific knowledge to perform the three competencies of scientific literacy within a range of personal, local, national and global contexts but knowledge is not the only thing that plays a role in the development of those skills: the competency-based perspective of PISA framework also recognises that there is an affective element to a student's display of these competencies, that is that the attitude or disposition towards science will determine the student's level of interest, sustain his/her engagement, and may motivate him/her to take action (Schibeci, 1984). Thus, commonly the scientifically literate person would have an interest in scientific topics and reflect on the importance of science from a personal and social perspective; this requirement does not mean that such individuals are necessarily disposed towards science itself: rather, such individuals recognise that science, technology and research in this domain are an essential element of contemporary culture. In Figure 1.3 is reported a visual representation of the PISA 2015 framework for Scientific Literacy Assessment.

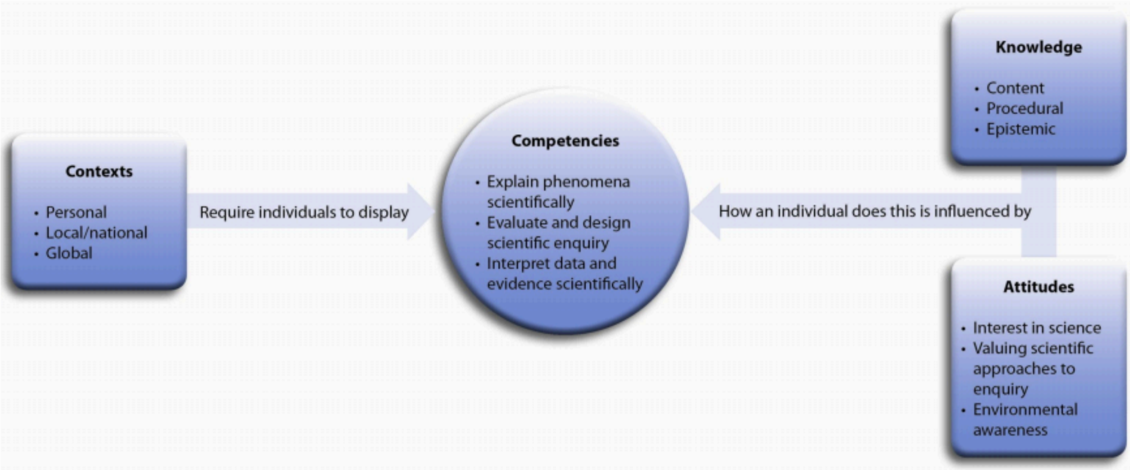


Figure 1.3. Framework for PISA 2015 Scientific Literacy Assessment.

The methodological approach adopted in this thesis can be consistently compared with the PISA theoretical framework. The context of a complex world in which citizens have often to deal with controversial issues (like that of climate change) requires hard-scientific skills in order to explain, interpret and manage certain phenomena; these skills consists, for example, of recognizing the types of circular causality within a problem or applying the concept of feedback also in apparently non-scientific contexts. These hard-scientific skills, in turn, can be reached through the three types of knowledge: content knowledge is provided when the concepts of science of complex systems are taught; procedural knowledge when the simulation is introduced as the preferential tool for the study of these themes or when the different kinds of graphical representations are introduced; epistemic knowledge every time the role of modelling is pointed out or the concept of system is inquired in its epistemological meaning.

1.5 From scientific skills to scientific citizenship

The competencies highlighted by the PISA framework can be interpreted, in a wider context, as elements that contribute to the so-called scientific citizenship. The scientific citizenship issue has been debating, in the context of science education, for over two decades. At the base of this issue there is the crucial importance attributed to citizenship education in general. The Eurydice report (Eurydice, 2012) affirms that, in order to increase engagement and participation, *people must be equipped with the right* *knowledge, skills and attitudes*, including social and civic competences; these are among the eight key competencies identified in the recommendation of the European Parliament and of the Council (EPC, 2006) as essential for citizens living in a ‘knowledge society’. The eight key competencies are the following:

- communicating in a mother tongue: ability to express and interpret concepts, thoughts, feelings, facts and opinions both orally and in writing;
- communicating in a foreign language: as above, but includes mediation skills (i.e. summarising, paraphrasing, interpreting or translating) and intercultural understanding;
- mathematical, scientific and technological competencies: sound mastery of numeracy, an understanding of the natural world and an ability to apply knowledge and technology to perceived human needs (such as medicine, transport or communication);
- digital competence: confident and critical usage of information and communications technology for work, leisure and communication;
- learning to learn: ability to effectively manage one’s own learning, either individually or in groups;
- social and civic competences: ability to participate effectively and constructively in one’s social and working life and engage in active and democratic participation, especially in increasingly diverse societies;
- sense of initiative and entrepreneurship: ability to turn ideas into action through creativity, innovation and risk taking as well as ability to plan and manage projects;
- cultural awareness and expression: ability to appreciate the creative importance of ideas, experiences and emotions in a range of media such as music, literature and visual and performing arts.

With respect to this context, science education has tried to provide instruments and reflections in order to give a contribution to the scientific citizenship issue. In one of first reports on this topic, *Beyond 2000: Science education for the future* (Millar & Osborne, 1998), it was stressed the need of a dialogue between science and society to sustain *a healthy and vibrant democracy*, through a renovation of science curricula. The main goal was to build a public consciousness among citizens who, whilst appreciating the value of science and its contribution to our culture, can critically engage in issues and arguments that involve scientific knowledge. Since 1998, EU has pursued similar goals, by proposing research programmes like *Science in Society* (2007-2013) and the most recent *Science with and for Society* within *Horizon 2020*. The history of programmes about scientific citizenship shows a progressive integration between science and society, up to an approach in which all societal actors are encouraged to work together during the whole research and innovation process: this kind of public participation in scientific research is exactly the real essence of citizen science. The necessity of providing *the space for open, inclusive and informed discussions on the scientific research and technology decisions that will impact citizens' lives* is pointed out also by the EU report presented and discussed at the last ESERA conference in Helsinki (EC, 2015).

In order to make the EU recommendations operative, we considered necessary to study approaches that, focusing on scientific contents and methods, design innovative ways to turn scientific knowledge in citizenship skills. The most common approach is summarized in *Science for citizenship* (Osborne, 2010) where it is stressed the need of *less emphasis on the facts of science and a broader knowledge of how science works*. On the other side, our work aims to investigate, in a concrete context, if, how and why the development of hard-scientific skills grounded in the discipline of complex systems can result in the development of transversal citizenship skills that can impact on people's way of facing problems and decisions.

1.6 Futures studies for citizenship skills

The citizenship skills we are mainly interested in are those related to the rational and emotional management of future.

The social implications of future competencies are very evident in the researches carried out within a branch of social sciences, named futures studies. It consists in the study of postulating possible, probable and preferable futures and it is intrinsically interdisciplinary: indeed, futures studies typically attempt to gain a holistic or systemic view because consider big and complex real systems that can be investigated only in a multidimensional perspective. In terms of methodology, the futurists – this is one of the term for referring at 'futures students' – employ a wide range of approaches, models and methods, many of which are derived from other academic or professional disciplines, from economics to political science, from computer sciences to statistics.

As the name itself of the discipline suggests, one of the fundamental assumptions in futures studies – adopted from the very beginning of this field of inquiry – is that the future is not singular but plural (Wells, 1932). Indeed, the future consists not of one inevitable future that is to be predicted, but rather of multiple alternative futures of varying likelihood which may be derived and described, and about which it is impossible to say with certainty which one will occur. In this sense, the epistemological determinist perspective is rejected by futurists together with the term 'prediction'.

The object of study forces the discipline to follow some principles that have been enunciated in four points, known as Sardar's four laws of futures studies (Sardar, 2010).

- "Futures studies are wicked": because of the complexity of the world, any exploration of the future has to face with such "wicked problems" (definition appeared in [Churchman 1967]), difficult or impossible to solve because of incomplete, contradictory, and changing requirements that are often difficult to recognize; moreover, because of complex interdependencies, the effort to solve one aspect of a wicked problem may reveal or create others. Futures studies are wicked not only because of their object of study but because their very nature is wicked: indeed, the discipline is open ended, offering not single solutions but spaces of possibilities, and borrows ideas and tools from other different disciplines and sciences. A sort of corollary of this first law is that Futures studies are so strongly multi- and trans-disciplinary that they can be considered also un-disciplinary.
- "Futures studies are MAD": MAD is an acronym for Mutually Assured Diversity, a concept, first introduced by Sardar in 2004, according to that full preservation of our humanity requires that the diversity (of cultures, forms of living, ways of adjusting to change) is assured in any desired future. Futures studies need to take account of this diversity in their frameworks of concepts, theories and methods.

- "Future studies are sceptical": the scepticism of Futures studies has the aim of opening up pluralistic potentials. This is the only way walkable in a world in which uncertainty, complexity and accelerating change are so fundamental components of the future that the future cannot be known with certainty.
- "Future studies are futureless": this law is true not in the dictionary sense of "having no prospect of a future" but it holds in a more technical sense. Since we can have no definitively true knowledge of the future, the impact of all futures studies can only be evaluated in the present. This does not adhere to the falsification criteria à la Popper because, according to falsificationism, the value of a scenario or a future activity in general would be determined by their realization when the future will become present. At the opposite, the real relevance of the discourse lies in the present: all future activities, from forecasts to visioning, must have a direct impact on the present, orienting behaviour, encouraging changes, managing anxiety.

The primary effort in futures studies, then, is to identify and describe alternative futures, collecting quantitative and qualitative data about the possibility, probability, and desirability of change. In order to reach this identification of different futures, a variety of approach can be used. In the followings, we present the different types of futures commonly used in futures studies; then a summary of the main approaches at them is provided.

At present, the most common model for futures studies includes four different types of futures, 'four Ps', or Possible, Plausible, Probable and Preferable futures, that can be represented in a visual way in the so-called 'futures cone' that we report in Figure 1.4 in the version used in (Voros, 2003) adapted from (Hancock and Bezold, 1994). Some futurists have in their model a fourth kind of future, 'a W', namely Wildcards that considers low probability but high impact events that can be either positive or negative; we are not going to discuss this future further.

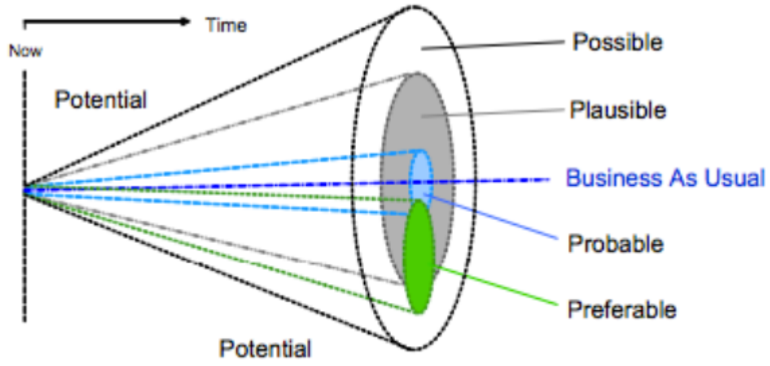


Figure 1.4. The futures cone representing the four Ps and, in blue, the business-as-usual future which can be considered as a linear extension of the present state.

The class of possible futures includes all the kinds of futures we can possibly imagine – those which might happen, even if unlikely. They might, as a result, involve knowledge that we do not yet possess, or might also involve transgressions of currently accepted physical laws or principles. In the futures cone, possible futures correspond to the biggest range.

The plausible futures are futures that could happen according to our current knowledge of how things work. They stem from our current understanding of physical laws, processes, causation, systems of human interaction, etc. This is clearly a smaller subset of futures than the possible and this is reflected from the futures cone too.

The class of probable futures, within the bigger class of plausible ones, contains those futures that are considered likely to happen and rely in part from the continuance of current trends. Some probable futures are considered more likely than others: the one considered most likely is often called 'business-as-usual' and it consists in a linear extension of the present.

While the three classes of futures described above are all largely concerned with informational or cognitive knowledge, the fourth class, of preferable (also named desirable) futures, is concerned with what we want to happen; in other words, these futures are largely emotional rather than cognitive. Because they derive from value judgements, they are more subjective than the previous three classes.

After having described the main features of the different kinds of futures, we are going to examine the main approaches used for obtaining it, named Forecast, Foresight and Anticipation: these can be considered three different ways of thinking about the future.
The forecast approach consists in thinking at future looking at what has happened before, taking information about the past history of the system. Because of this feature, the forecast is a past-oriented approach and it is the closest approach to the determinist view of future. The traditional futures studies do not include forecast, with its time series analyses and their extrapolations, as a proper part of the discipline, while the new futures studies include it as a legitimate component of the discipline, since it contributes to the building of quantitative models that work well with pretty short (e.g. econometrics) and very long (e.g. climate change) temporal windows.
Another approach is the foresight that, on the other side, takes directly on the future in an explorative viewpoint. This approach recognizes that the future is unpredictable and that there is not any certainty about it: then, a possible thing to do is imagine the future, staying bound by some data and information but providing qualitative models. In this sense, the foresight is considered a future-grounded approach. The main distinction between forecast and foresight is that the forecast considers only an extrapolation of the past toward the future, while the foresight contemplates also surprises, novelties and changes; for example, the foresight approach knows that some present trends could deflect, may vanish and new trends may arise in the future.
The last type of approaches at futures studies is the anticipation. According to this approach, the future is far from being a problem of either extrapolation from trends or exploration of possible futures: instead, the future becomes a problem of modifying end expand our capacity to act in the present since the understanding of the future mover from a static believe of it as something that is ‘there’, to a dynamic view of the future as something that can be generated or consumed by our deeds (Poli, 2010). As a consequence, we have that anticipation is essentially a present-oriented approach because it includes the outcomes from forecast and foresight, using them for action.

The tools used by forecast, foresight and anticipation approaches for outlining possible, plausible, probable and preferable futures are various and come from a wide range of disciplines. Kreibick names the following methods: trend analysis and trend extrapolation; envelope curve analysis; relevance tree techniques; morphological methods; analogy techniques; input-output models; techniques involving questionnaires; surveys of experts and interview techniques; cost-benefit analysis; cross-impact analysis; innovation and diffusion analysis; construction of models and simulation techniques; brainstorming; Delphi methods; scenario methods; roleplaying; creativity methods; future workshops (Kreibich, 2006). This is not the right place to analyse in-depth all these techniques, so we are focusing on the scenarios making, since it is one of its most widely used methods and constitutes one of its most comprehensive and complex approaches, and often integrates within itself different methodological manners of tackling issues, such as scientific techniques, evaluation techniques, decision-making techniques, event-shaping techniques, and participative techniques (Grunwald, 2002).

A scenario can be defined as a description of a possible future situation, including paths of development which may lead to that future situation (Kosow and Gaßner, 2008). It is not a comprehensive image of the future but its goal is to direct attention to clearly demarcated segments of reality. The definition given by Kahn and Wiener confirms this point: '*scenarios are hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision points*' (Kahn & Wiener, 1967). The selection and combination of key factors with regard to a future time horizon is also a construct because it forces to consider certain events as relevant and to ignore others: this perspective is similar to the modelling process used by science, since a selection of 'what is considered' is always needed. Moreover, every scenario is based on (even if not always explicit) assumptions about how the future might one day look: what direction certain trends might take, what developments might remain constant and which ones might change during the course of time.

The theoretical framework and the tools provided by futures studies have been applied also in the context of school education and, more specifically, also in science education. Recent research studies show that the futures thinking provides a useful model to guide teaching and learning programmes and can be used to encourage students to develop critical, reflective, and flexible responses to future-focused issues that affect them as individuals and as citizens in local, national and global communities (Jones et al., 2011).

1.7 From the theoretical framework to the definition of future-scaffolding skills

To conclude this chapter on the theoretical framework, I present and discuss the first main result of the work carried out by the research group in physics education of Bologna within the project *I SEE* and within the context of my thesis: the individuation of two types of future-scaffolding skills and their description.

1. *future-scaffolding scientific skills*. These skills refer to the concepts, words, ideas elaborated by science throughout its history to manage, rationally, the fear of the unknown and the unpredictable. As already argues, they are linked to the temporal patterns and models of causal explanation, that go beyond the linear deterministic models of Newtonian physics and include the probabilistic models of quantum physics and models of the physics of complex systems (applicable, for example, also to climatology, geophysics as well as to social and economic issues). Such skills refer, for example, to the elaboration of the concepts of space of possibilities, future scenarios, projection, feedback and circular causality instead of deterministic prediction, linear causality.
2. *future-scaffolding transversal skills*. Further skills, that can support students to push imagination toward the future, come from other disciplinary fields like entrepreneurial real, sociology, project planning. Among the skills strongly required by the labour market, some of them are intrinsically related to future and, hence, are particularly interesting for *I SEE*. They include, for example, *strategic thinking and planning, risk taking, possibilities thinking, managing uncertainty, creative thinking, modelling and argumentation*. They also include the abilities to use techniques that have been developed in the field of future studies to play with future scenarios and to investigate their relations with present situations, like *back-casting* and the distinction between possible, probable and desirable futures.

To recap, in Figure 1.5, we provide a visual representation of the skills we refer to in the present work.

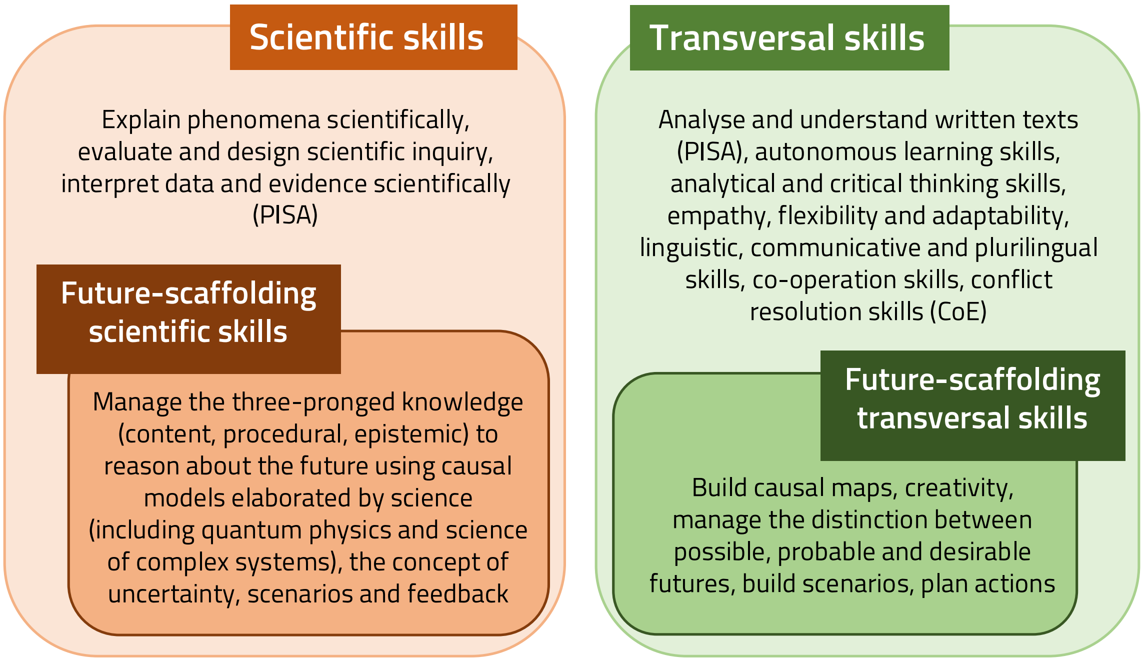


Figure 1.5. Visual representation of the various kinds of skills we have highlighted.

The scientific skills (*explain phenomena scientifically, evaluate and design scientific inquiry, interpret data and evidence scientifically*) and the distinction between the three types of scientific knowledge (*content, procedural, epistemic*) are adopted from the PISA framework (PISA, 2015). The transversal skills come from the same PISA framework (*analyse and understand written texts*) and from the most recent European document (CoE, 2016) that describes the competencies which need to be acquired by learners if they are to participate effectively in a culture of democracy and live peacefully together with others, in culturally diverse democratic societies (*autonomous learning skills, analytical and critical thinking skills, empathy, flexibility and adaptability, linguistic, communicative and plurilingual skills, co-operation skills, conflict resolution skills*). We have chosen it as our framework for transversal skills because it is intended that this model will be used to inform educational decision making and planning, helping educational systems to be harnessed for the preparation of learners for life as competent democratic citizens. As pointed out above, the definition and clusterization of future-scaffolding skills is original and has been elaborated by the research group in physics education of Bologna within the project *I SEE*.

On the basis of the previous remarks and in order to contribute to develop these skills, we have designed two different types of activities:

- activities on scientific knowledge about the content, the procedure and the epistemology of the science of complex systems;
- activities on future-scaffolding scientific skills from the science of complex systems;
- activities on future-scaffolding transversal skills from futures studies.

In Chapter 2 the designed activities and their learning outcomes are described. These activities have been experimented in order to check if and how they were able to develop future-scaffolding skills. The description of the pilot study and the analysis of results is presented in Chapter 3.

The overall work has been carried out within a team made of Laura Branchetti, Olivia Levrini, Giulia Tasquier and myself and discussed with the teachers involved in the *I SEE* project (Michela Clementi, Paola Fantini, Fabio Filippi).

My specific contribution concerns: a) the design of the activities on the science of complex systems and their implementation in the trial; b) the collaboration in the design of the activities on future competences from future studies and their implementation in the trial; c) the data analysis.

Chapter 2
Description of the activities

In the following sections the three sets of activities are described and the main common features that characterize each set of activities are stressed.

2.1 Activities A

The first set of activities has the main goal to *develop hard-scientific knowledge about complex systems science*.

In the design of these activities, we paid specific attention to underlining the characteristic aspects of disciplinary content, application context and form of presentation of the activities themselves (cfr. Table 2.1 for an overview).

Table 2.1. Overview of activities A.

Activity	Disciplinary content	Application context	Form of presentation
Lotka-Volterra predator-prey model	non-linearity	ecological science	mathematical description and simulation
Feedback Ted-Ed lesson	feedback and circular causality	ecology, climatology, economics, computer science, molecular biology	video-lesson and interactive test
Schelling's segregation model	self-organization and emergent properties	sociological modelling	simulation
The Game of Life	self-organization and emergent properties	biological model	simulation

Despite the variety of issues treated in this set of activities, they have common characteristics that can be traced specifically in the procedure that has leaded to their design. First of all, a wide literature on the theme of complex systems has been taken into account in order to isolate the main and most fundamental concepts of the theory. Then, I have searched on the Internet web resources about the theme, in order to find videos, simulations and other tools that could be useful in order to spread those concepts. In particular, I was convinced that the study of this particular scientific discipline would difficultly be effective if a traditional teaching and learning approach was applied (using, for example, just taught classes or lectures). This study, I believed, had to pass through the use of one of most used tools in the science of complex systems: the simulation. That is why this first set of activities contains a lot of different simulations, related to various application contexts. But the material tools are not the unique contents of the activities. Indeed, after having found suitable resources on the Internet, I have made the conceptual dimension explicit in order to transform the tools in completely original activities equipped with purpose, description and comments. The resulting activities have a strong disciplinary dimension, because we wanted to build a solid knowledge about the scientific discipline. At the same time, particular attention has been given to the playful dimension as a learning one, so that the learning process about the discipline could foster students' engagement. At the end of the design process, the activities were submitted to teachers in order to check if they were comprehensible, and, so, appropriate, for secondary school students.

2.1.1 The Lotka-Volterra predator-prey simulation

The first activity focuses on the concept of non-linearity through one of the simplest model in complex systems science. It describes the variation of number of preys and predators, if specific conditions hold. In order to present this model (also known as Lotka-Volterra) this strategy has been followed: first of all, the mathematical equations are verbally presented and commented, in order to explain the meaning of the variables and the modelling role of the various coefficients, as showed in Figure 2.1.

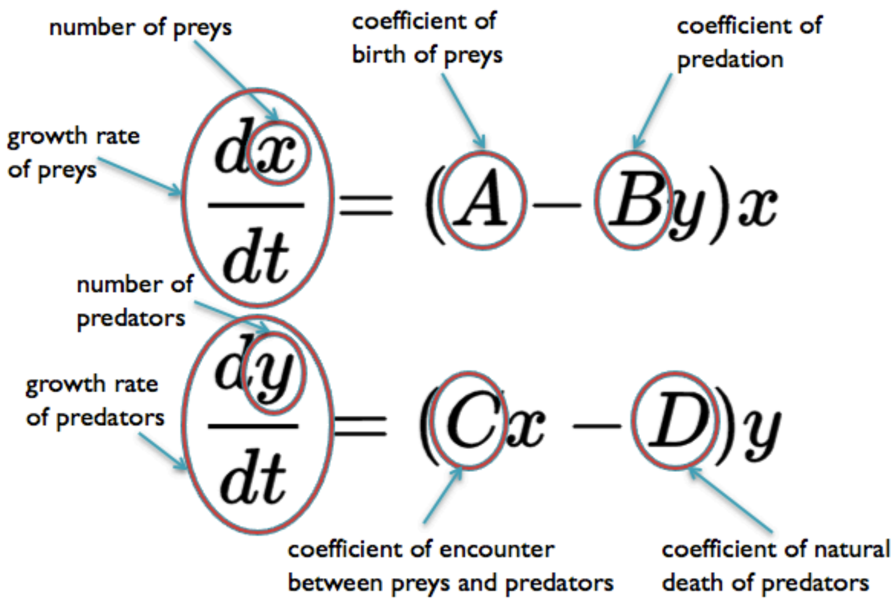


Figure 2.1. Equations of the Lotka-Volterra model in which the names of the variables and the parameters are made explicit.

Secondly, to make students "see" the mode of operation of the model, a simulation is presented: http://mathinsight.org/applet/lotka_volterra_versus_time_population_display. Changing the values of the parameters A, B, C and D, the simulation gives two graphs, like the ones in Figure 2.2, representing the evolution of prey and predator populations.

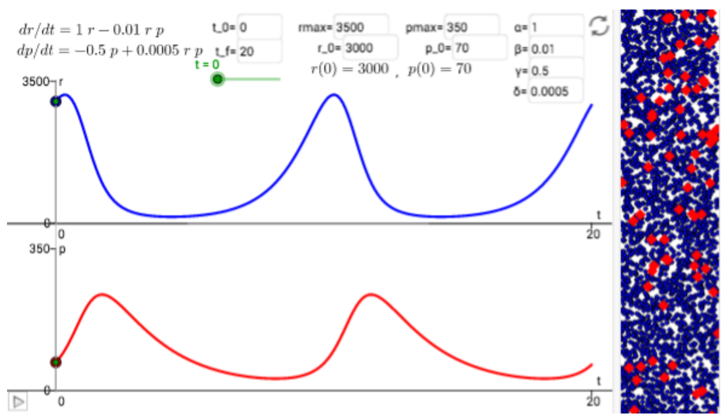


Figure 2.2. Graphs of the time-evolution of prey (blue) and predator (red) populations, according to the Lotka-Volterra model, with a suitable choice of parameters A, B, C and D.

After this phase of the activity, the results of the simulations are compared with the real data coming from the observation of a real predator-prey relationship, considering the interaction between wolves and moose on Isle Royale, an island in Lake Superior.

Showing the difference between the two graphs, here reported in Figure 2.3, it is pointed out that all models, through all the possible improvements with the addition of other coefficients, can never take into account the whole complexity of the real world. To clarify this point, a second simulation, available online at the link http://www.phschool.com/atschool/phbio/active_art/predator_prey_simulation/, is showed. It allows students to change some more parameters which soften some validity conditions of the model.

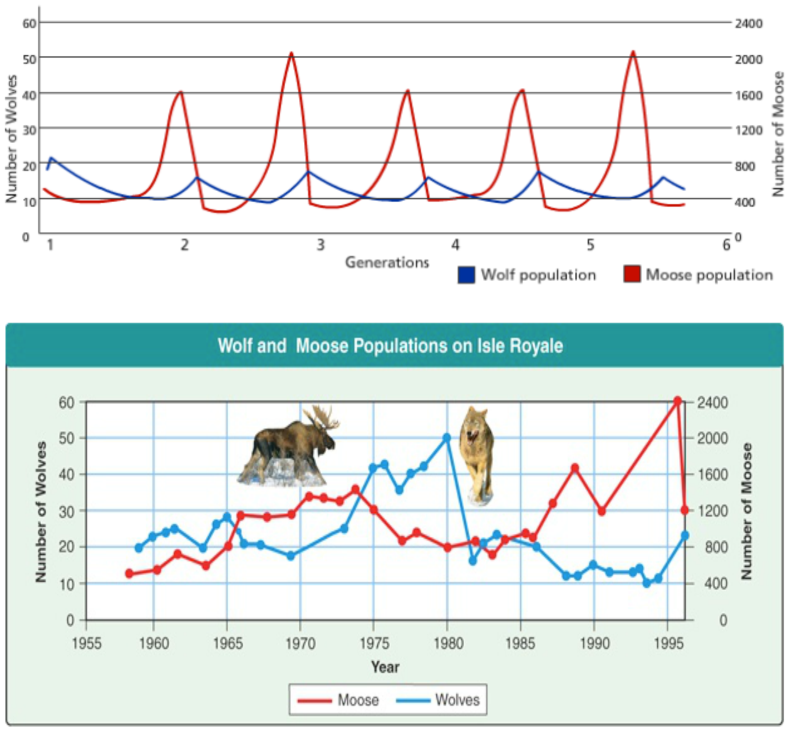


Figure 2.3. Comparison between ideal and real graphs: X.top) ideal graph obtained with the application of the Lotka-Volterra model, with fixed parameters; X.bottom) real data for 40-years evolution of wolf and moose populations on Isle Royale.

So, to recap the design aspects of this activity, we have: i) a disciplinary content represented by the non-linearity between variables in a complex system, ii) an application context within the ecological science and iii) a form of presentation that uses a simulation that allows the student to “play” with the different parameters of the model.

We anticipate that this activity worked very well during the trial and an extended, more ambitious and more technical version has been produced to be used, in case, in regular classes or in contexts where teachers wish to address these topics in some depth. The extended version is reported in Annexes 1-2 and, in the followings, we are describing its main features. After a detailed discussion about the equations of the model and about the parameters involved, we focus on the zero-interaction model, obtained when there is not any significant interaction between the two species. Then, a comment about the periodic solutions of the model is provided, showing how the non-linearity can be reread in terms of circular causality, through the concepts of feedback. In order to explore the roles of the various parameters, a script code in Python programming language is provided: it can be used to plot the time evolution of the populations of preys and predators in function of the values of coefficients. Finally, the already presented comparison between model and reality is discussed. This activity has been designed in two different versions, one for teachers and one for students. The teacher version (see A1) contains the explanation of the model and all the graphs, while the student one (see A2) has the form of a tutorial which guides the students through the analysis of the model with exercises and questions to answer; in the student version the graph are not provided in advance, because they have to be found and commented by students after launching the Python programmes.

The new version of the activity about the Lotka-Volterra model inspired the design of another activity focused on the logistic map: this activity, reported in Annex A3, was not used in our trial. We chose the logistic map because it is the simplest mathematical equation that leads to complex behaviour. The logistic model is non-linear and it is written in the form of an iterative map, dependent of a parameter. The choice of this parameter is not neutral because it leads to very different time evolutions, from stable conditions to chaotic behaviour, passing through periodic evolutions. The model allows to introduce the concept of attractor as well as a particular kind of graph (the bifurcation diagram) which is often used in the explanation of complex systems. The main characteristics, common at a lot of other complex systems, that can be found also in this very simple model are the presence of fractals and the high sensitivity at initial conditions. The activity is expected to guide teachers and/or students to the discovery of the logistic model, focusing on the mathematical and programming aspects (also using scripts in Python language for producing graphs) as well as on epistemological and conceptual related issues.

2.1.2 The feedback TED-Ed lesson

The second activity focuses on the concepts of feedback and circular causality as crucial aspects that characterize a complex system. The activity is a sort of follow up of the previous activity. Its main goal is to refine vocabulary, ideas and arguments in order to examine more and more deeply and consciously the sense of giving up linear causality when talking about complex systems. The activity is organized as a TED-Ed page, based on an animated video-lesson: http://ed.ted.com/lessons/feedback-loops-how-nature-gets-its-rhythms-anje-margriet-neutel#watch. The topic is positive and negative feedbacks in biological systems. Using a musical metaphor, the video gives imaginative tools for thinking the raising up of self-organization starting from a complex substrate of feedback cycles.

The video-lesson is equipped with different kinds of questions (multiple choices or open-ended), to boost on-line learning about the topic; the questions asked to students are reported in Annex A4. Moreover, there is a summary about the contents of the video, with some details for a deepest analysis of the topic (links to other Ted-Ed lessons, to scientific papers, etc.). It has also been created a section for discussion, where everyone can leave questions, comments or remarks that all participants can read and answer.

At the end of the interactive lesson, the activity is supposed to be completed by a classroom discussion of other types of feedback that can be recognized in a lot of fields of interest. In our implementation, we chose the example of the relationship between atmosphere absorbance and the growth of the temperature at the Earth surface (climatology), the law of supply and demand (economics), the violation at central dogma of molecular biology (molecular biology) and the selection bias (computer science).

So, to recap the design aspects of this activity, we have: i) disciplinary content represented by the concepts of feedback and circular causality, ii) an application context that embraces different areas of interest (from ecology to climatology, from economics to computer science) and iii) a form of presentation that uses a video-lesson, an interactive test to verify the knowledge acquired and a classroom discussion to share examples and what was learnt.

2.1.3 The Schelling's segregation model simulation

The third activity of this set regards the concept of self-organization. It uses a method that is itself a disciplinary content of complexity science: the simulation. For many reasons, it is practically impossible to study complex social systems through the experimental technique: we think about the great difficulty in manipulating deeply woven variables (the adjective 'complex' has properly this etymology: cum-plexus, woven together), but we also think about the ethical consequences of such an approach; because of these reasons, simulations are used, in which one can replicate, through a specific software, the principal properties and the dynamics of a social system and, through the controlled manipulation of some reference materials, one can perform "experiments". The "playable post" presented for this activity refers to the Thomas Schelling's dynamic model of segregation and is available at link http://ncase.me/polygons/. In this model, the environment is a 2-dimensional world populated by squares and triangles, in which simple cohabitation rules convert themselves in scenarios of racial segregation.
This last aspect allows us to see how, in complex systems, to small causes at the level of individuals and their interactions can correspond big effects at the level of system. We confer on this activity an important role because we want, in our research, to build agency skills that can be acquired only if there is a comprehension of the fact that one can do something and that his/her personal action does make the difference.

So, to recap the design aspects of this activity, we have: i) a disciplinary content represented by the concept of self-organization and sensitivity to initial conditions, ii) an application context that refers to a model very well studied sociological model and iii) a simulation as form of presentation.

2.1.4 The 'Game of life' simulation

The fourth and last activity of this set considers another face of the emergent properties in complex systems science that is the showing up of geometrical patterns, starting from minimal rules.

The tool that has been used is an applet based on a simulation named "Game of life", invented by the mathematician John Conway: https://bitstorm.org/gameoflife/. The basic rules of the simulation reproduce in a simplified way the behaviour of cells.
With the applet, the students can "play" with the simulation, experimenting their favourite initial geometrical conditions and watching the time-evolution of the system. But before leaving them autonomous, three main classes of objects have been introduced: still lifes, oscillators and spaceships. They are shown in Figure 2.4.

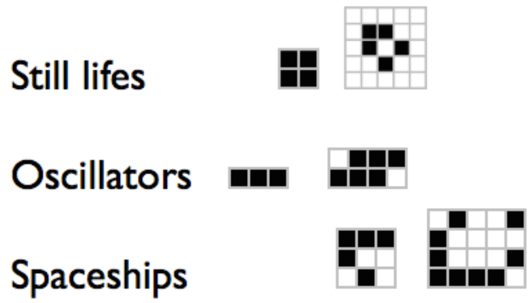


Figure 2.4. Examples of patterns, with alive cells shown in black, and dead cells shown in white.

So, to recap the design aspects of this activity, we have: i) a disciplinary content represented by the concept of self-organization and emergent properties, ii) an application context that refers to a biological model in a very simple version interpreted by computer science and iii) an applet based on a simulation as form of presentation.

To strengthen the concept of self-organization, many other examples can be used. One of them is the "world of ants" that students do appreciate[1]. A brief description of it is reported in Annex A5.

2.2 Activities B

The second set of activities has two main goals: to develop i) *hard-scientific skills about the science of complex systems,* like recognizing and imaging feedback loops; ii)

[1] This example has been used by Zanarini and Fantini in a class of scientific lyceum in Rimini (grade 12), in a seminar about the science of complex systems (March 2017, personal communication).

transversal skills, like reading, analysing a scientific text and building causal maps. The set consists of two activities that in the followings are illustrated.

2.2.1 Activity on the IPCC report

The first activity, reported in Annex A6, consists of the reading of a synthesis of an IPCC report, related to the issue of global warming. Through this activity, we asked students to read this text, to underline the problems suggested by the text about the main issue of global warming and, finally, to build a map "or another way of organization at one's own choice" in order to sketch up a hierarchy between the highlighted problems in terms of cause-effect relationships.

After the execution of this activity, the teachers showed to the students a map that could be drawn starting from the same text; it is reported in Annex A7. From this map, the students are guided to recognize how, starting from the big issue of climate change - with all its social, environmental, technological and political themes – an area of the map can be chosen, in order to analyse in depth the cause-effect net that, in the big map, collapses in a single link. In these terms, a focus on the problem of transports is provided, with a procedure of zooming illustrated in Figure 2.5.

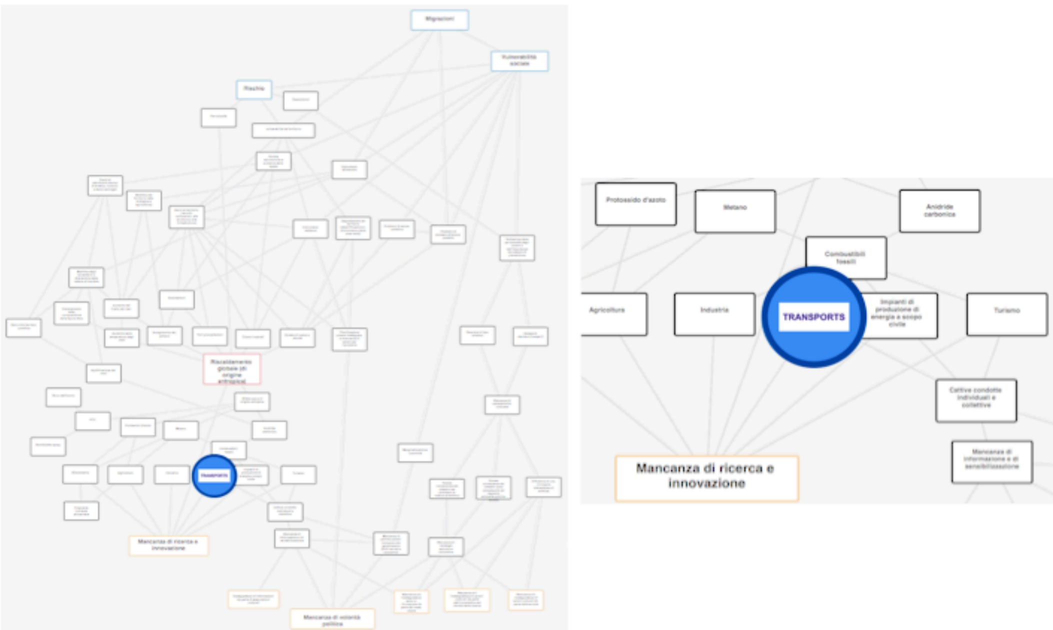


Figure 2.5. Procedure of zooming from the issue of global warming to the more specific problem of transports.

2.2.2 The ‘Biodiesel story’

The second activity of this set is made up of four different parts that are explained in the followings.
The starting point is a scientific text that we named the ‘Biodiesel Story’ (Annex A8) and that treats the most important aspects related to the use and the production of biofuels. The text has been written by Giulia Tasquier and myself with a clear objective: to offer the students a text on which they can exercise to recognize and abstract the logical and causal structure of the phenomena described in it.
The scientific text that we produced situates the specific theme of biofuel within the more general issue of transports which in turn is related to the even wider problem of mitigation of climate change: the previous activity about the synthesis of the IPCC report was designed specifically for providing this contextualization. Although the fact that the issue of biofuels is often treated in terms of pros and cons, advantages and disadvantages, we avoided mentioning these words, limiting the text to detail the cause-effect relationships, without making it too explicit (in the sense, that we avoid using expressions like ‘this causes this’).
The text presents a lot of notes for an in-depth analysis about the chemical details and the technical terms that comes from climatology. These notes are intended to be to completion with respect to the text: it is readable and comprehensible also without reading them. A particular attention, along the whole text, is given to the references.
After we drafted the text, we asked two experts, Prof. R. Rizzi and Prof. Margerita Venturi, to check and validate the contents. Readability by secondary school students has been instead checked by secondary school teachers, Prof. Michela Clementi, Paola Fantini, and Fabio Filippi.

The activity consists of reading the Biodiesel Story and, as first step, to build a map that summarizes the cause-effect net that the text displays. Our proposal of map is reported in Figure 2.6 and in Annex A9.

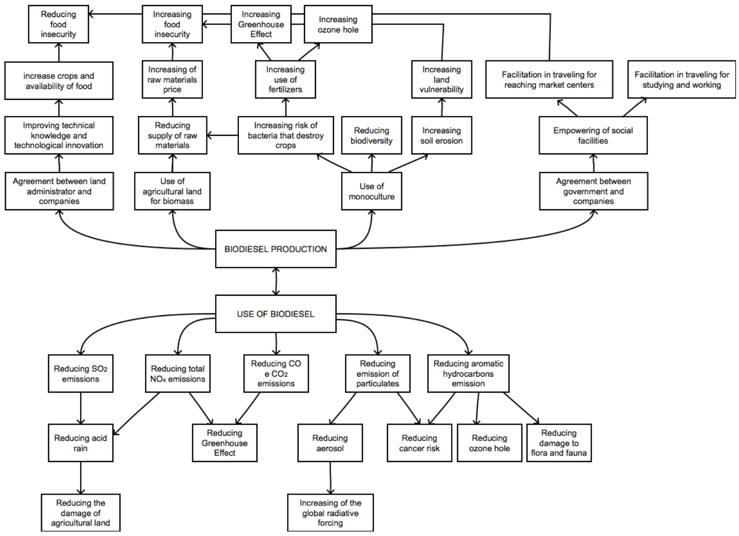


Figure 2.6. Our proposal of map drawn starting from the text of the "Biodiesel Story" (see Annex A9 for an enlarged version).

In it, two main areas are identified: one is related to the use of bio diesel, while the other is related to its production. The arrows indicate the different levels of causality. This map is a linear one: starting from a cause, the consequence follows, then it becomes cause of another thing and so on.

After this first part of the activity, in which the scientific text is organized into a logic map, the mechanism of feedback is introduced, showing that, in this linear map, some links can be enriched if one considers the underlying feedback loops.

Two sub-activities have been designed in order to build a proper skill about the concept of circular causality.

The first sub-activity consists of considering the scheme of feedback loops that we prepared (see A10), detailing them in an extended form. In particular, each group of students received two feedback loops and, after having provided the detailed description of the phenomena summarized in the schemes, they had to situate the loops they received in our map of the biofuel issue. Our proposal of map, in which all the feedback areas are highlighted, is reported in Figure 2.7 and in Annex A11.

The second sub-activity consists of the request of finding in the map other possible loops, different from those given in the previous phase, related to the issue; students are asked to detail the loops found in an extended way and to represent them in a scheme.

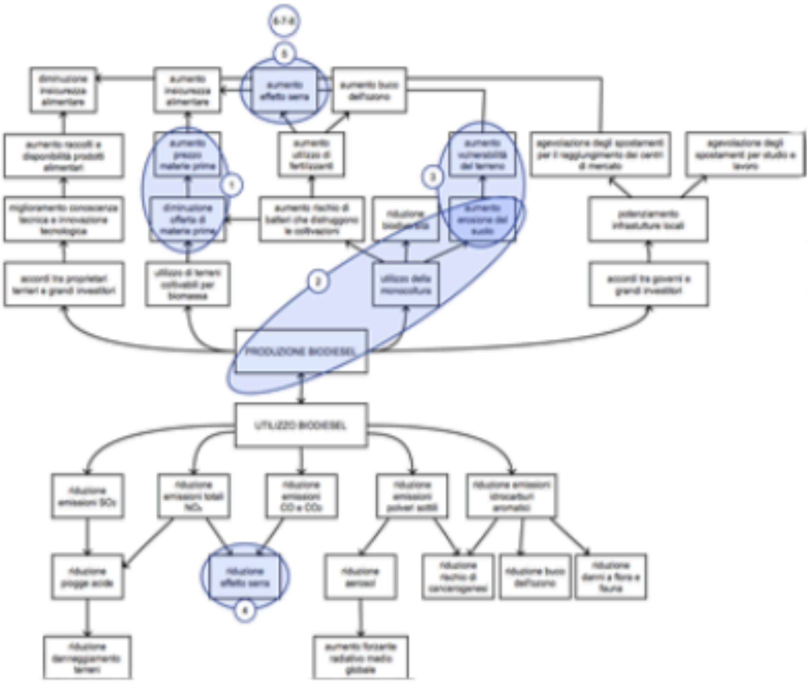


Figure 2.7. Our proposal of map where the feedback areas have been highlighted (see Annex A11 for an enlarged version).

After the pilot study in which the activities have been carried out, a supplementary activity has been designed in order to support students in building their causal maps. This activity, reported in Annex A18, is an introduction to the Logical Framework Approach (LFA). Developed in the late 1960's, the LFA is at the same time an analytical process and a set of tools designed to support project planning and management. It has been described as an 'aid to thinking' because its aim is to give structure to the analysis so that important questions can be asked, weakness identified and decision makers can make informed decisions based on their improved understanding of the project rationale, its intended objectives and the means by which objectives will be achieved.

2.3 Activities C

The third set of activities has the main goal *to turn hard skills into specific transversal skills that we identify as future-scaffolding skills*. The first implementation of these activities was during a pilot study with adult citizens of the town of Dozza (Albertazzi, 2017). In the context of that experimentation, two different group activities were designed.

2.3.1 An urban problem for the town of Irene

The first was "Probable, possible and desirable futures for the Town *Irene*", an activity related to a problem of urban planning, inspired by a real situation. The second one was "The fishback game", a board game for four players, concerning the activity of fishing businessmen, that had the main goal of reinforcing the renounce to linearity by thinking, in a dynamic way, about feedback mechanisms and about the long-term consequences of players' actions and intentions. In this game, adapted from the proposal found in the website http://www.molleindustria.org/blog/designing-games-to-understand-complexity/, the strategy emerges as a characteristic of the group of players: depending on the strategy planned, one is the winner or everyone loses. It is not easy to agree upon the sure strategy to win, but it is pretty simple to identify the best way to lose: indeed everyone loses if the players does not consider the feedback loops the game is based on. In Annexes from A12 to A14 the material related to this activity can be found: it consists of a detailed description of the rules of the game (see Annex A12), the printable material (see Annex A13) and the description of four positive and negative feedback loops that have been tracked down during the game playing (see Annex A14).

During the pilot study carried out in that context, it was found that "The fishback game" activity was really appreciated by almost all the participants but it required too much time to be completed, because players had to spent a lot of time to become familiar with the rules and with the dynamic of the game. So, this activity has been abandoned, while the first one, about the town of Irene, has been revised and improved for the experimentation which is object of this work; the final version of this activity is reported in Annex A15. Here I sum it up by stressing its goals and structure.

It consists of four different parts, all related to the macro-activity named "probable, possible and desirable futures for the Town *Irene*".
The problem presented in these group activities is related to urban planning and it has been inspired by a real situation (Albertazzi, 2017).

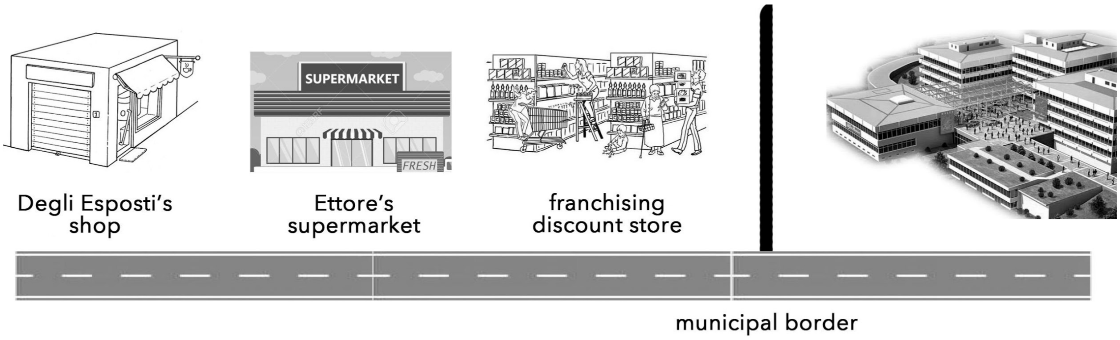


Figure 2.8. The spatial disposition of the commercial areas of the town of Irene.

Irene is a small town that counts three commercial areas operating in the food sector: they are spatially arranged as shown in Figure 2.8. There is Degli Esposti's shop, in the town centre: it is a well-furnished and very looked-after shop managed by the Degli Esposti family and, properly because of this, they survived the economic crisis. At a short distance, away from the small town, there is Ettore's supermarket; he has six employees and though being allowed permission by the existing urban regulations, he has never renovated his offer nor enlarged his place, so to extend the range of available products: the reason why is to be found in his approaching retirement age and the scarcity of money possessed to invest. Finally, farther off the town centre, there is a small discount store belonging to a large chain, where 10 employees work: the chain owners wish they could double the surface and add a nearby parking lot where now there is an agricultural field, but they should have an alteration of the urban regulations approved by the Municipal Council, because the present Urban Planning Regulations would not allow any possibility of expansion.

The first activity consists of the analysis of the present situation and the identification of probable scenarios. To analyse the present situation, students are expected to build a map considering the stakeholders, their needs and interests, the existing interactions between the stakeholders. The activity in Annex A18, about the Logical Framework Approach, has been designed after the pilot study in order to explain the characteristics and exemplify a stakeholder analysis too.

After doing that, starting from the plan scheme of the present situation, one has to identify and describe two possible scenarios at 2025: the first will have to illustrate a possible condition of evolution of the system as a consequence of granted expansion; the second must envisage a possible situation of evolution after a denied expansion.

The second activity has the main goal of identifying positive or negative feedback loops that can give reasons for the realization of possible scenarios. The first scenario sees the periphery of Irene has become an attractive centre thanks to its many commercial activities that have been developed beyond the commercial area, but the historical centre has become progressively empty. The second one shows Irene as a centre of attraction for a local and diversified tourism, thanks to the gastronomic offer of shops and restaurants of the town centre and to the street market stalls regularly organized.

The third activity is about the imagination of a desirable scenario for the town Irene in 2025. The scenario has to be accompanied with a catchphrase that characterizes Irene as the ideal town where to live or to visit. After this, each group of students has to plan an action that they may undertake (as singles or as a group) in the present, in order to favour the realization of the desired scenario. They are asked to describe who they are and the position they hold when realizing the action (for instance: political decision maker, private citizen, an association, society, company or firm, a bank, the headmaster of a school, etc.), what they intend to do and why they think this action favours the realization of the desirable scenario.

As final part of Irene activity, the groups of students have to decide if allow extension to the discount or not, explaining why.

The transversal skills that we intended to reach with Irene are future-scaffolding skills because the distinction between the three types of future, after a solid analysis of the present situation, is the starting point for a conscious and personal agency.

2.4 Learning outcomes of the activities

The activities presented above can be summarized in terms of learning outcomes which are statements of what learners (in our case, students) are expected to know, understand, succeed in, after completion of a process of teaching/learning. We summarize these learning outcomes in Table 2.2, divided in sets of activities. Although the activities have been designed with a multidimensional approach that often strictly links knowledge and skills, for each learning outcome, we specify what type of knowledge and/or skill is *mostly* involved.

Table 2.2. Learning outcomes of the three sets of activities with the related knowledge and/or skills that are mostly involved.

Set of activities	**Learning outcomes**	**Knowledge and/or skills mostly involved**
A	Students get acquainted with basic concepts of science of complex systems: complex system, nonlinearity, sensitive dependence on initial conditions (butterfly effect), self-organization, circular causality, positive and negative feedback loops.	Scientific content knowledge
	Students become familiar with one of the main tools of the science of complex systems, the simulation, and understand that it can be considered a third way to study phenomena beyond the two traditional ones (laboratory experiments and theories); they learn that the simulation does not use normal words or symbols of mathematics but uses a particular language that incorporates into a computer program that can be used as a virtual laboratory.	Scientific procedural knowledge
	Students recognize that linear causality is not the only way to think and talk about the future and get acquainted with a new vocabulary elaborated by the science of complex systems to think and talk about future (e.g. the concept of projection as distinct from deterministic prediction; the concept of possible future scenarios).	Scientific epistemic knowledge
	Students learn that approaching science phenomena that involve citizenship issues (e.g. climate change) implies a change in the epistemological way of looking at the phenomena itself: they learn, for example, that climate is a complex system and that the interpretation of phenomena related to it implies new type of explanation, modelling and argumentation.	Scientific epistemic knowledge
B	Students become able to analyse scientific texts by recognizing the causal net made by links and nodes.	Analyse and understand written texts
	Students become able to distinguish from linear and circular causality, within the scientific texts, recognizing the nature of the causal links and individuating possible feedback loops that can be found starting from the text.	Explain phenomena scientifically; manage the three-pronged knowledge (about the concept of feedback and of causality) to reason about the future
	Students learn to transform the causal nets present in the scientific texts into cause-effect maps.	Build causal maps

C	Students become able to apply concepts of science of complex systems (e.g. feedback loop) in an urban problem.	Explain phenomena scientifically; manage the three-pronged knowledge (about the concept of feedback and of causality) to reason about the future
	Students learn that approaching climate change implies a change in ways we live in everyday life and we, collectively, make decisions.	Decision making
	Students get acquainted with basic concepts coming from future studies (forecast, foresight, anticipation, backcasting, the distinction between probable, possible and desirable futures) and manage these concepts to reason about an urban problem.	Manage the distinction between possible, probable and desirable futures
	Students learn that scenarios are hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision points and practice for elaborating them.	Build scenarios
	Students become able to imagine possible future careers to aspire, putting their creativity into play.	Creativity
	Students become personally committed to outline a desirable scenario and/or to point out a desirable objective to be reached in the future.	Active participation
	Students take the agency to plan an action to make their futures possible.	Plan actions
	Students work in group to reach shared decisions.	Cooperation and conflict resolution skills

Chapter 3
The pilot study: context, methods and data analysis

3.1 Context, methods and research questions

The activities described above have been used in a teaching module implemented within a laboratory-course about the topic of climate change. The class was comprised of 14 voluntary students (6 males and 8 females) who, for six afternoons, decided to attend these optional lessons organised by the Department of Physics and Astronomy of the University of Bologna, within the *Piano Lauree Scientifiche* project (the acronym PLS in English could be translated into *Scientific Degree Plan*). The students were 17-18 years old; most of them attended scientific-oriented high schools ('Licei Scientifici'), but there was also a group of 3 students coming from high schools focusing on humanities ('Licei Classici').

The course was organised in two main parts.
The first part (9 hours) included: 1) a lesson about the difference between meteorology and climatology sciences, including an introduction to climate system as a complex one (the concept of feedback was introduced here for the first time) (teachers: Prof. R. Rizzi and Dr. G. Tasquier); 2) two laboratory experiences about the interaction between radiation and matter and the greenhouse effect, where the role of modelling in climate science was stressed (teacher: Dr. G. Tasquier) (Tasquier, Levrini, Dillon, 2016).
In the second part of the course the set of activities described before were implemented (9 hours). In the first lesson of this part, the students were exposed to an interactive lesson

about the science of complex systems, where the activities of set A were carried out (teacher: E. Barelli). In the second lesson, the students were guided to analyse, in group, the document on the synthesis of the fifth IPCC report and the "Biodiesel story" (activity of set B) (teachers: G. Tasquier and E. Barelli). The third lesson completed the course. It started with a collective discussion on the results of their homework and, hence, on the feedback loops they found in the bio-fuel document. Then, two hours were devoted to the activity of set C about the town of Irene (teachers: G. Tasquier and E. Barelli).
The data analysis and the pilot study have been carried out only on those students who attended the lessons of the second part of the course. The graph of Figure 3.1 reports the presence of each student at the different lessons in the second part of the course.

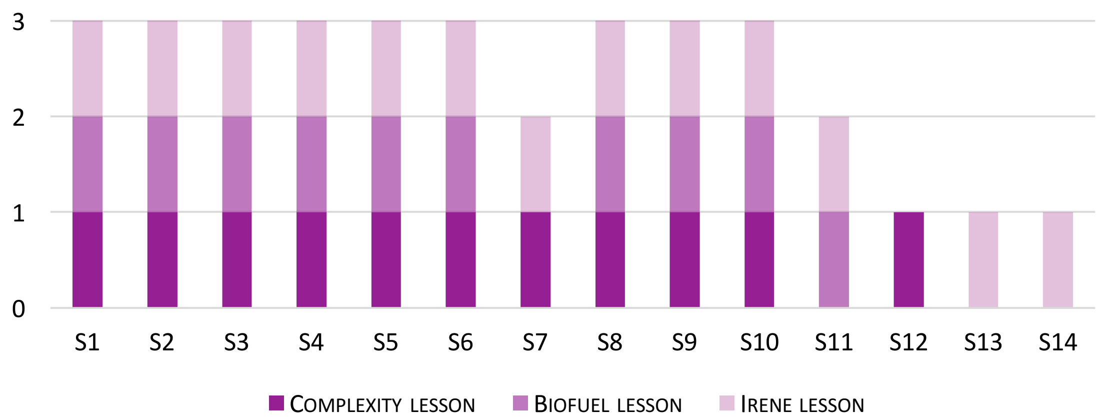


Figure 3.1. Students' attendance to the second part of the lesson: 11 out of 14 students attended complexity lesson; 10 out 14 students attended biofuel lesson; 13 out of 14 students attended Irene lesson.

During the pilot-study, many data were collected in order to monitor the study. A pre-questionnaire about the different dimensions of the module (disciplinary, epistemological, personal) was submitted (see Annex A16). Students were asked to answer an intermediate conceptual questionnaire after the first lesson of the second part (the lesson on complexity) about the main scientific contents (see Annex A17). Every lesson was audio-recorded and we considered the students' outputs produced during the working groups, as well as the notes of the researchers who attended the lessons.

The data have been analyses to answer four research questions. The research questions reflect the main goals of the activities:

1. *Have the students developed scientific knowledge about complex systems science?*
2. *Have the students developed scientific skills?*
3. *Have the students developed transversal skills?*
4. *Have the students developed "future-scaffolding skills"?*

In the following presentation of the results, we report, for each question, the specific data we considered and the specific methodologies we used to analyse them. Generally speaking, a qualitative strategy was iteratively implemented in order to build a synthetic picture of what happened and to interpret it by recognizing criticalities, trends and behaviours during the activities. After the first round of data analysis, the results were tested against the literature on students' difficulties and understanding or on youth's perceptions of future in order to frame the results and to value their reliability and relevance.

3.2 Scientific knowledge: data analysis and results

In this section, we analyse the results of the interactive lesson on the concepts of the science of complex systems. The analysis will provide all the elements to answer our first research question: *Have the students developed scientific knowledge about complex systems science?*

The question will be answered through a pre-post analysis, that is by contrasting the knowledge students acquired throughout the activity (and displayed in the intermediate questionnaire) against the knowledge they had before the course (and showed in the introductory questionnaire).

3.2.1 Initial state of students' knowledge

The introductory (or pre-) questionnaire was submitted to 13/14 students (one was absent). It concerned the concepts of system, feedback and prediction (in reference to climate change).

Students' answers were analysed through a bottom-up process, aimed to point out emergent patterns (clusters) in students' knowledge and outline the initial state against which we will test whether and how knowledge evolved.
According to this goal and to the features of the sample, the analysis does not have any statistical value. Tables and graphs are meant to be nothing but a synthetic way to represent what emerged here, without any demand of generalization. In the tables, the clusters are illustrated both through a brief description and examples of students' answers.

With respect to the concept of system and its definition, in the pre-questionnaire, students were asked to answer this question: '*In physics or generally in science, you have certainly heard about system. How would you define it? What properties do you identify? You can help yourself by providing some examples'*.
In their answers, almost all the students refer to the distinction they learnt at school between isolated, close and open system:

> *'[A system] is a container that, into a universe, is defined as open, if it exchanges either energy or matter with the universe, close, if it exchanges just energy, and isolated, if it does not exchange anything' (S8).*

A comment that will become more sensible after the analysis of the intermediate questionnaire is that the students did not consider possible interactions among the components of a system: school definition leads the students to focus their attention on the distinction between system and environment and to their type of energy/matter exchange.

With respect to the concept of feedback and its definitions, students were asked to answer this question: *'You have surely heard the word feedback. In what contexts have you heard it? What meaning do you ascribe to this word? Have you ever heard about it referring to science? In your opinion, what does it mean when it is referred to physical systems? Try to give some example'*.
Only one student did not answer the question. In analysing students' answers, two clusters emerged. For almost half of them, the term 'feedback' was associated to the e-commerce field, so the meaning of feedback is very similar to 'evaluation', opinion. Thus, the adjectives 'positive' or 'negative' were associated to 'good' or 'bad' service.

All the other students answered by referring to feedback in terms of response to a stimulus: an action (not necessarily in a scientific perspective) that causes a reaction.
An example of how we identified the emergent cluster from the analysis is reported in Table 3.1 and the distribution of students' answers over the two clusters is reported in Figure 3.2.

Table 3.1. Clustering of students' answers on feedback (pre-questionnaire).

Cluster	Description which reflects the meaning of the cluster	Representative students' answers for the cluster
Feedback as an evaluation	Evaluation of a service or of an object. Mark or review about something. The evaluation or mark or review can be good (positive feedback) or bad (negative feedback).	*"I give to the term 'feedback' a meaning of 'evaluation'; with regard to physical systems, it can describe the utility."* (S13)
Feedback as a response to an input	Response to a phenomenon or an event or an action. Reaction of the system to a stimulus, not necessarily in a scientific perspective.	*"Feedback is the response to a specific event. In physical systems it can be the response of the environment to human actions."* (S10) *"[...] in general it is a response to a specific action. For example, if you asked me an opinion about the course I am attending, my answer would be a feedback."* (S7)

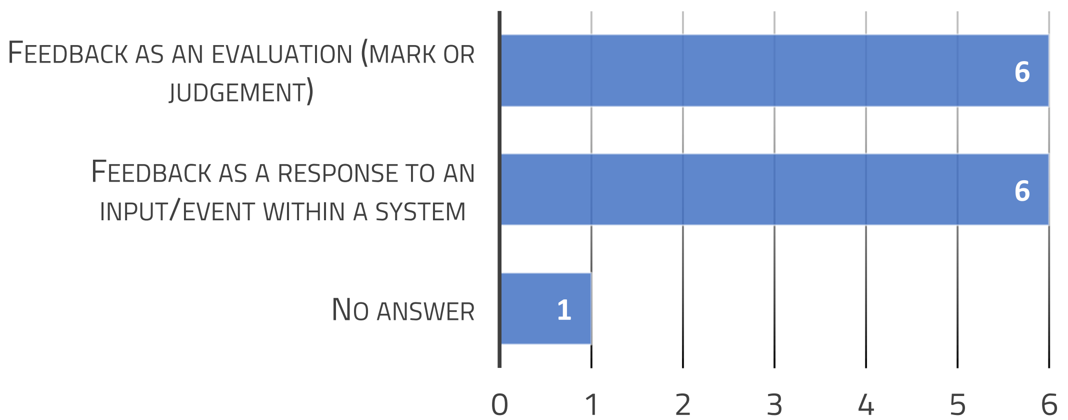


Figure 3.2. Students' conceptions of feedback (pre-questionnaire).
(Total number of students: 13)

The answers show also an interesting tendency to consider feedback as a multifaceted concept that can be inherent to science but also to other fields, including social phenomena. A couple of examples of answers that show this aspect are the following:

'I have typically heard the word feedback in economic and medical contexts and I give to it the meaning of 'answer'. In a physical context it could be the outcome of a process applied to a specific system.' (S4)

'In biology, referring to the study of human body, feedback is when we have a growth or a decrease (positive or negative feedback), an answer to a specific phenomenon.' (S12)

On the basis of this initial picture on the concept of feedback we can observe that:

1. there is an idea of feedback as 'evaluation of an e-service' that has to be problematized or displaced since it can interfere with the scientific meaning of the concept;
2. students have productive resources on which it can be worth building. They concern both the idea of feedback as a response to a stimulus and the recognised multi-disciplinary relevance of the concept. As for the idea of feedback as response to a stimulus, it should be made to evolve toward a more explicit idea of circular causality (in the initial answers it seems very implicit, if it exists). As for the multi-disciplinary relevance of the concept, it represents a very important resource to be exploited both when the scientific content is fixed and strengthened, and when the transition from scientific skills back to transversal skills is discussed.

With respect to the concept of prediction about climate change, students were asked to answer this question: *'What does it mean, in your opinion, to make predictions (relating to climate but not only)?'*

Four clusters emerged from the analysis of students' answers. The four clusters are the result of a process of triangulation with the literature on the future students (Miller 2007; Poli, 2010). The first three are related respectively to *forecast, anticipation, foresight* (see Table 3.2 and Figure 3.3). The first cluster (*Using present and past for knowing future*), typical of *forecast,* implies a way of thinking *based on* what has happened in the past and what is happening in the present; the attitude that characterizes this way of facing the future is a sort of *planning attitude*: the future is perceived like something that will happen and what we have to do is just going where it is. According to this way of thinking, prediction is the tool used to *analyse the present (or the past)* in order to predict what will happen in the future. The main marker we used to analyse students' answers and to recognise the forecasting attitude is the presence of expressions like '*on the basis of … [what we know so far, our certain theories, our data…]'*.

The second attitude (*Using future as an anticipation strategy to act in the present*) is typical of *anticipation*, which is a means to imagine, in advance, what can happen so as to orient an action in the present. The direction is *from the future to the present* and, unlike in the cases of forecasting, anticipation refers to '*see in advance*' possible future developments of something *that has not yet happened* in the present but *can* happen. '*To see in advance*' and the reference to *possible* actions/events in the present are the two markers that we used to recognise, in students' discourse, an anticipation attitude.

The third attitude toward the future (*Exploring probable/possible futures*) is typical of *foresight*; it consists of an explorative way of thinking possible futures/trends/scenarios. Exploration is freer than in forecast, since it does not start from present strict conditions and futures can be influenced by choices not yet made. The markers that we used to recognise a foresight attitude are the presence of a probabilistic language, the emphasis on future uncertainty and no explicit reference to present actions.

Three students provided tautological answers like *"to make predictions mean to try to know what it will happen in the future."*

A typical example of answer for each cluster is reported in Table 3.2 and the distribution of students' answers over the four clusters is reported in Figure 3.3.

Table 3.2. Clustering of students' answers on prediction (pre-questionnaire).

Cluster	Description which reflects the meaning of the cluster	Representative students' answers for the cluster
Using present and past for knowing future	Observing, organising and analysing present data or laws obtained from the past in order to know what will happen in the future or to implement a model for predicting a future trajectory.	*"Making predictions means trying to figure out what will happen in the future by studying what has already happened and having obtained the laws."* (S14)
Using future as an anticipation strategy to act in the present	Analysing a set of possibilities and identifying possible future developments or future trends that may happen; they can be influenced or not from the past.	*"Making prediction, for me, means to analyse a series of possibilities and hypothesis and to try to understand in advance what it could happen in a specific context."* (S2)
Exploring probable/possible futures	Identifying the probability of possible events within a range of possibilities and a plethora of choices.	*"Making prediction means to calculate the probability of an event, taking as the real prediction the maximum probability of happening." (S10)*

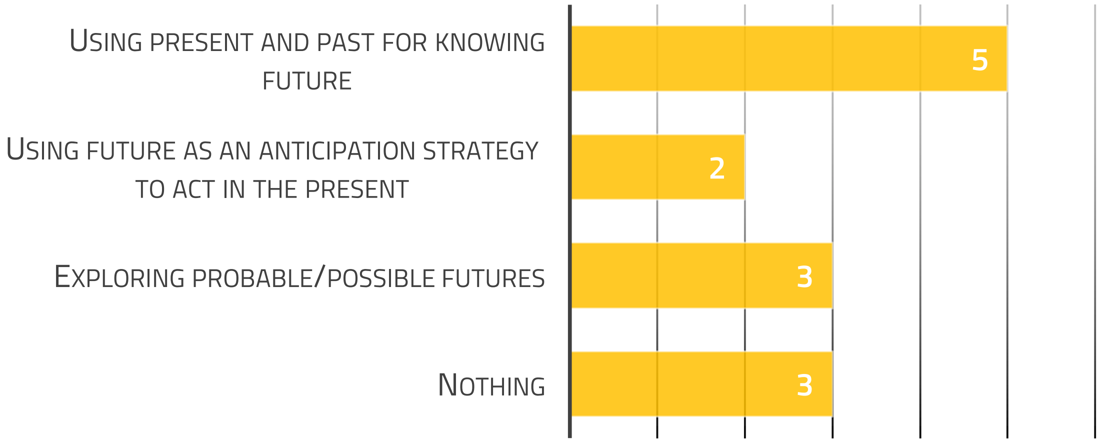


Figure 3.3. Students' ideas on the concept of prediction in climate change (pre-questionnaire).
(Total number of students: 13)

The forecast attitude as well as tautological answers are not surprising because prediction evocates immediately meteorological models. However, there are 5 students which show anticipation and foresight attitudes. Even though in a germinal way, they showed that possible future scenarios, uncertainty and probability are part of their ways of thinking.

A detailed representation of the characteristics identified by each student is provided in Figure 3.4.

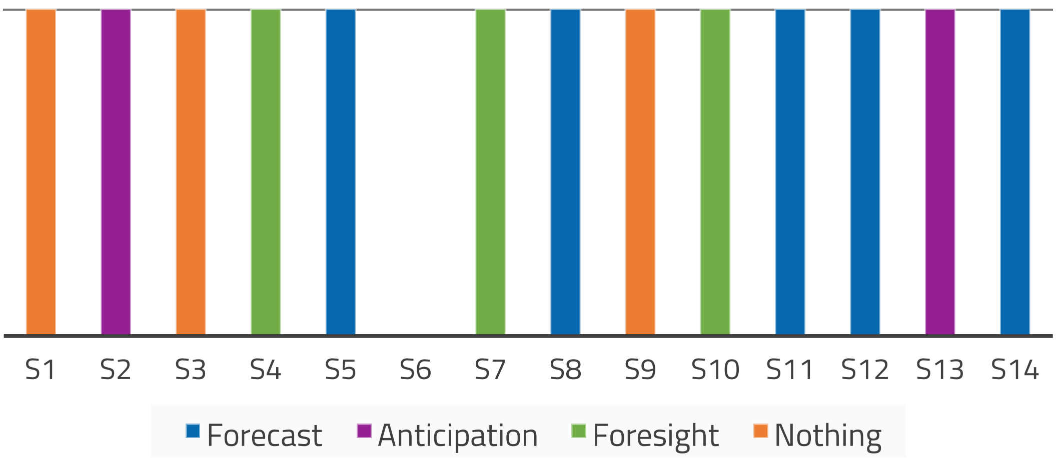


Figure 3.4. Students' attitude toward future (pre-questionnaire).
(Total number of students: 13)

3.2.2 Students' knowledge about complex systems science: how it evolved and changed throughout the activities

As shown in Figure 3.1, 11 out of 14 students were present when the intermediate questionnaire (on the concepts of system, feedback and previsions, see Annex A17) was submitted at the end of the complexity lesson.

Students' answers were analysed through the same method that was used for the analysis of the initial state: emergent patterns (clusters) were pointed out and are here presented in tables where examples of students' answers are reported. The results will be here reported concept by concept and discussed with respect to the initial state.

As for the concept of system, in the intermediate questionnaire students were asked to answer this question: '*Thinking about the activities done so far, how would you define a "system"? You can also help by trying to provide examples'*.

In their answers, students' definition changed with respect to the answers they gave into the initial questionnaire. The answers show a new focus of attention on the inner *components* of a system and on their *mutual, internal, interactions*. The key-words of the answers became indeed 'components/composition' or 'interaction/interact'. Examples of answers are:

'A system can be considered as a set of factors that interact among them.' (S10).

'A system is a limited environment in which we study internal and external interactions and its composition.' (S8).

One student also stressed the feature that the whole is not necessarily the mere sum of its components:

'A system is the set that is generated by the interaction between more elements that influence each other. The system is not necessarily the mere sum of its components.' (S4).

Only 2 students out of 11 did not use the words interactions/interact in reference to the inner components and, instead, provided a 'space' description, in the sense that they have still considered a system as something that is *in relation with the environment*. However, they seemed to stop to consider the system as a whole and introduced that it can have an internal composition.

In all the cases, we appreciated the enlargement of the way of looking at a system and the new focus on the inner dynamics. We see here an important step toward the recognition of the active role of the researchers to define the system according to the goals of their investigation and, we guess or hope, it was suggested by the wide discussion we had in questioning the problematic issue of 'cutting the nature of its joints' (how can a researcher decide what is important and how he can check the eventual effects of the neglected variables and/or of the interactions with the not considered environment).

With respect to the concept of feedback and its definitions, students were asked to answer this question: *'Thinking about the activities done so far, has your idea changed with respect to the word feedback? If so, what new meanings do you attribute to it?'*.

The first important result is that the interpretation of feedback as 'evaluation' completely disappeared and the students who had before answered in these terms explicitly recognized that their initial idea had changed after the activity:

"[My idea of feedback] has changed in sense that I intended 'positive' and 'negative' as qualitative characteristics while now I realize that they do not affect a 'good' or 'bad' event" (S7).

Most of the students answered by referring to feedback in terms of a cause-effect dynamic (first two clusters in Table 3.3) and they mention the possibility of having either positive or negative feedback. Through the first cluster we emphasized the students who explicitly used the term 'circular causality', but the distinction between cluster one and two remains not so substantial.

Instead, clusters 3 and 4 report the definitions that we do not consider satisfactory (see Table 3.3): 2 students seem to show the residual of reasoning typical of linear causality, whilst 1 student gave a vague definition that cannot be interpreted properly.

In Table 3.3 we report the clustering with an example of answer to illustrate the cluster. The distribution of students' answers over the clusters is reported in Figure 3.5.

Table 3.3. Clustering of students' answers on feedback (intermediate questionnaire).

Cluster	Description which reflects the meaning of the cluster	Representative students' answers for the cluster
Feedback as cause-effect relationship	The effect and the cause are not just consecutive events, but the effect can, in turn, influence its causes and	*"Now I can give it [the concept of feedback] a more general (more 'relevant') meaning. It is an element*

	induce an interaction between the two. The circular causality can amplify or soften a phenomenon (its causes).	*within a circular cause/causes-effect/effects relationship and it amplifies or softens causes themselves."* (S4)
Feedback as an "action back"	Effects can act back to the cause, amplifying or softening it.	*"Feedback is that set of conditions that affects what has caused it and, according to how it affects the cause, the feedback can be positive or negative."* (S9)
Feedback as a series of actions/events	Linear concatenation and/or repetition of two or more phenomena, considering events as sequences, one after the other	*"My idea of feedback has changed a lot and I have understood that we mean the results of interactions between two or more phenomena and that they are often indirect, because they are the effects of a series of action during the time."* (S10)
Vague answer	Feedback as a set of relation	*"Feedback is the set of reactions that happen in a specific environment and it can be positive or negative."* (S5)

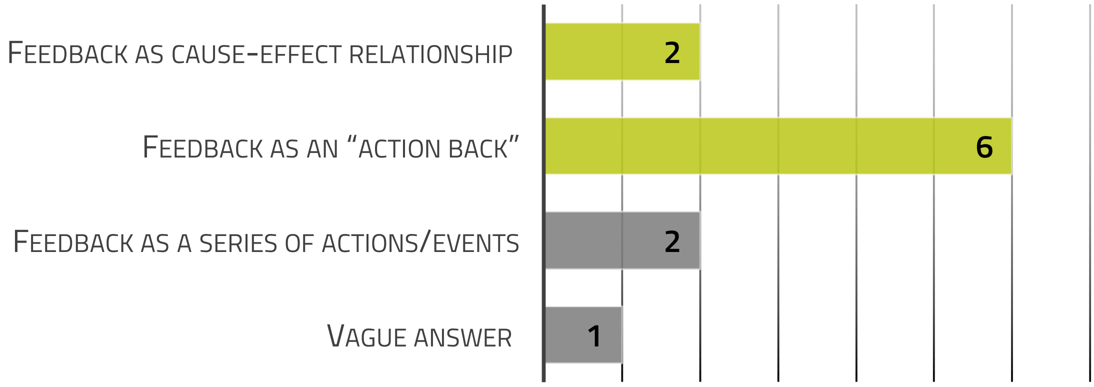


Figure 3.5. Students' definitions of feedback (intermediate questionnaire. (Total number of students: 11)

After the question about the definition of feedback, students were also asked to define, recognize and invent examples of positive and negative feedbacks. In the first part of the activity, four brief descriptions of feedback loops were given them (about thermoregulation mechanism, usury loop, flush feedback, propagation of nervous impulses) and they had to recognize if the descriptions corresponded to negative or positive feedback loops, explaining also why. In the graph of Figure 3.6 there is a representation of the cases of success and failure in the recognition of loops: on average, 8 students (almost two thirds of students) were able to provide correct answers.

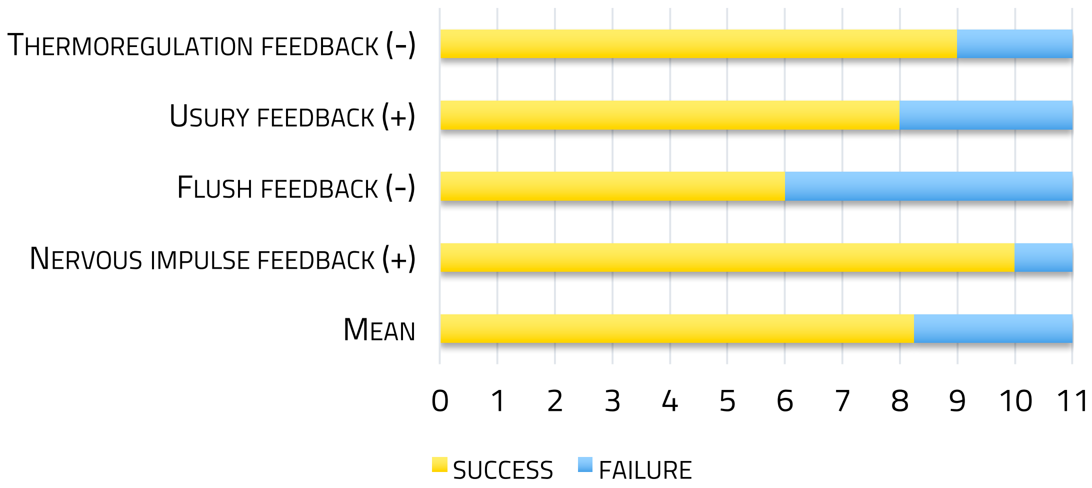


Figure 3.6. Students' recognition of positive and negative feedback loops (intermediate questionnaire).
(Total number of students: 11)

After the recognition step, students were asked to invent two examples of feedback loops, one positive and one negative. As shown in Figure 3.7, for the negative feedback, 10 students out of 11 were able to write and schematise feedback loops different from the four examples given before, while for the positive feedback the successful cases were 9 out of 11. We observe that students tend to reproduce examples of feedback loops already explained during the lessons about complexity. However, we do not consider this as a limit of the questionnaire or, more in general, of our teaching, because, at this phase of the research, our goal was to monitor the development of scientific knowledge about some important concepts: the creativity in imaging completely new loops was the goal of the last part of the module.

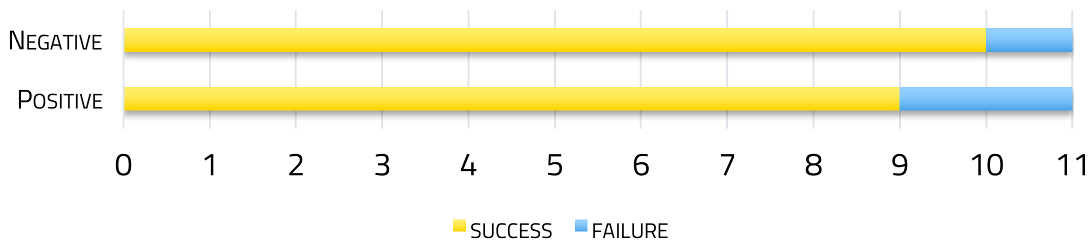


Figure 3.7. Students' description and representation of positive and negative feedback loops (intermediate questionnaire).
(Total number of students: 11)

With respect to the concept of prediction about climate change, students were asked to answer this question: *'What does it mean to make predictions when it comes to climate change? What did you learn about this aspect from the activities that have been carried out so far?'*.

Students' answers sound rather different with respect to the answers they gave into the initial questionnaire.

Four clusters emerged from the analysis of students' answers which represent four characteristics of prediction stressed by the students. Their occurrence is represented in the graph of Figure 3.8. In this case (as in the analysis about prediction of the initial questionnaire) the clusters are not mutually exclusive because students' answers, as it will be shown, are rich and nuanced.

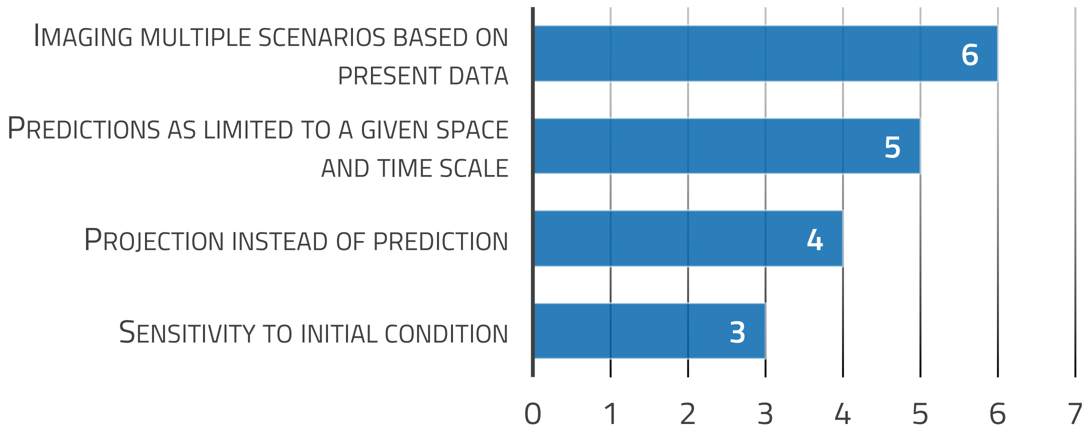


Figure 3.8. Students' ideas on the concept of prediction in climate change (intermediate questionnaire).
(Total number of students: 11)

The first important result is that students' ideas on the concept of prediction started to be problematized and the span of words and concepts related to prediction increased significantly. They started to recognize climate as a complex system, that means they started to introduce the idea of *projection*, to move from the idea of a univocal prediction to a *range of possibilities* as much wide as there are numerous and various *scenarios*, etc. This can be considered a success of the pilot study because it seems to support the ideas that the concepts of complexity science can be indeed the basis upon which future-scaffolding skills are fostered.

In the followings, students' sentences are reported as examples of the nuances/features that appeared the most evident aspects emerging from students' discourses.
The first feature, identified by 6 students, is the capability to talk about prediction in terms of possible and multiple scenarios based on present data:

'[Making predictions means] trying to know, imaging some scenarios about future climate, but I have learnt that this is very difficult to know.' (S9)

Another crucial characteristic identified by 5 students regards the limits of prediction to a given space and time scale:

'About climate change one can make predictions within few days because the complexity of the system makes impossible to know what will happen in a month.' (S12)

The difference between the terms 'prediction' and 'projection' is stressed by 4 students in the following way:

'[Instead of 'prediction'], a more precise term would be 'projection' because, since the system is very complex, we cannot take into account all the variables and so we can just make hypothesis about what could happen.' (S2)

At last, 3 students identified the link between the uncertainty of predictions and the sensitivity to initial conditions as a typical characteristic of complex systems:

'It is impossible to make predictions about complex problems because little mistakes cause enormous differences in consequences: instead, we talk of projections, which are hypotheses of scenarios.' (S7)

Figure 3.9. Students' definitions of feedback (intermediate questionnaire). (Total number of students: 11)

A detailed representation of the characteristics identified by each student is provided in Figure 3.9.

The features we have found in students' answers show the increasing of *foresight* attitude in students' way of thinking about future.

3.2.3 Discussion of the results

An overall view of the achieved results shows that we are able to answer positively to the first research question: *Have the students developed scientific knowledge about complex systems science?*

Most students reached the level of knowledge that we expected (hoped). In particular, most of them seemed to be able to: a) focus their attention on crucial aspects of the concepts we introduced as typical of complex systems science; b) manage the meaning of feedback and the distinction between positive and negative feedbacks; c) use the concepts of science of complex systems to re-think about the meaning of prediction and to problematize it.

3.3 Scientific skills: data analysis and results

To answer our second research question (*Have the students developed scientific skills?*), the group activity on biofuel and the second part of Irene activity were considered (see Annexes A8-A11 and A15).

As explained in chapter 2, the activities were designed to encourage the students to recognize feedback loops in complex phenomena and, hence, to apply the three-pronged scientific knowledge as a tool to *reflect critically* on a text or on a situation. Within the framework provided in Chapter 1 and adopted from PISA (PISA, 2015) the scientific skill of which we intend to monitor the development is the skill of explain phenomena scientifically, managing the scientific knowledge that consists of content, procedural and epistemic knowledge.

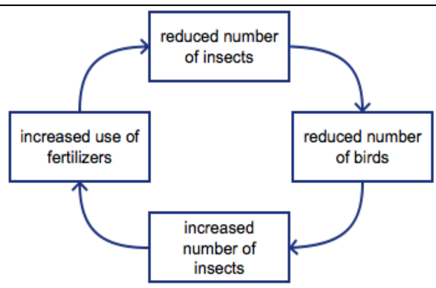
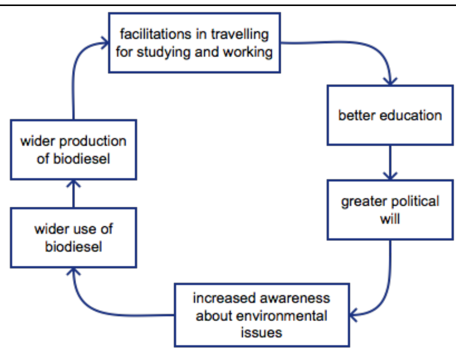
3.3.1 The biofuel activity

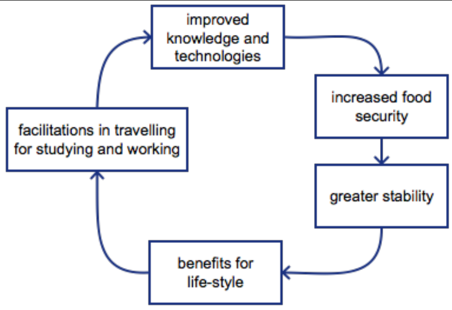
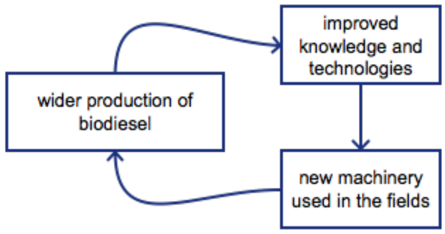
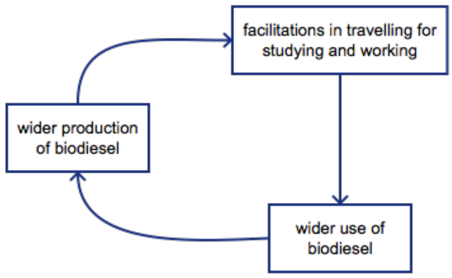
In the biofuel activity, the students, divided into three groups, were given two examples of feedback loops among those reported in Annex A10, different for each group, and were asked to describe and to place them in the logic map of the biofuel. Moreover, they were asked to find further possible feedbacks in the biofuel problem.

The analysis of students' outputs (written answers, description of feedbacks) and the audio-recordings of the team-workings and of the collective discussions showed that the students did not encounter particular difficulties in this activity. Still more interesting, they found the activity very stimulating and put their creativity into play: the feedback loops they found are very nice also for the many dimensions they refer to, since environmental, social-political and technological dimensions can be traced.

In the followings, to give back how students reacted to this activity, we report, in Table 3.4, excerpts from the audio-recording of their group works, where the students describe "their" own feedback loops. To facilitate reading, a scheme of the feedback loop associated to each conversational sentence is reported.

Table 3.4. Summing up of students' answers about loops created starting from the "Biodiesel story".

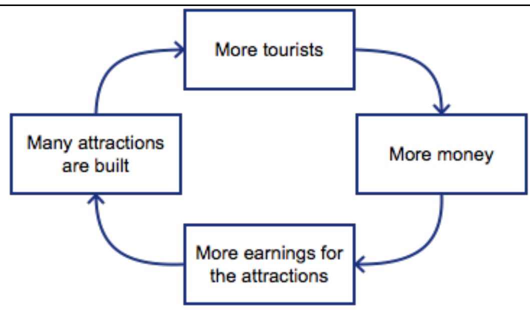
Dimension	Students' description	Loop scheme
Environmental	*'The increased use of fertilizers reduces the number of insects and, so, the reduction of insects reduces the birds because they have no more things to eat and, with the reduction of predators, the number of insects, as well as the use of fertilizers, grow.'* (G3 = S6, S8, S10)	
Social-political	*'Starting with the production of biodiesel and connecting to the facilitations in travelling for studying and working, I have seen that there is a better education that leads to a greater political will, then to better information and awareness about the environmental issues and, then, to a wider use of biodiesel which brings to a bigger production of biodiesel.'* (G2 = S1, S3, S4, S11)	

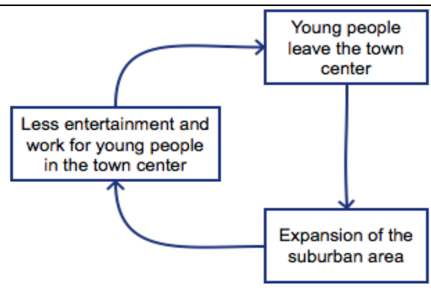
	"We have found a feedback linking the facilitations in travelling for studying and working to the improvement in knowledge and technologies, because, if one can move, maybe one can know more things and learn more technologies, so [this leads] to an improvement in food security that produces greater stability, then it returns back to benefits in life-style so that one can move, for studying." (G1 = S2, S5, S9)	
Technological	*"I have started with the improvement in technical knowledge and with the technological evolution in this area, [and I have seen] that [this] leads to [have] new machinery it the fields that increases the production of biodiesel."* (G2 = S1, S3, S4, S11)	
	"Always about the facilitation for the transports for studying and working, after an increase in transports, we connected this to the use of biodiesel, so a wider use of biodiesel leads to a wider production of biodiesel and so we return back to the transfers." [this holds in case, if I move, I use biodiesel as a fuel] "Yes, because we have thought that if one moves for studying about this issue, is more aware in using biodiesel." (G1 = S2, S5, S9)	

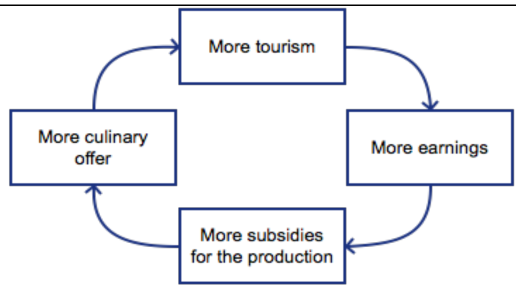
3.3.2 The town of Irene activity

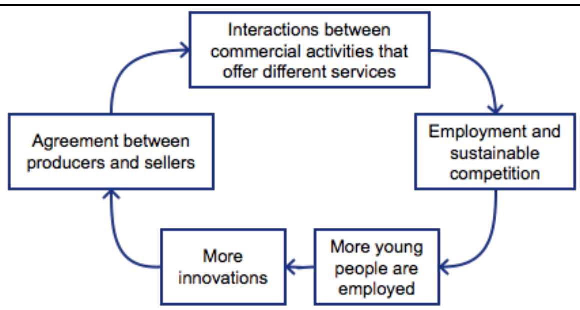
Similar results have been found with regard to Irene activity (see Annex A15), in which students, divided into four groups, were asked to find feedback loops that had led to two given scenarios, drawing a scheme. Each group found a loop for each scenario, so we analysed eight answers: we report in Table 3.5 four representative schemes, two for the Scenario 3 and two for the Scenario 4.

Table 3.5. Students' most representative feedback loops found to justify the realization of two given scenarios.

<table>
<tr><th>Scenario</th><th>Students' loop scheme</th></tr>
<tr><td rowspan="2">Scenario 3</td><td>


(G1 = S2, S5, S9)</td></tr>
<tr><td>


(G2 = S1, S3, S4, S11)</td></tr>
<tr><td rowspan="2">Scenario 4</td><td>


(G1 = S2, S5, S9)</td></tr>
<tr><td>


(G2 = S1, S3, S4, S11)</td></tr>
</table>

It is interesting to notice that all the five feedback loops found in biodiesel activity and all the eight ones found in Irene activity are positive. Students' ability to identify negative feedbacks is thus good, but, asked to look for circular causalities along a text, students seem to have difficulties in inventing negative loops.

A possible explanation is that such a difficulty can be interpreted as an index of the difficulty in *recognizing the dynamism of an equilibrium situation*. It is easier to find amplifying situations because one is aware in identifying cause-effect links where something is progressively moved from the equilibrium position. By the other side, it is more difficult to recognize the existence of an 'equilibrium-process', at the opposite of the common conception for which equilibrium and static conditions are strictly synonymous.

3.3.3 Discussion of the results

The previous analysis allows us to answer positively also our second research question: *Have the students developed scientific skills?*

Most of the students were able to move from the knowledge of the disciplinary concepts toward their application in the analysis of a multidimensional problem.

The search for feedback loops has been experienced as a creative experience that students deeply enjoyed, because it was at their reach and also productive to analyse critically and personally a text, going beyond it.

The circular causality learnt from the complex systems science became a lens through which multidimensional phenomena could be analysed.

Nevertheless, the analysis seemed to show a sort of difficulty to find negative feedback loops.

3.4 Transversal skills: data analysis and results

In this section, we present the analysis of the development of students' transversal skills. To address our research questions concerning this aspect (the third question and the last one), we analysed data collected during one individual and two group activities:

respectively, the synthesis of the IPCC report (see Annex A6), the biodiesel activity (see Annex A8) and, finally, Irene activity (see Annex A7).
The main research problem here is the elaboration of an analytical tool that can allow us to check if learning outcomes have been achieved. Because of this, two layers of results will be presented: i) the overall synthetic picture of students' ideas, knowledge and strategies, that emerged from a *bottom-up* analysis; ii) the analytic markers we pointed out and used for the analysis. The second type of result is particularly relevant within the *I SEE* project: it drafts an operational tool that can be shared within a larger community with the scope of evaluating modules' implementations and comparing experimentations in different contexts, where other variables have to be taken into account (e.g. cultural diversity of the members of the groups).

3.4.1 The activity on the synthesis of the IPCC report

As already pointed out, in this activity students were asked to read a synthesis of the fifth IPCC report (IPCC, 2014), to individuate the problems written in the text and to draw a conceptual map or, as suggested in the introduction of the activity, 'another way of organization'. The assignment we gave to the students was to recognize the problems and organize them in a map by highlighting their causal relationship.
Students had to write on their own their maps or texts at home and, during the fifth lesson of the course, five of them presented the results of their homework to the classmates, commenting the strategy they had used in building their personal tool to approach our request of schematization. The assumption behind this activity was that the students, through their direct involvement (*learning by doing*) and through the follow-up collective discussion, could develop skills like: i) analyse a complex text and organize information, ii) identify dimensions in a problem, iii) figure out different stakeholders and represent relationships between them.

The first step in the analysis of students' outputs (homework and classroom discussions) has been the identification of a criterion that could account for the most evident differences in students' approaches to the task (reading and searching for information strategy, organization of information retrieved strategy). The analytic process resulted in the choices of two macro-markers:

- presence/absence of links between causes and effects (blue and green in the graph);
- list/map as a tool to organize the problems (orange and violet in the graph).

The graph in Figure 3.10 reports the overall picture of students' approaches, according to this criterion.

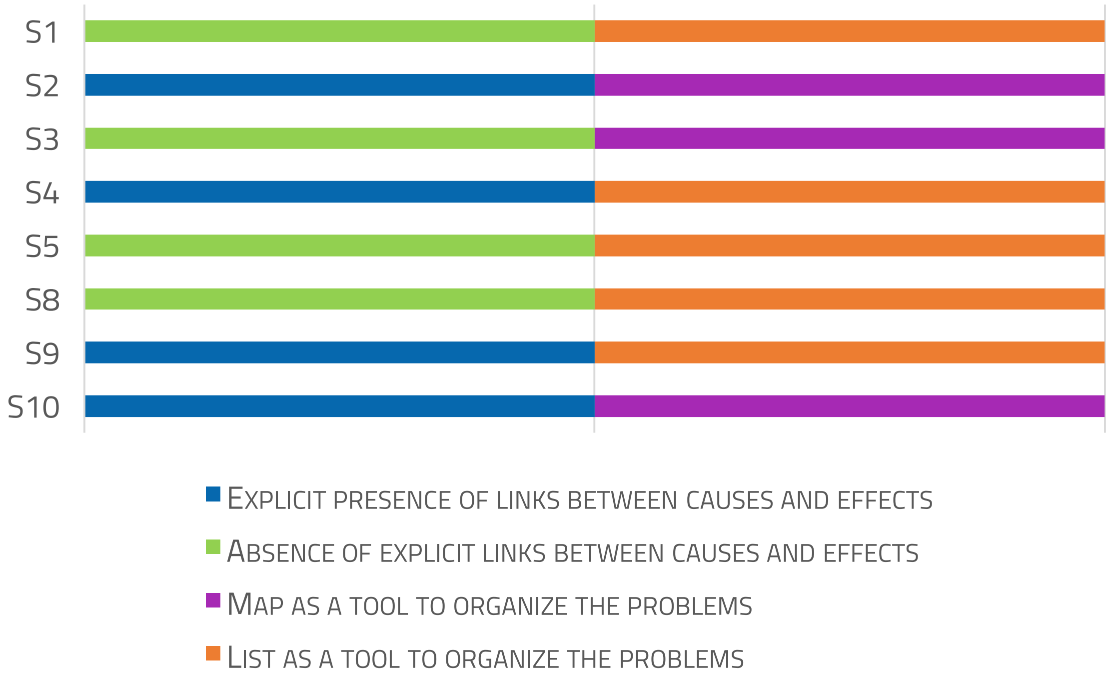


Figure 3.10. Picture of students' approaches to the request of schematization of the scientific text in the IPCC report activity.

The graph shows that only four students (out of ten) explicitly pointed out the causal links between the problems described in the text (blue marker); only three students used a map as a tool to analyse the text (orange marker). In total, only two students, out of ten, built what we expected: a 'causal map' (combination of blue and orange).

The aims of the second step in the analysis were to unpack this evidence, identifying *bottom-up* markers in the texts, and to understand how the students interpreted the task. In particular, four cases have been chosen as representative of different students' approaches: S8, S3, S4, S2.

S8 and S2 can be considered the 'extreme cases', respectively representative of the combinations green-orange (the attitude farthest from our expectations) and blue-violet (the attitude closest to our expectations). S3 and S4 are the 'mixed cases'.

Each case is discussed in the following by reporting a part of the scheme built by the student and excerpts of transcripts where the student comments her/his scheme and her/his work.

The analysis will allow to exemplify what we mean by 'list' and 'map', as well as 'explicit presence/absence of causal links'.

First case: S8

The structure of the scheme built by S8 is reported in Figure 3.11.

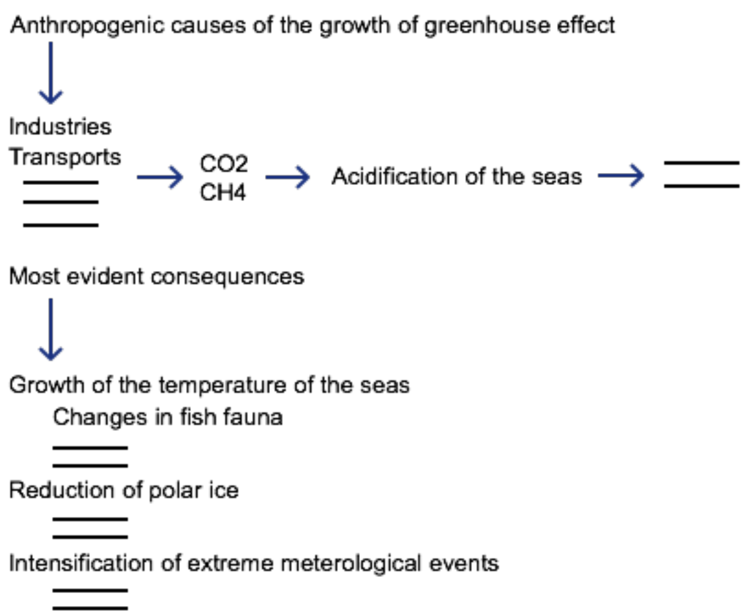


Figure 3.11. Output of S8 for the IPCC report activity.

S8 comments the scheme as follows:

> *'I didn't do a map: I have written a text, following the text point by point. First of all, I focused, as the text does, on the global warming due to man and then I have written the **causes** that brings to the greenhouse effect and to the acidifications of the seas. Then, I have put the most evident consequences and the other causes related to these. [...] I focused on a strictly scientific dimension because the other ones are **consequences**, it is about **how the man reacts** to these facts, so I have just draw a little arrow...' (S8)*

The excerpt shows clearly how the student worked on the text: she/he went through it 'chronologically', following a *sequential approach to reading and search for information*. To organize the pieces of information, she/he consistently *listed* them in *the order they appeared*. The discursive markers that characterize this approach (and that we marked as underscored) are words and adverbs typical of a chronological and narrative approach adverbs (*first of all .., then*).

The student uses the words ***causes, consequences*** and ***reactions*** but she/he does not really used them as analytic tools to work on the text, in the sense of pointing out the specific problems and their causal relations: she/he uses these words as an *a-priori and external criterion* to distinguish between scientific facts (*causes* to global warming) and social *consequences* of global warming. *The arrows do not have any specific or clear meaning* and they, in particular, do not express any causal relation.

Second case: S2

S2 built a very complex map, characterized by a rich system of arrows that details the links between causes and effects she/he recognised in the text (see Figure 3.12)

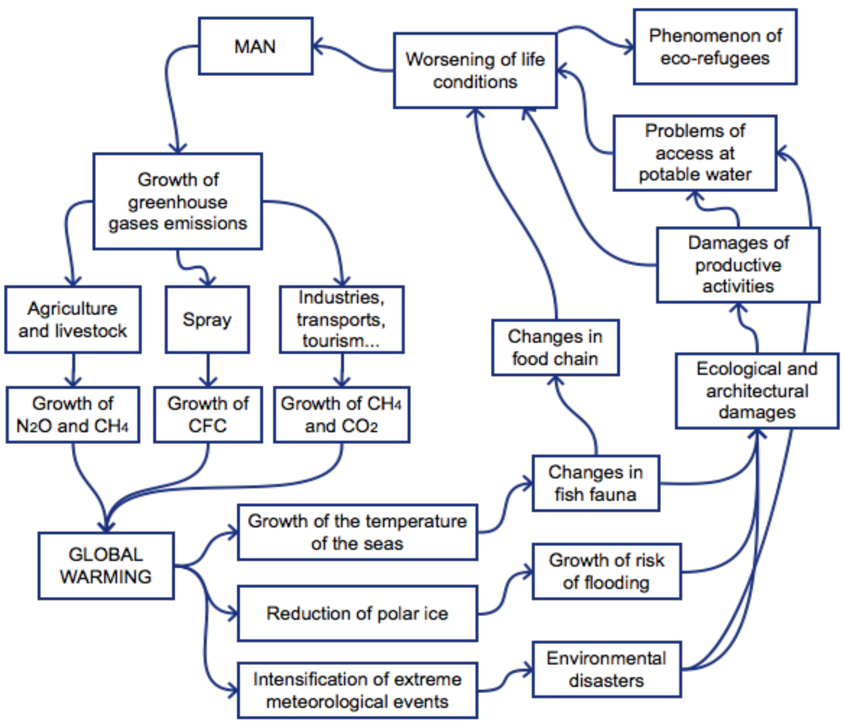


Figure 3.12. Output of S2 for the IPCC report activity.

S2 describes her/his approach as follows:

> *"I started from man, I can say, and from the causes that he produces; they cause the global warming which in turn has consequences that reflect on man himself. […] For example, the increasing temperature of the seas causes a change in the fish fauna and so causes a variation in the food chain, for instance in coastal areas, then this causes a worsening of human conditions and… all has an effect on everything!" (S2)*

The *map* of S2 is completely different from the *list* of S8. It is not the order information appeared in the text that guided the student. The selection of both the problems and the links is guided by the search for causal relations among them. From the comment emerges that S2 was very aware that she/he searched a starting point that was *not* the first issue presented in the text, but a problem that could represent a *knot* in an overall picture. The chosen knot was the 'man', around which the text was analysed *globally* in terms of *problems and their reciprocal links*. In this sense, the student chose a *global approach to select and organize the information*. The discursive markers that characterize this approach are words and utterances typical of a personal *choice* oriented to focus the *knots* (*I started from man*) of a *global* picture (*in turn, has an effect on everything*).
Unlike S8, the causal links are represented, in the sense that the arrows can be read in terms of relations between causes and effects. Moreover, this student, in her/his search for knots, shows that she/he was stressing the circularity of the overall causal map.

Third case: S3

S3 drew two different maps: one for the causes of global warming and one for the effects (see Figure 3.13).
He/she comments as follows:

> *"I have separated* **between causes and effects***; all the causes are anthropogenic and I have divided in 'man that uses the nature', for example with agriculture and livestock, 'man's action as real products', for example spray, and then 'man's action as use of other inventions', for example industry, transport, energy… after this I have seen what they cause, what all this brings about. […] I have divided the map of causes and that of effects because, in my opinion, all brings about… in sense that, slowly, one way or another, the growth of CO2 causes everything!" (S3)*

Like S2, the student made a choice (*I have separated between)* to find a way to organize the information of the text and adopted a *global approach* (*all brings about, everything*).

Her/his analysis resulted in a map that can be easily read and that stresses effectively what she/he found more interesting; the anthropogenic origin of global warming and the feedback effects on humans (*circularity* in the overall phenomenon).

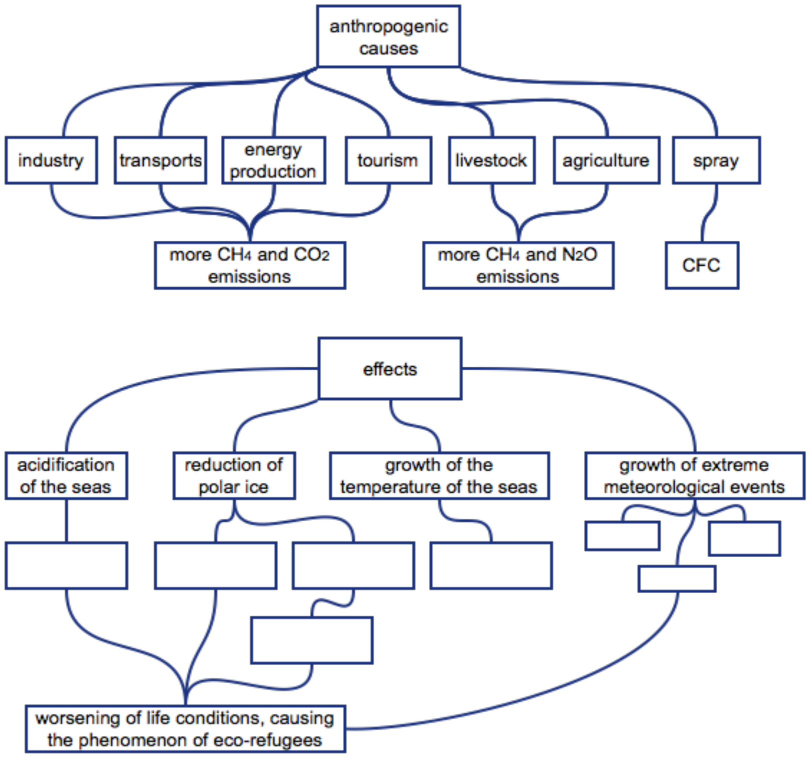


Figure 3.13. Output of S3 for the IPCC report activity.

The map is rather refined since he introduces *different levels and dimensions*: she/he searched for a finer distinction both in the causes *(I have divided in 'man that uses the nature' [...] 'man's action as real products', [...] 'man's action as use of other inventions')* and in the effects. In particular, she/he was very careful to represent the scientific effects on the same level, then social on the same level and different than the previous one. In this case, the recognition of the *different dimensions in the problem* (social and environmental) and their *clusterization* (their separation in levels) were used as criteria to retrieve information in the text and organize them.

However, like the first students we analysed (S8), the words **causes** and **effects** are used as an *external macro-criterion* to read the text and the arrows do not have, in general, the meaning of a cause-effect relations. They are, instead, a graphical way to organize the information in terms of dimensions and levels.

Fourth case: S4

The output of S4 is reported in Figure 3.14.

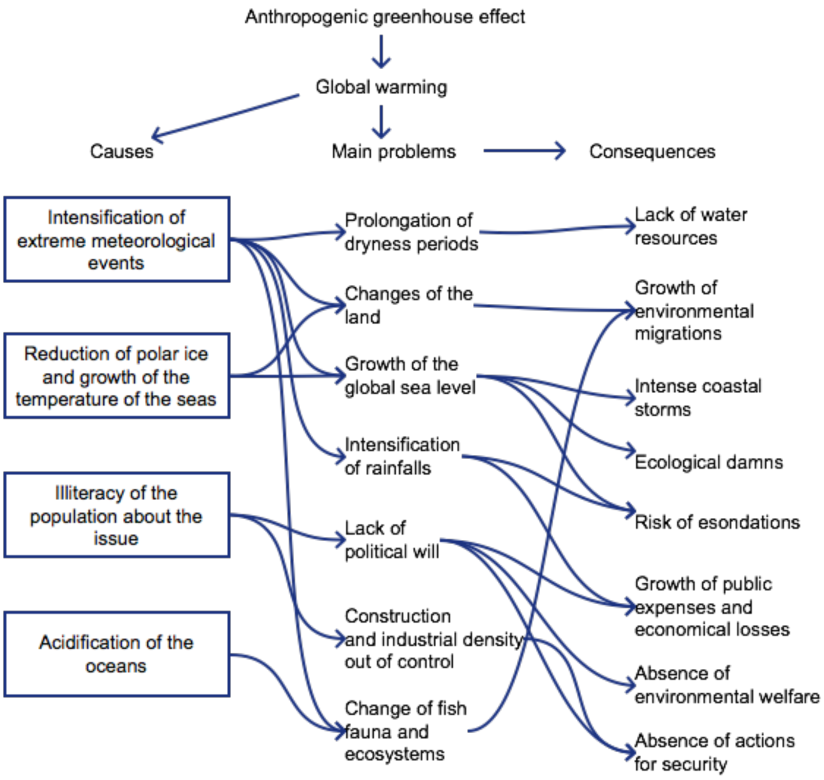


Figure 3.14. Output of S4 for the IPCC report activity.

The student's comments are:

> *"I have divided my scheme in three parts, putting in the middle the main problems and at one side four **general causes** that generate most of these problems, whereas at the left side I have written the problems affiliated of the main ones; then I have tried to highlight how, starting from the main problem, more than one can originate and how a cause can actually influence very different aspects in the long term." (S4)*

The approach of this student is also very interesting. She/he started from a list of problems and, then, relates them with the causes and the effects through a rich and complex system of arrows. The student adopted a *global approach* to the search for information, created *links between* **causes** and **effects**, organizing them into a map according to a particular criterion: she/he separated clearly the causes (on the environmental side) and the consequences (bad effects on mankind), listing causes, problems and consequences.

A first result of the analysis of these preliminary outputs consists of the consideration that the logical map is not a spontaneous organizational tool for all the students, since someone prefers other kinds of synthesis.
Starting from this evidence, during the collective discussion, the different approaches were compared and analysed. In particular, both the concept of map and of causal relations were stressed and shared with the students.

3.4.2 The biofuel activity

As already described, during this activity students were asked to read a scientific text on the biodiesel issue and to apply what they were supposed to have learnt in the previous activity to draw the cause-effect map that the text displays. The 10 students present at this lesson were divided into three groups, so we have three maps for analysing the different approaches they had toward this request.
In the following, we report a synthesis of the three schemas (Figures from 3.15 to 3.17), in which the main characteristics are highlighted. The markers elaborated before are re-tested and used to compare the students' strategies before and after the activity.

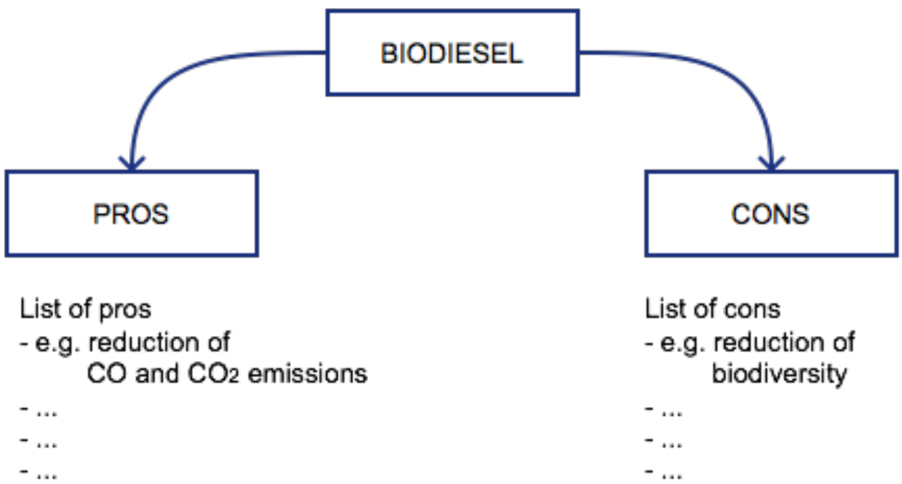


Figure 3.15. Output of G1 (S2, S5, S9) for the biodiesel activity.

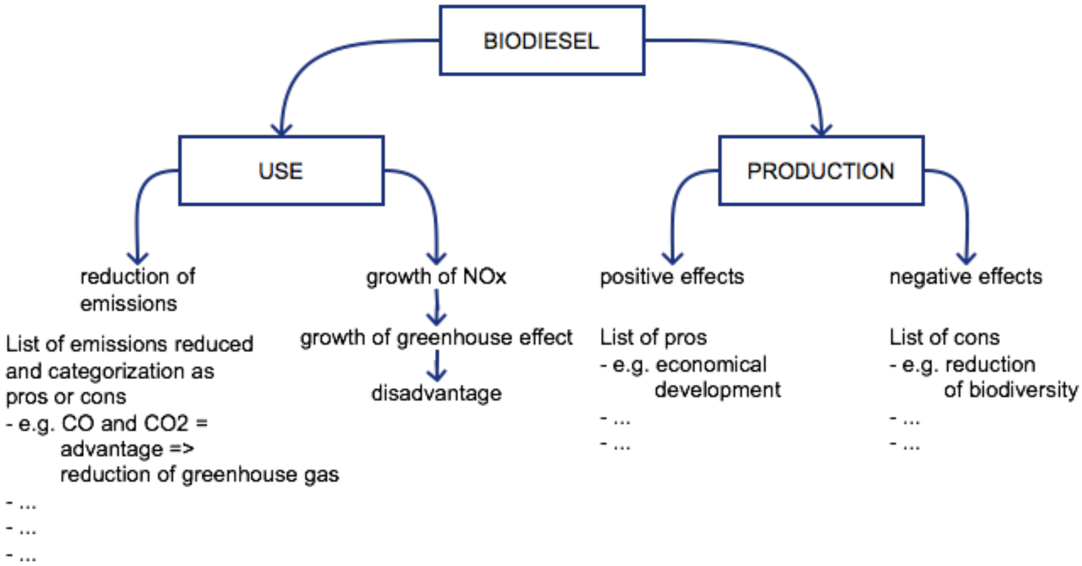


Figure 3.16. Output of G2 (S1, S3, S4, S11) for the biodiesel activity.

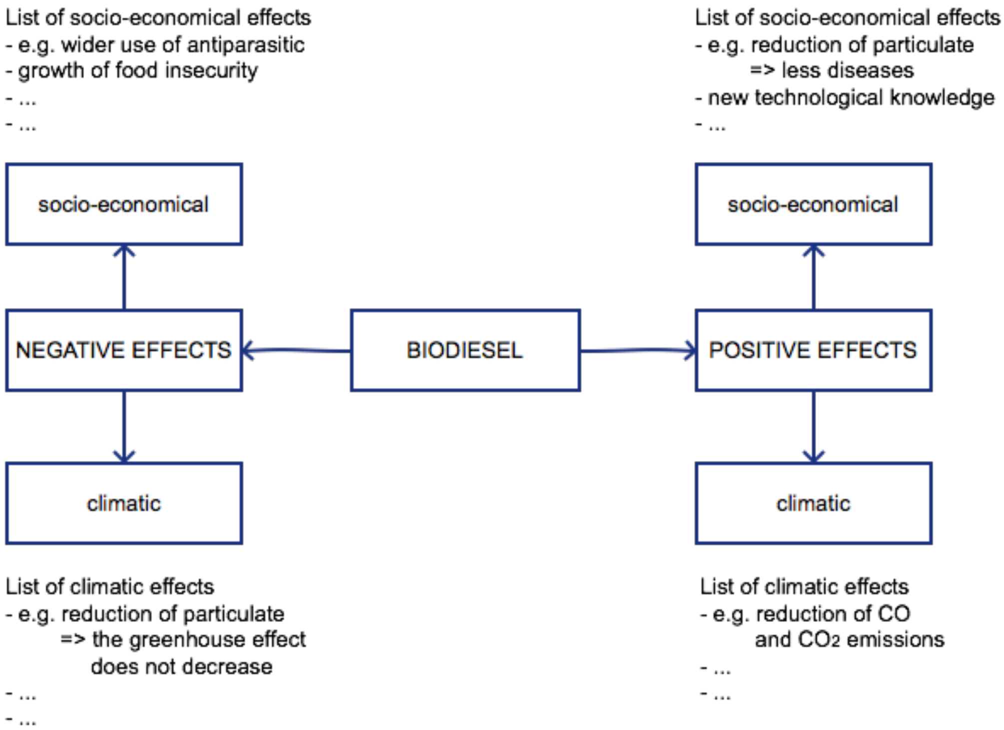


Figure 3.17. Output of G3 (S6, S8, S10) for the biodiesel activity.

In the map of the first group (Figure 3.15), we observe the *choice* and the use of a *criterion* to find and organize information (*global approach*): the students decided to separate clearly positive and negative effects, but they used *lists* in both the cases and no links are present.

In the map of the second group (Figure 3.16), we can observe a pattern similar to the first group's map in one of the branches (production branch). The map is however a little bit more complex, according to a selection based on the criterion to distinguish between use and production of biodiesel, but the map is a mixture of lists and causal implications without a suitable causal structure.

In the third group's map (Figure 3.17), positive and negative effects are once again stressed and the map is clearly divided *in absolute positive and negative effects*. Furthermore, environmental and social aspects are clearly separated; within each category (positive socio-economical, negative socio-economical, ...), the consequences are listed without connections. Arrows are just used to create different *lists, without causal meaning***.**

To resume, two groups have explicitly organized their maps according to a macro-distinction between pros/positive effects and cons/negative effects; the other group does not provide this macro-distinction, but widely uses the same categorization in the map, associating the terms 'advantage' and 'disadvantage' to every fact found in the text.

The third group, after the macro-distinction between positive and negative effects, sketched out its analysis separating the climatic effects and the socio-economical ones; this clusterization makes running into a contradiction since, for example, the reduction of particulate is a climatic effect as well as a socio-economical one.

In general, the results of this activity reveal a weakness in the activities and in the approach: students did not develop suitable skills to construct complex maps in which the problems and the causal net are represented. The concrete activity on the IPCC synthesis was not effective for this purpose. Drawing maps and writing schemas require soft skills that one has to learn and practice explicitly also, we guess, through a theoretical presentation of a reference framework. In a previous experience where students were asked to analyse the same text extracted from IPCC by drawing a causal map, we did not observe this problem (Venturelli, 2015). The main difference between the two contexts is that there, unlike in the present case, the practice activities were introduced by an expert (Dr. Monica Russo) of *Logical Framework Approach* (EC, 2004), who stressed the role and the meaning of causal map as analytic tool from a theoretical perspective. Without any introduction of the approach, students tend to analyse a text by projecting their own

judgement about the issues and by clustering. Judgement and clusterization are instead just the last steps in *Logical framework*.
What we learnt from these results is that the ability to analyse a text in order to extract the relevant information and their causal links is difficult to be developed, since the temptation of premature judgment and clusterization is very strong. After the analysis of these data and after having pointed out this result, a supplementary activity about LFA, already introduced in Chapter 2, has been designed and is reported in Annex A18. In this way, for future experiences, students will be guided more explicitly to develop these transversal skills: *learning by doing* did not work.

3.4.3 The town of Irene activity

Through this activity, the students were involved in a *stakeholder analysis* and guided to approach the concepts of *probable, possible and desirable futures* that were just introduced briefly before the activity.
The stakeholder analysis is a sort of variation of the previous activity where students are asked to: i) point out all the possible stakeholders (and their interests) that can be directly and indirectly involved or interested in the specific urban plan decision; ii) draw a map with possible causal links among them. This type of analysis was explicitly designed to encourage students to model the initial state of the system and to recognize its richness beyond the apparent simplicity.
The distinction between probable, possible and desirable futures was instead new and was supposed to be crucial to move them toward anticipation and foresight attitudes.
The results are presented following the order of the various parts of the activity.

Stakeholder analysis

Thirteen students were present during the Irene lesson and were divided in four groups.
Two groups found the stakeholder analysis point particularly difficult; group G1 completely skipped this part of the activity and went directly at the second part of the activity in which the future scenarios had to be analysed. When asked why they had skipped the present analysis, the students answered:

'We did not succeed in considering the present scenario without taking into account the possible evolutions.' (G1 = S2, S5, S9)

A similar problem, even if not explicitly recognized by students, was encountered by group G3: the students tried to carry out a present analysis for Degli Esposti's shop and Ettore's supermarket but they reasoned about the discount only in terms of effects of the granted expansion, as can be seen in the scheme in Figure 3.18.

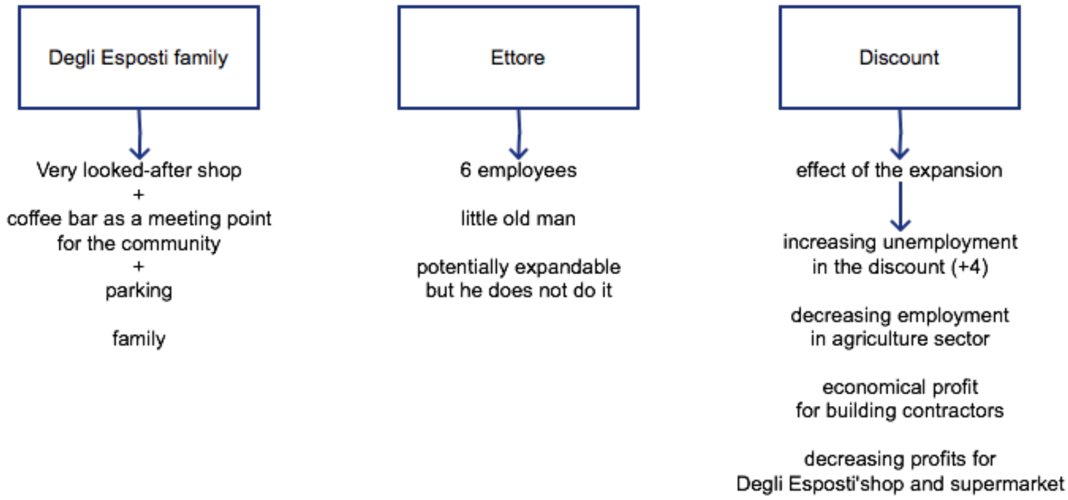


Figure 3.18. Output of G3 (S6, S8, S10) for the stakeholder analysis of Irene activity.

Also in these drawings, the use of *lists* can be recognized as well as *the lack of causal connections*. Moreover, we observed again the *chronological approach* that we had found in the IPCC activity too. Since the text was not 'causally organized', the students had no suggestions to connect them in a causal way and the problems with the maps became more and more evident.

The other two groups were able to sketch out a stakeholder analysis (see Figures 3.19 and 3.20). However, they did not develop a complete analysis, because they took into account just the three stakeholders explicitly mentioned in text as the 'main characters' of the story of Irene.

In both the cases the maps had not in general a causal structure, but just represented a generic competition, that suggested an approach focused just on personal *'pros and cons'* (what is good for one of them, what they lose if …). Consistently, the words used to describe the causes were merely concerning the stakeholders' personal advantages or disadvantages.

This result confirms some weaknesses in the activities we planned and the need to find other ways to develop the transversal skills (for example through the introduction of *Logical Framework*) as a way to analyse the present.

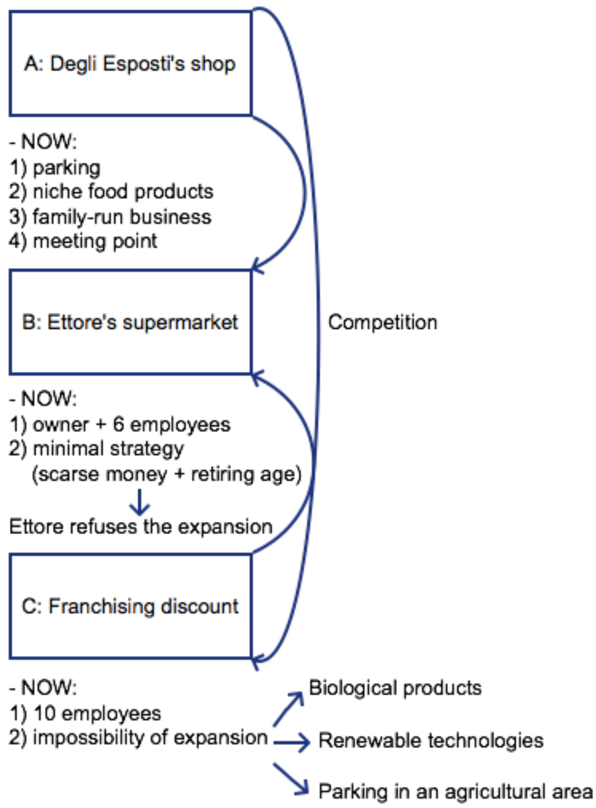


Figure 3.19. Output of G2 (S1, S3, S4, S11) for the stakeholder analysis of Irene activity.

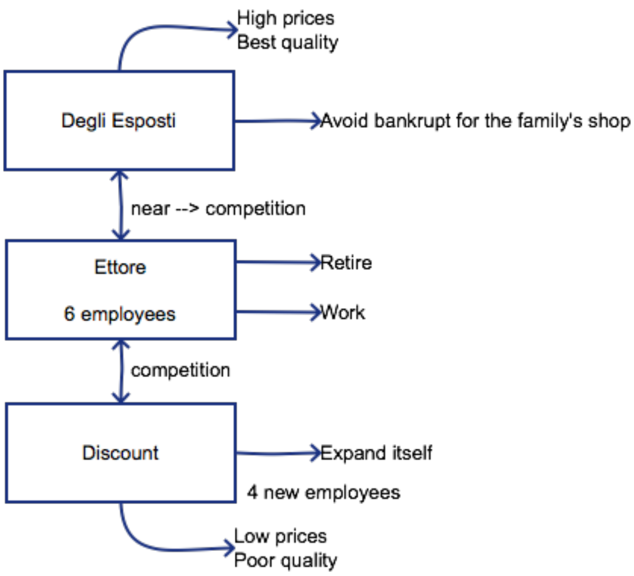


Figure 3.20. Output of G4 (S7, S13, S14) for the stakeholder analysis of Irene activity.

Possible futures

The second step in the activity of the town of Irene consists of the identification and description of two possible scenarios at 2025, one for the granted expansion and another one for the denied expansion of the discount.

What we observed in terms of analysis of the evolution of the situation is interesting: the maps became more complex and students' analysis of future scenarios is quite rich (see Figures from 3.21 to 3.24). In all the cases, a way of looking in term of *possibility* was considered by the students. Introducing time apparently enlarged the perspective.
The maps mirror some requests we made to the students and apply concepts that were introduced during the activities:

1. they are usually logical maps organized according to the *stakeholders*;
2. they move from the present to the future, that is they built *probable futures*, following a *forecasting approach*;
3. some of them consider explicitly the various *dimensions* of the problem and *cluster* the evolution;
4. they suspend the judgment and approach the task with an *analytic 'neutral' approach*.

The main weaknesses of the maps are that they represent possible evolutions of individual situations as consequences of linear 'chains of if-then' and they do not result in *possible scenarios*, as they can emerge through interactions between phenomena and from a new equilibrium between them. The result is a *fan-map* where *interactions among stakeholders and phenomena in the future* are not considered. The transition from probable futures to possible scenarios appeared out of the attention of students.

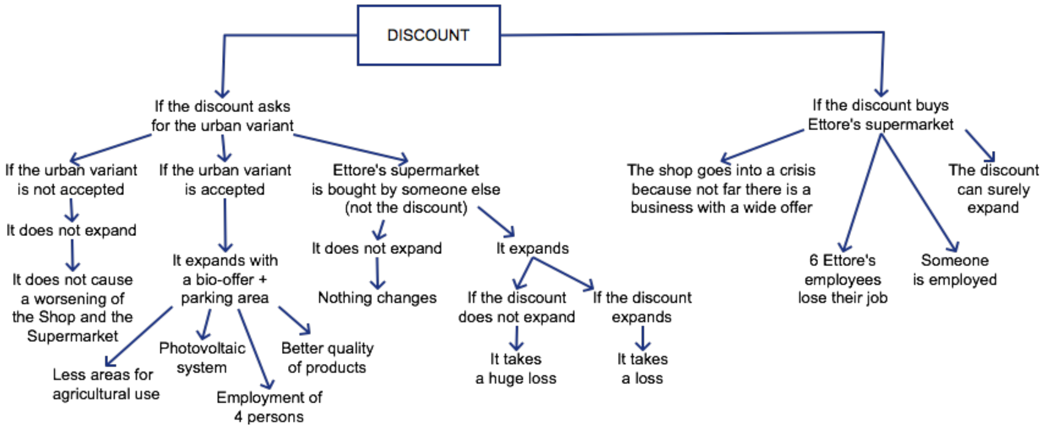


Figure 3.21. Output of G1 (S2, S5, S9) for the yes-no scenarios activity for the town of Irene.

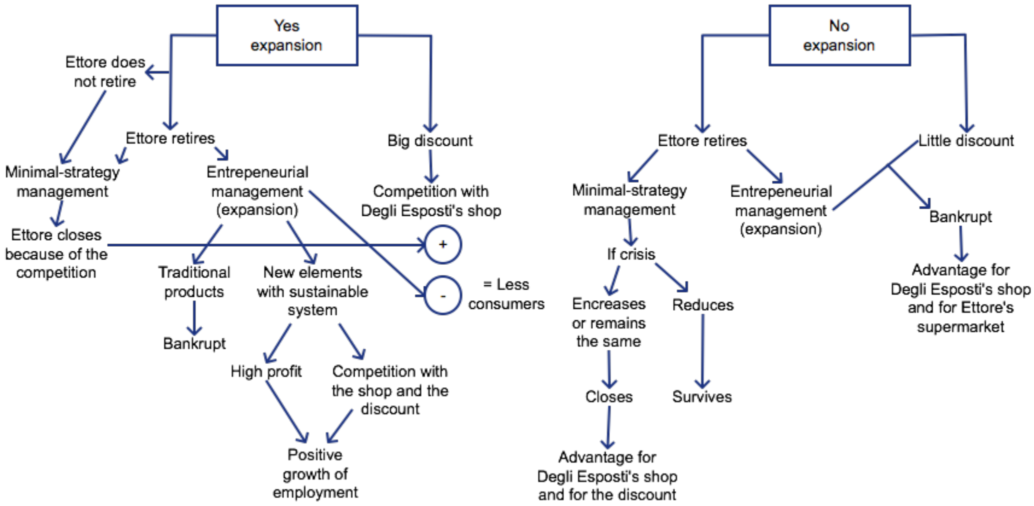


Figure 3.22. Output of G2 (S1, S3, S4, S11) for the yes-no scenarios activity for the town of Irene.

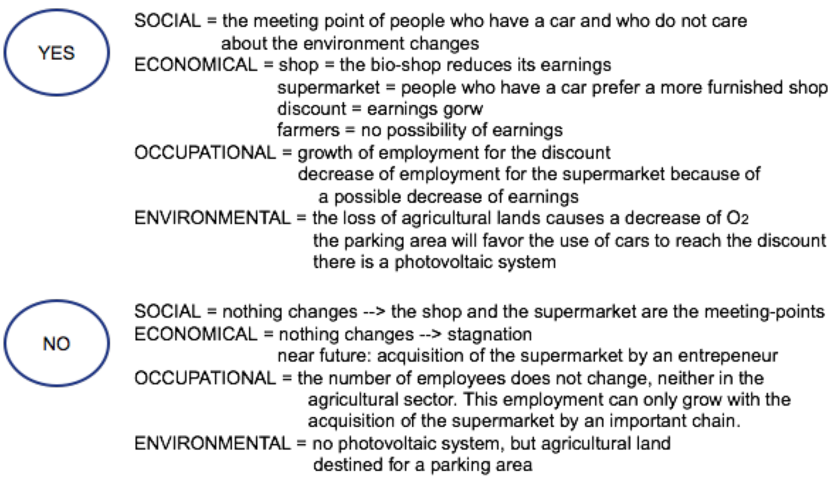


Figure 3.23. Output of G3 (S6, S8, S10) for the yes-no scenarios activity for the town of Irene.

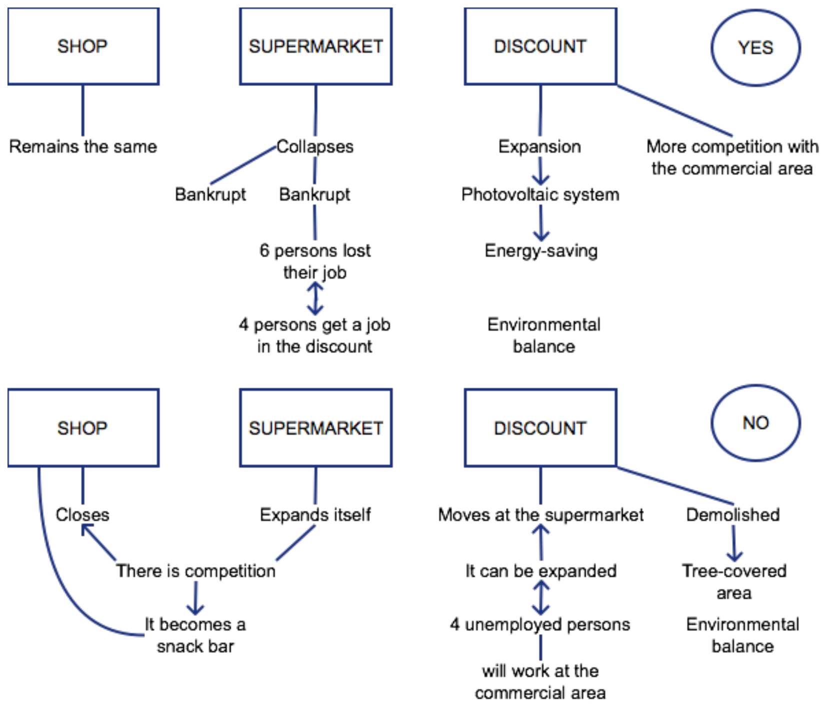


Figure 3.24. Output of G4 (S7, S13, S14) for the yes-no scenarios activity for the town of Irene.

Desirable futures

The last activity was about the imagination of a desirable scenario for the town of Irene; the scenario found by each group had to be accompanied with a catchphrase that had to characterize Irene as the ideal town where to live or to visit. After this, each group of students had also to plan an action that they might undertake (as singles or as a group) in the present, in order to favour the realization of the desired scenario.

The request to elaborate a global future scenario according to desires and to 'come back' to the present thinking to plan an action that can lead to such a scenario is composed by two different phases, that can and should be carried out independently. The activity is inspired by the method of *backcasting,* after that students were encouraged to imagine their scenario without constraints imposed by us.

This activity was a success for many reasons:

1. It stimulated, in some cases, interesting creative processes that led them to invent also inexistent professions:

> *'We are competition regulators for Irene tourism office. We listen to the needs of manufacturing activities, propose compromises when conflicts occur, provide legal and fiscal advice, offer promotional*

campaigns, propose prizes for the most innovative start-ups that work with renewable energy.' (G2 = S1, S3, S4, S11)

2. The students felt personally engaged and found this 'apparently' strange activity perfectly consistent with the previous activities on climate change:

   'We started from the analysis of the present situation and imagined possible scenarios; at the end, we analysed the different choices that could have been brought to the best scenario, the desirable one… Then, trying to link this with what we have done before [during the course], maybe this choice has been guided from the fact that, also with regard to climate change, it is the weight of single choices that can cause wider mechanisms that influence, in a complex system, a lot of other variables.' (S4)

However, three interesting aspects of students' imagination toward desirable futures can be noticed.

1. *The strong link to present.* Even though the students were invited to express their desires, the picture of the city of Irene was very similar to its description in the text and the reference to contingent and present events is very strong. For example, one group wrote:

   'IRENE: ideal future, real town. The franchising gets the permission and starts a new extension in the sign of sustainability, both from an energetic point of view or from the products point of view. […] Ettore closes and gets retired; his activity is taken over by an entrepreneur who transforms it in a multi-purpose area for the entertainment, expanding it thanks to the permission.' (G2 = S1, S3, S4, S11)

2. *The reference to values, supposed to be universal.* All the groups, when they have to describe desirable futures, refer to values like sustainability, eco-friendly towns, security, cleanliness, cohesive community, as their assumption was universal, obvious and uncontroversial. For example, one group wrote:

   'More we are, better we live. [There are] many meeting points because of the presence of a park with fountains and multi-purpose centres. The cohesive community causes a higher security and more care of the cleanliness of the town. It is a sustainable place (photovoltaic systems, km0 products, bike lanes). There are services for the community, activities and meeting for the citizenship. The station favours the movement toward other centres (connections).' (G3 = S 6, S8, S10)

3. *The lack of attention on possible conflicts between interests or people.* It is

intrinsic to the notion of future scenario the description of a state of future equilibrium of the system. The equilibrium state, to be realistic, has to foresee *differences among the interests and the stakeholders*, *circular interactions* between agents in the systems. The examples already reported of students' descriptions give back, instead, a picture of, metaphorically speaking, thermodynamic equilibrium where conflicts, interactions and differences among the stakeholders and the phenomena are minimized.

All these aspects can be interpreted in several ways. On one hand, they seem to confirm students' difficulties to deal with the future. On the other hand, they mirror, in our opinion, the lack of an explicit reflection in the module on what a scenario is and on the critical concept of sustainability in making a future scenario realistic. Sustainability is, indeed, one of the main criteria that futurists use to judge the quality of scenarios (Greeuw et al., 2000; Kreibich, 2007; Wilson, 1998), together with other features like: logical consistency, openness to evaluation, terminological clarity, simplicity, definition of range, explanation of premises and boundary conditions, transparency, relevance, practical manageability, and fruitfulness (i.e. in terms of gain in knowledge, orientation, innovation, motivation etc.), differentiation, consistency, decision-making utility and challenge.
In our context, we guess, the concept of sustainability would have help to stimulate creativity and to guide students to position themselves in a different way toward the concept of scenario and the task of building possible and desirable ones.

In any case, as last positive result, I stress how the activities impacted their approach to the present, widening up possibilities, dimensions, challenges/problems but also chances.

'Today I realized how much my approach has been changed [throughout the course]. Two months ago, I would have made the decision yes/no [on the city of IRENE] in two seconds. Today we discussed two hours and I am not yet sure about the decision. I discovered that there are many things to take into account'. (S8)

3.5 Overall discussion of the results

In this chapter, an articulated data analysis has been carried out and presented. The analysis allowed us both to examine how students experienced the module and to point out original markers to analyse students' discourse and evaluate if the learning outcomes have been reached.

The analysis showed that the set A of activities drove students to reach a good level of scientific knowledge that, according to PISA framework (PISA, 2015), is articulated as a three-pronged knowledge. The compared analysis between introductory and intermediate questionnaires has allowed to see that:

- students became acquainted with basic concepts of science of complex systems and, in particular, with the concepts of system, feedback and prediction (scientific content knowledge);
- students understood important features typical of the method of the science of complex systems, such as the use of the simulation as a language with specific characteristics (scientific procedural knowledge);
- students recognized the importance of circular causality and the necessity to abandon, when studying complex systems, the determinist and reductionist paradigm and they also learnt that approaching science phenomena that involve citizenship issues (e.g. climate change) implies a change in the epistemological way of looking at the phenomena itself (scientific epistemic knowledge).

To enhance all these aspects that characterize the scientific knowledge, new activities have been designed, in order to open the fan of phenomena, models, mathematical languages, tools of study that the science of complex systems has developed. For this purpose, have been designed the activities about the Lotka-Volterra model (in its two versions, a complete one for teachers and a tutorial one for students, see Annexes A1 and A2), about the logistic map (see Annex A3) and about the self-organized world of ants (see Annex A5).

The set B of activities revealed a particular success since students became able to distinguish from linear and circular causality, within the scientific texts, recognizing the nature of the causal links, individuating possible feedback loops that can be found starting from the text and also inventing new ones. These can be considered, according to PISA framework (PISA, 2015), skills of explaining phenomena scientifically, managing the three-pronged knowledge that has provided lenses through which critically reading texts. However, the analysis of the results of the pilot study displayed multifaceted students' approaches and attitudes to texts. Among those, we stressed the tendency to organize the information in lists and/or according to pros-cons (advantages/disadvantages) a-priori judgments. The request to use causal relationships as criterion to read and analyse a text was either not clear or too far from their approach to reading and this contributed to the unsuccessful achievement of this learning outcome. This point suggested to design a supplementary activity to find new ways to make students learn to transform the causal nets present in the scientific texts into cause-effect maps and, so, to develop transversal skills (like building causal maps, analysing and understanding written texts) more effectively. The activity that has been designed (see Annex A18) consists in an introduction to the *Logical Framework Approach* presented as an 'aid to thinking' because its aim is to give structure to the analysis of a problem, of a text or of a situation, so that important questions can be asked and weakness identified.

The set C, with the Irene activity, was deeply appreciated by the students, who perfectly understood its sense at the end of a long module on climate change, where science of complex systems was introduced and discussed. They became able to apply concepts typical of the science of complex systems, particularly the concept of feedback, also in a non-scientific context, showing that they had developed scientific skills. Moreover, the activity supported the development of future-scaffolding skills because:

- students became acquainted with basic concepts and methods coming from future studies, like forecasting and backcasting, and managed these concepts to reason about an urban problem;
- students learnt that the concept of scenario requires a language of 'possibilities';
- students became able to imagine possible future careers to aspire, putting their creativity into play;

- students changed their perceptions of the present and the future, learning that approaching climate change implies a change in ways we live in everyday life and we, collectively, make decisions.

However, a bunch of criticalities have been pointed out: student's difficulties in inventing negative feedback loops; the lack of any attention to analyse possible causal relations and mutual influences between stakeholders and phenomena in the fan map they build in the activity of forecasting; the uniformity of the values and in the interests of all the stakeholders in their desirable futures. All these aspects can be interpreted as the absence, in the pilot study, of an explicit reflection about the need to include the concept of sustainability in the definition of a future scenarios. A special focus on sustainability could have maybe introduced a new element to think that a future scenario, to be sensible, has to be based on a dynamic equilibrium between interacting parts of a system that coexist maintaining their differences.

A reconsideration of this aspect has been pursued for the second implementation of the three sets of activities that will be carried out during the first *I SEE* summer school that will take place in Bologna, 5-9 June 2017. In that international context, new data will be collected and it will be interesting to apply and to refine the markers that this work started to point out. The production of markers to analyse students' discourse has been the most complicate problem. The future-scaffolding skills that the module aimed to develop are indeed new and this study has been the first attempt, within the *I SEE* project, to recognise and evaluate them.

Conclusions

Can the contents of physics be reconstructed so as to make disciplinary learning a place to develop competencies to deal with the future?

In the introduction to the present work I made this question and the thesis is just my personal answer – mine and of the research group in Physics Education of the University of Bologna (particularly of Prof. Olivia Levrini, Dr. Giulia Tasquier and Dr. Laura Branchetti – to it. Yes, the contents, the methods and the epistemological perspective of science, in general, and physics, in particular, can be studied, analysed and reconstructed in order to design teaching modules that favour the development of skills to deal with the future.

The results of our pilot study demonstrate this, as discussed in Chapter 3. The data analysis showed that the first set of activities drove students to reach a good level of knowledge about the crucial aspects of the concepts of the science of complex systems. Then, this knowledge was transformed into scientific skills because the scientific concepts became lenses through which analysing scientific and non-scientific texts. We pointed out that some specific scientific skills help students dealing with the future, through the understanding of causal patterns elaborated by science: they are future-scaffolding scientific skills. But these are not the only skills that provide ways of managing the future. The analysis of the Irene activity shows that it supported the development of another type of future-scaffolding skills because students displayed a successful understanding of the methods of futures studies and put into play their imagination in this sort of 'laboratory of creativity': these are named future-scaffolding transversal skills. Moreover, one of the most important results of the whole pilot study was the recognition of the fact that the activities about future-thinking impacted on the students' perceptions of the present and of the future, enhancing the consciousness that also our little actions in the present, done as individuals, as groups, as associations or as policy makers, reveal their consequences on the future, also if they can be difficult to imagine.

Of course, the study has revealed criticalities too. The imagination of negative feedback loops was much more difficult than the imagination of positive ones. Moreover, the students found difficulties in detaching themselves from the present situations to imagine the future and, even when tried to project into a desirable scenario for the town Irene, the future they anticipated was characterized by the absence of any conflict and any diversity, since, during the elaboration of the scenario, the students referred to values, supposing to be universal, like eco-sustainability, security, cohesive community. These criticalities mirror, in our opinion, the lack of an explicit reflection in the module on what a scenario is and on the critical concept of sustainability in making a future scenario realistic. Sustainability is not (not only) the eco-sustainability described by the students but is, indeed, one of the main criteria that futurists use to judge the quality of scenarios (Greeuw et al., 2000; Kreibich, 2007; Wilson, 1998). Sustainability accepts (better, requires) differences, challenges, conflicts, diversities of priorities on values. A reconsideration of this aspect has been pursued for the second implementation of the three sets of activities that will be carried out during the first *I SEE* summer school that will take place in Bologna, 5-9 June 2017.

It is exactly the context of this European project that has hosted the work I have presented in this master thesis. During this year of research, has been very important for me to have several opportunities to explore various research contexts. In particular, I have had the special opportunity of developing my research together with a lot of professors, expert researchers, professionals and I appreciated the multiplicity of points of view and perspectives on the discipline of science education. Moreover, the various research steps that have leaded to this thesis made me meet methods, types of argumentation and ways of presenting results. The elaboration of the theoretical framework required to explore the literature about a wide range of disciplines: from physics to sociology, from mathematics to education. The design of the activities challenged me because I had to put my creativity into play but, at the same time, to stay anchored to the authenticity of the disciplines I treated. The implementation in the pilot study taught me what realizing a teaching module concretely means while from the data analysis I learnt how is possible to develop strategies to explain research results and, at the same time, not to cut the precious complexity and richness of the students' outputs.

If I had to express with a single word what I have learnt in this year about the discipline of physics education, I would say that this word is *chorality*. Chorality of researchers who work together in a perspective of constructive debate. Chorality of contexts of research and of dissemination. Chorality of points of view and ideas. Definitively, chorality of the dimensions of the discipline that, only if considered together, can build the *complexity* that makes its sound.

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It is beautiful and touching, after a climb on mountains, stopping for a while, enjoying the panorama on the valley but, at the same time, thanking who, along the road, has been a travel companion, a friend, a pioneer, a supporter, a mentor, a cornerstone.

'The world needs good thoughts'. The first thanks go to Prof. Olivia Levrini, who has made me discover from the very first lesson I met her, why I chose to study Physics at university. And this reason was (and is) the 'good thoughts'. Thank you for having given me expertise, professionalism, knowledge and support. Thank you for believing in me and for offering me great opportunities for growth: you have changed my life. Thank you, Prof.

'We all are working, sharing goals and values'. Thanks to Dr. Giulia Tasquier for generosity in giving me experience, time and patience. Thank you for the confidence that you have demonstrated to me from the very beginning and that has resulted in collaborations that have allowed me to learn a lot. Thank you also for the constant encouragement, both professional and personal, made of good and smiling, but truthfully told, word. Thank you, Giulia.

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'La lüna la lüsea'. Who knows me well knows also that my great passion has always been music: I have always loved it and it has always helped me to love. Thanks to my choir-mates for the sympathy, the friendship, the esteem and the care they have always devoted to me since the very first rehearsal, when at sixteen I started singing with them. Thanks also to everyone who the music has allowed me to meet, during Gregorian Chant courses or rehearsals of the children choir.

‘A friend knows the melodies of our heart and sings them when we forget the words’. Friends are undeserved gifts, people who choose to stay in moments of quiet and of storm, who tell that you are wrong but they do it with delicacy, they offer you a firm hand and at the same time make you feel light. It's a treasure that we have been given and of which, however, we rarely remember to be grateful. I cannot name each of you, but you know very well the place you occupy in my heart.

‘Donating life and giving love’. Finally, a thanksgiving that flows from the depths of my heart. To my family, to the nest to which I came back every night, to the house that welcomes, to the embrace that reassures. To you, mom, because we do not need any word to understand each other and because you are the most special woman I know. To you, dad, because our family is founded on your goodness and your capability to forgive. To you, Edoardo, because you are irreplaceable and generous, but you do not bring it up to anyone. To you, Alessandro, because seeing you grow with us every day has been one of the greatest joys of my life. Thanks to my grandparents for their love and for the example they have been giving me since I was born: you taught me what mean to be strong, to face the real challenges, to accept suffering, to live with the pain, to struggle with tenacity, to work with seriousness, to be honest people. Thank you, grandpa Giancarlo (I would love so much you to be here with me, but I know you are here and you are proud of me), grandma Liliana, grandma Agnese and grandpa Italo: I will never be grateful enough.

Thanks to everyone was, thanks to everyone is here.

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