

Science of Complex Systems and Citizenship Skills: A Pilot Study with Adult Citizens

Eleonora Barelli ^{1*}, Laura Branchetti ², Giulia Tasquier ¹, Luca Albertazzi ³, Olivia Levrini ¹

¹ Alma Mater Studiorum – University of Bologna, ITALY

² University of Parma, ITALY

³ Municipality of Dozza, Bologna, ITALY

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ABSTRACT

The issue of scientific citizenship in the context of STEM education has been under debate for over two decades. We present a preliminary study which aims to investigate if, how and why the development of hard scientific skills grounded in the discipline of complex systems (suitably simplified and adapted) may foster the development of citizenship skills that can impact on people's approaches to facing problems and making decisions. We carried out a pilot study with a group of 34 volunteer adult citizens. The data analysis showed that: i) in the beginning, only a few participants were comfortable dealing with scientific and epistemological concepts related to complex systems, favouring instead a "common sense" approach towards decision-making; ii) in some successful cases, there was an alignment between scientific competences and decision-making strategies, suggesting that it is possible to design activities based on authentic scientific concepts in order to develop citizenship skills.

Keywords: adult education, complex systems, experts and novices, scientific citizenship, social skills

RESEARCH FRAMEWORK

STEM Education for Citizenship

For over two decades, within the field of STEM (Science, Technology, Engineering and Mathematics) education, a crucial importance has been attributed to the issue of citizenship education in general and to scientific citizenship in particular. 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" (p. 3), including social and civic competences; these are among the eight key competences identified in the recommendation of the European Parliament and of the Council (EPC, 2006) as essential for citizens living in a "knowledge society". In one of the first reports on this topic, *Beyond 2000: Science education for the future* (Millar & Osborne, 1998), some experts in the field of Science Education stressed the need for a dialogue between science and society "to sustain a healthy and vibrant democracy" (p. 4), through a renovation of STEM curricula. The main goal was to build public awareness among citizens who, whilst appreciating the value of science and its contribution to our culture, can critically engage in issues and debates that involve scientific knowledge. Since 1998, the 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, culminating in an approach in which all societal actors, both shareholders and stakeholders (Greco, 2014), are encouraged to work together throughout the entire research and innovation process. This kind of public participation in scientific research is the real essence of citizen science, which also takes advantage of living laboratories (Mitchell, Larson & Pentland, 2010), tangible environments that embody this type of choral conception of scientific research and practice. The necessity of providing "the space for open, inclusive

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✉ eleonora.barelli2@unibo.it (*Correspondence) ✉ laura.branchetti@unipr.it ✉ giulia.tasquier2@unibo.it

✉ lucalbert13@gmail.com ✉ olivia.levrini2@unibo.it

Contribution of this paper to the literature

- Our approach presents original activities on the science of complex systems and shows how the educational reconstruction of mathematical models and scientific disciplinary contents can foster the development of citizenship skills and stimulate rational attitudes towards collective decision-making.
- Our approach is sustainable for citizens (in terms of time spent on tasks at home and in collective meetings, preliminary skills and knowledge required) and encourages non-experts to deal with activities based on mathematical modelling and scientific concepts.
- Our approach allows the spontaneous emergence of citizens' attitudes, and informs activities designed to involve adults in analysing complex problems (as a group) and making collective decisions.

and informed discussions on the scientific research and technology decisions that will impact citizens' lives" (p. 5) is also underlined in the EU report which was presented and discussed at the 2015 ESERA conference in Helsinki (EC, 2015).

In order to make the EU recommendations operative, it is necessary to explore new approaches and design innovative ways to develop citizenship skills on the basis of scientific knowledge. The most common approach is summarized by Osborne (2010) who has stressed the need for "less emphasis on the facts of science and a broader knowledge of how science works" (p. 67). Our aims were slightly different, since we used scientific concepts as bases to scaffold citizenship skills. Indeed, we investigated if, how and why the acquisition by citizens of hard-scientific skills (skills based on authentic scientific concepts, problems and methods) could result in the development of citizenship skills (skills able to impact on people's approaches to problems, such as the skills necessary for making informed decisions about societal issues).

The scientific discipline that we retained appropriate in this study in order to acquire a good basis for the development of such competencies is the science of complex systems. In the following paragraph, the reasons for this choice are discussed and we argue specifically as to why it can provide a contribution to the development of citizenship skills; in particular, we clarify what we mean, in our context, for hard-scientific skills and citizenship ones.

Science of Complex Systems as a Heritage to Develop Citizenship Skills

Within the scientific community, complex systems are usually defined in terms of their features and behaviours they display: in such systems, numerous individual elements or agents, often relatively simple, interact with each other and the resulting systems frequently display features that the classical ones do not have, such as non-linearity, high sensitivity to initial conditions, feedback loops, self-organization and emergent properties (see, for example, the Wikipedia article "Complex system"). The science of complex system is an intrinsically interdisciplinary field since the same general approach regarding the role of the mathematical modelling informs all the application contexts. Examples of complex systems can be found in many disciplinary fields: in scientific fields, such as the climate in climatology, living organisms and cells in biology, the human brain in neuroscience, and ecosystems in ecology but also, concerning economics and sociology, in social and economic organizations like cities (Omicini & Contucci, 2013). The consequence of considering a specific system as complex is that it can be approached (from both quantitative and qualitative perspectives) with an appropriate attitude and a suitable conceptual, technical and epistemological framework.

Together with its set of concepts, which are generally absent in classical physics, the science of complex systems has developed specific methods of analysis, including computational simulations. Going beyond the traditional laboratory experiments and theories, simulation can be considered the third important tool of science (Parisi, 2001): when a simulation runs on the computer, it gives rise to empirical predictions that derive from the theoretical mathematical model of the phenomenon under exam, and it works as a virtual laboratory in which, just as in the real laboratory, the researcher monitors the phenomena under controlled conditions, manipulates the conditions themselves and discovers the consequences of such manipulations.

Research in the field of science education has been investigating students' difficulties in learning about the basic concepts and methods of the science of complex systems, showing to what extent they can be challenging to learn (Jacobson & Wilensky, 2006). Indeed, many concepts may be counterintuitive or in conflict with common beliefs (Casti, 1994; Wilensky & Resnick, 1999): for example, the idea that small causes correspond to small effects while large effects result only from large causes is common; moreover, it has been proved that people also tend to use deterministic causality and "top down" approaches to describe systems in which self-organization, with its decentralized processes, is displayed (Feltovich, Spiro & Coulson, 1989; Resnick & Wilensky, 1993). These findings, documented by the research literature, anticipated us the challenges we were expected to face working with adult

citizens with different backgrounds; indeed, we imagined that they could approach problems using, more or less explicitly, their common beliefs, since they could feel unease with counterintuitive ideas.

Because of its new concepts and methods, the science of complex systems has laid the foundations of a new epistemology (Morin, 1986) characterized mainly by: the concept of uncertainty, a new approach to causality and a focus on the role of the single agent within the system. This new epistemology is very different from that which was embedded in the linear determinism of classical science (e.g. Newtonian physics) and which is often implicit in science teaching at school and in most citizens' conceptions of physics. In order to understand the phenomena under examination, such an epistemology requires a change in learners' perspectives. The learners' difficulties about science of complex systems has been interpreted also in terms of a widening gap between science and citizenship (Jacobson & Wilensky, 2006) or, better, between, on one hand, the scientific communities and, on the other, policymakers and citizens. Indeed, challenging social and global problems of the 21st century often require scientific competences coming from this new scientific perspective of complexity. Many problems, whether on a local or global scale, from decisions in municipal councils about urban planning to global debates about climate change, often require an awareness that actions can have multiple causes and consequences that constitute non-linear patterns of interaction, since positive and negative feedback loops exist and contribute respectively to the divergence or equilibrium of the system (Omicini & Contucci, 2013). Nowadays, also because of some weaknesses in STEM education, citizens are not equipped with the knowledge and skills usually needed to face these complex problems and challenges. For these reasons, we argue that the science of complex systems is suited to addressing the citizenship issue, as it can be considered a heritage of concepts and methods capable of fostering specific skills and, then, of informing citizens' approaches to facing problems and decisions.

The goal of our work is to outline an approach that can explicitly support the teaching of the basic concepts of the science of complex systems in informal contexts of adult citizen education. The approach results in the design of activities aimed both to introduce basic concepts of the science of complex systems and to turn "hard-scientific skills" into "citizenship skills". By "hard-scientific skills" we mean skills that typically belong to science, like the ability to give up linear causality to embrace circular patterns of complex relationships between causes and effects, recognising feedback loops. By "citizenship skills" we mean skills needed to address typical citizenship issues, like the ability to make decisions, to recognise the various stakeholders involved in a civic problem and so on. As we will show, in our activities hard-scientific skills are exploited to reveal their potential in contexts that go beyond science and, in this sense, they are expected to become citizenship skills.

In the next sections, we present the activities that we designed for a pilot study in which adult citizens were involved.

THE PILOT STUDY: CONTEXT, DESIGN AND DATA COLLECTION

The pilot study was carried out in collaboration with one of the co-authors of this paper (LA) who is the Mayor of Dozza, a little town close to Bologna (Italy). The group of people involved in the qualitative study consisted of 34 volunteer adults recruited by the Mayor to represent a heterogeneous sample of the local citizens (Albertazzi, 2017): they differed in age, gender, job, scientific education and type of engagement in the local administration. The graphs in [Figures 1-3](#) give a more concrete idea about the composition of the sample, showing some correlations between the characteristics taken into account when recruiting the sample group. The sample composition is particularly relevant as the whole planning process had to take into account evident differences between the participants, particularly regarding their professional roles and levels of scientific education.

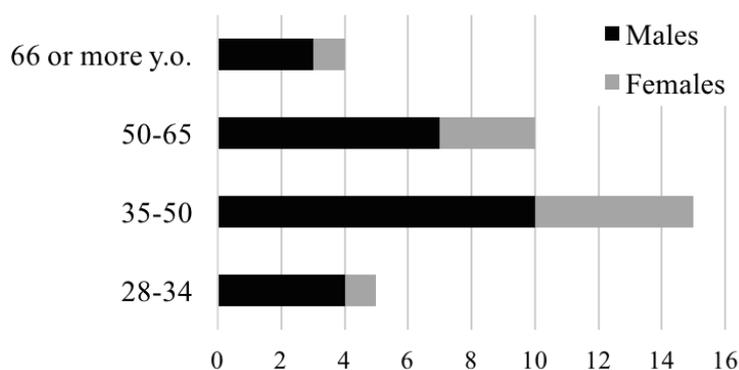


Figure 1. Age distribution of the sample (Total number of citizens: 34; number of males: 24; number of females: 10)

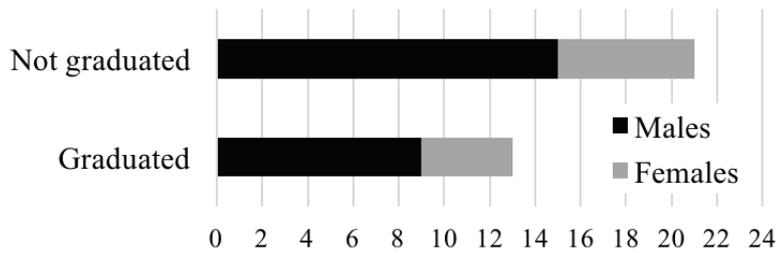


Figure 2. Differences in education between males and females in the sample (Total number of citizens: 34; number of males: 24; number of females: 10)

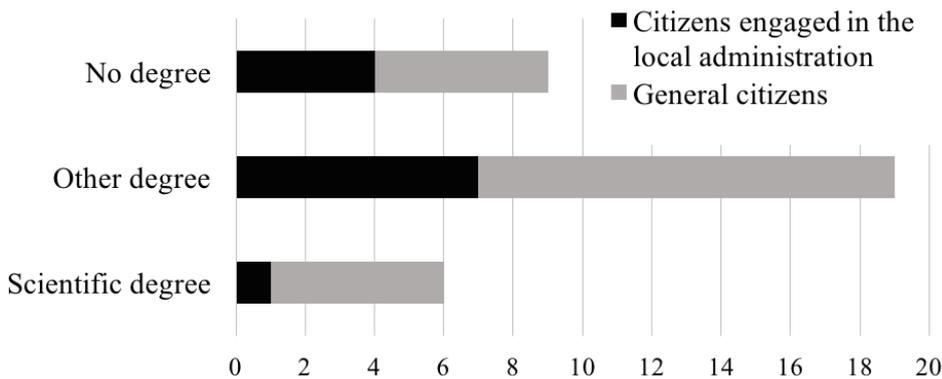


Figure 3. Differences in the types of engagement in the local administration (council members or assessors) according to the participants' education (Total number of citizens: 34; number of citizens engaged in the local administration: 12; general citizens: 22)

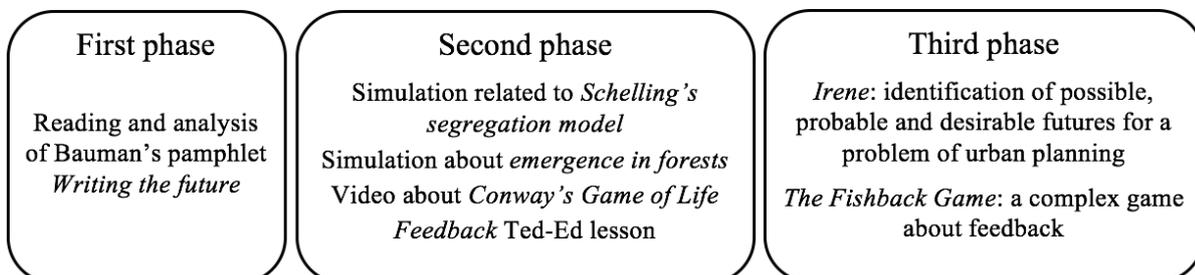


Figure 4. Outline of the activities across the three phases of the experimentation

Across all the phases of our teaching/learning experiment, we collected data about citizens' progressive development in order to answer two research questions, that we present in the Data Analysis section. The study was articulated in three phases and a set of original activities was designed for each stage by our research group in STEM Education of the University of Bologna: a summary diagram is provided in **Figure 4**.

First Phase

The first phase has been designed with the aim to introduce the citizens to the conceptual apparatus of the science of complex systems. In this context, we also planned to investigate whether and how the group of citizens held scientific and epistemological knowledge about science in general and science of complex systems in particular. For these purposes, the participants were asked to read and analyse a pamphlet by Bauman (2016) in which the Polish sociologist used terms derived from the science of complexity (such as uncertainty, order, turbulence, system, probability, predictability) in order to interpret recent social transformations like migrations, assimilation of strangers, and gated communities characterized by the dualism between mixophilia (the attitude of attraction and tolerance toward strangers) and mixophobia (the tendency to avoid relationships with people of other cultures in the effort to safeguard personal goods). Bauman's argumentation begins by presenting the concept of determinism *à la Laplace*, in which the future is certain since, as a matter of principle, it is perfectly predictable by a supreme intelligence who could measure precisely the state of all the components even of a huge and

complicated system. Secondly, the *world of becomingness* is presented with its characteristic concepts, including uncertainty, probability, instability, irreversibility and future. Continuing his argumentation, Bauman introduces the term *complex world* to refer to the presence of apparently contradictory processes made of both order and chaos and characterized, within a new view of causality, by a strong dependence on initial condition; in this kind of world, the renunciation of a deterministic certainty is associated with the relevance of every action of every single member of the system, who consequently carries a high degree of responsibility since he/she can really make a difference. The pamphlet ends with the sociological analysis of some noticeable on-going social transformations, pointing out the role of single choices of individuals within a world that cannot be considered anything other than authentically complex.

This text is substantially the transcript of a public lecture addressed to citizens within the context of the 2014 edition of *Futura Festival* in Civitanova Marche (Macerata, Italy). Considering the general public nature of that audience, the author wished his language to be straightforward and comprehensible to a citizen without any presupposition about mathematical, scientific or sociological knowledge. This feature of the text convinced us to use it for the first phase of the educational intervention, since our audience was quite varied in terms of scientific education. In practice, we prepared a questionnaire (QA) with two sections and the participants were required to read the pamphlet and to answer, either by writing or by oral interviews, some questions about the content of the text. In the first section, there were 11 guided open questions aimed at focusing the debate on salient points of Bauman's argumentation, with specific attention to the scientific terms used by the author (e.g. *How would you explain, in your own words, the fundamental meaning of Laplace's claim? Why does the author write that this is a "seductive perspective" and which less "seductive" consequences does (or did) it have? What characterizes the "world of becomingness"? In your opinion, does the "world of becomingness" have positive or seductive aspects? If so, which ones? If not, why? What characterizes the "complex world"? In your opinion, does a "complex world" have positive or attractive aspects? If so, which ones? If not, why?*). Consistently with the double goal of the study, the questions were supposed not only to direct the readers to reflect on the main concepts of the text as a sort of guide to reading (educational goal), but also to encourage answers that could show the citizens' level of scientific and epistemological knowledge (research goal). These answers allowed us to elaborate a description and categorization of the initial state of the group in terms of attitude towards such scientific concepts and societal challenges.

The second part of QA consisted of 3 open-ended questions aimed to stimulate reflection beyond the text (e.g. *What are the on-going changes that affect or worry you most and, in your opinion, what are the changes that will characterize the future throughout the next 20-30 years? What does "making history" mean today, both individually and collectively? What are the differences between "making history" today and at the end of the 90s?*).

Second Phase

The second phase of the pilot study aimed to investigate whether, and how, adults can be guided to understand the conceptual and methodological core of complexity. In the design of these four activities, conceived and developed mainly by EB (Barelli, 2017), we paid specific attention to underlining the characteristic aspects of disciplinary contents, application contexts and forms of presentation of the activities themselves (cfr. [Table 1](#) for an overview).

Table 1. Overview of activities for the second phase of the intervention

Activity	Disciplinary content	Application context	Form of presentation
Schelling's segregation model	self-organization and emergent properties	sociological modelling	simulation
Emergence in forests	self-organization and emergent properties	ecology, biology	user-adjustable simulation
The Game of Life	self-organization and emergent properties	biological model	simulation
Feedback Ted-Ed lesson	feedback and circular causality	ecology	video-lesson and interactive test

Despite the variety of issues tackled in the activities, they all have common features that can be recognised chiefly in their design procedure. First of all, a wide literature about complex systems was taken into account in order to isolate the main and most fundamental concepts of the theory. Then, web resources were searched in order to find tools that could be useful to communicate the concepts effectively in an informal context. This research revealed that one of the most popular tools for introducing complex systems is interactive simulation: this is the reason why the second set of activities contains three different simulations, related to variegated application contexts. Another common feature of our educational materials about complex systems is the important role attributed to mathematical modelling, a fundamental aspect in the whole field of complex systems. Even though we decided not to use a mathematical language in our activities (since our experimentation did not involve students in a curricular context but general citizens with many differences in their mathematical background), we took care

of preserving the authenticity of the main mathematical issues when addressing the themes from our educational perspective.

After having located suitable resources on the Internet, we made the conceptual dimension explicit and transformed the tools into completely original activities equipped with purpose, description and comments. In order to collect data to investigate the development of citizens' knowledge and skills during this phase, every activity of this set ends with the same task: *Summarize (in 3-4 lines) the main message of the activity and the most significant aspects*. We refer to this set of questions as Q_B. The resulting activities have a solid disciplinary dimension, since our purpose was to build as strong a knowledge as possible about the scientific concepts, maintaining also the authenticity of the process of mathematical modelling; at the same time, we devoted special attention to the playful dimension, so that the learning process about the discipline could foster learners' engagement and motivation (Chen, 2017; van Bilsen, Bekebrede & Mayer, 2010).

The first activity regards the concept of self-organization as an emergent property of a complex social system. It refers to Thomas Schelling's dynamic model of racial segregation (Schelling, 1971), according to which local interactions (displaying a relatively mild preference for neighbours of similar race) can lead to unexpected and unpredicted aggregate patterns (segregation), without any simple correspondence of individual behaviour to collective results. In this first activity, we used a playable simulation, available on an interactive webpage (Vi Hart & Nicky case, A) that guided the users through a story. The protagonists (squares and triangles) share the same environment (a grid in which every element occupies one place); the users can modulate a parameter that indicates the protagonists' preference to live near similar individuals, observing the final rate of segregation of the simulated "social system". The choice of a simulation is not only due to the intrinsic difficulty in manipulating deeply woven variables in complex systems - the term *complex* can be traced etymologically to *cum-plexus*, woven together - that makes practically impossible to study complex social systems through the experimental technique. The ethical consequences of such an approach were also relevant to us: using a simulation one can implement the equations of the model and replicate, through a specific software, the principal properties and the dynamics of a social system and, through the controlled manipulation of some reference materials, perform "experiments".

The second activity has the same conceptual core as the first and is a re-editing of a web resource (Vi Hart & Nicky Case, B): it is a user-adjustable simulation in which the concepts of science of complex systems are applied to the life of a forest. Through the manipulation of the main parameters at the base of their lives (rate of growth of trees, weeds and occurrence of fires), the players become familiar with the concept of emergent property, complex behaviour that arises from basic rules, feedback loops and self-organization. These observations reveal the rise of an order initiating from spontaneous behaviour, which is not imposed top-down from the beginning like a sort of "town plan".

An in-depth analysis of the concept of emergence is provided in the third activity with a brief video (Channel 0524432, 2012) that illustrates John Conway's "Game of Life" (Gardner, 1970). The simulation is a zero-player game, since the evolution is determined by the initial geometrical configuration of "alive" or "dead" cells on a grid, requiring no further input. The evolution is ruled by a few, basic rules that reproduce, in a simplified way, the behaviour of biological cells in an environment; for example, they die by overpopulation or underpopulation if they have too many or not enough neighbours. The interest of this game originates from the fact that the system autonomously evolves, showing up surprising geometrical patterns ("still life objects", "oscillators", "spaceships") and providing an example of emergence and self-organization.

The final activity in this set focuses on the concepts of feedback and circular causality as crucial aspects that characterize a complex system. It is organized as a Ted-Ed page and is based on an animated video-lesson (Neutel, 2014) in which the topic is positive and negative feedbacks in biological systems; using a musical metaphor, the video provides imaginative tools for thinking about the genesis of self-organization from a complex substrate of feedback cycles. The issue of mathematical description of feedback loops in terms of negative or positive parameters that express the "strength" of the causal link is also addressed in the video. In addition to the general task common to all the activities, this page presents different kinds of questions (multiple choices or open-ended), to boost on-line learning about the topic; moreover, there is a summary about the contents of the video, with guidance for deeper analysis of the topic (links to other Ted-Ed lessons and scientific papers, etc.). A discussion section has also been created, where everyone can leave questions, comments or remarks.

Third Phase

The last phase of the intervention aimed to investigate through two activities whether citizens were able to use their acquired knowledge of scientific concepts in order to analyse complex problems and, in this way, to develop citizenship skills on the basis of said knowledge. This phase was implemented during a 3-hour meeting in which the participants were divided into 5 groups of four members each; citizens who did not participate in the meeting were given a questionnaire (Q_C) to complete, containing the tasks related to the second activity of this set only. At

the beginning of the meeting, before approaching the first activity of the third phase, a common discussion was carried out to highlight and discuss together the main concepts which emerged from the activities of the second phase.

The first activity of the last phase is “The Fishback Game”, a board game for four players about the activity of commercial fishermen, which had the main goal of reinforcing the rejection of traditional linear thinking in favour of a dynamic thought process about feedback mechanisms and the long-term consequences of players’ actions and intentions. In this game, adapted from a proposal found in Pedercini and Burke (2013), the strategy emerges as a characteristic of the group of players: depending on the strategy adopted, either one is the winner or everyone loses. It is not easy to agree upon the sure strategy to win, but it is rather simple to identify the easiest way to lose: indeed, everyone loses if the players do not consider the feedback loops the game is based on. In this sense, the authentic scientific knowledge about the concept of feedback is supposed to be able to foster the development of a scientific competence (the recognition of loops implicit in the rules of the game) and a citizenship skill too, since the complex system in which it is used is nothing but a model of the real market. Together with the cards and the printed material for the game, the learners-players received a detailed description of the rules and, after a first autonomous round, another sheet containing an outline of two positive and two negative feedback loops that could be identified during play.

The final activity of the pilot study is “Probable, possible and desirable futures for the city of Irene” – this is related to a problem of urban planning, and we invented it inspired by a real situation (Albertazzi, 2017). In a document given to the group, Irene is described as a small town with three commercial companies operating in the food sector; the owners of one of these are interested in enlarging their business and, consequently, the area of their discount store, but this move would require an alteration of the Local Council’s urban regulations as the present Urban Planning Regulations would not allow any possibility of expansion. The problem has been intentionally formulated so as to require the application of a systemic view, as well as the scientific concept of positive and negative feedback to evaluate how the Mayor’s decision today (i.e. whether or not to provide the licence to extend the commercial activity) could impact the evolution of the city in the future; for these reasons, the activity is considered as an appropriate context in which the development of an important citizenship skill (i.e. taking decisions about societal complex issues) can be monitored. The activity consists of three parts, wherein the goal is to stimulate reflection on strategies for thinking about probable, possible and desirable futures (Hancock & Bezold, 1994; Voros, 2003). In the first stage, the participants are required to make a decision as though they were the public administrators of Irene, after having carried out an analysis of the present situation and written two probable scenarios for 2025 which illustrate the probable conditions of evolution of the system as a consequence of granted or denied expansion of the discount store. The second part requires them to develop *backcasting* skills (a procedure of thinking that begins with the possible future scenarios and evaluates backwards on the possible paths of events that have determined them) in two given scenarios; moreover, the participants have to identify positive or negative feedback loops that can explain how possible scenarios were arrived at; after having completed this second part of the activity, they have to confirm whether they would still take the same decision as before. The third and final task about Irene involves developing a desirable scenario for the town, in which the values of individuals have to be taken into account. To collect data about the skills that this activity was able to foster, 5 focus groups were organized during the group discussion about the problem of Irene, asking the citizens which competencies they planned to put into play to resolve the urban planning problem.

The data collection was organised, across the three phases of the study, as reported in [Table 2](#).

Table 2. Sources of data for a later analysis across the various phases of the experimentation

Phase of the study	Main data sources
First phase	<ul style="list-style-type: none"> • 27 questionnaires (Q_A) • 7 interviews
Second phase	<ul style="list-style-type: none"> • 2 questionnaires (Q_B) • audio-recording of the 20-minute group meeting
Third phase	<ul style="list-style-type: none"> • audio-recording of a 15-minute focus group • 4 questionnaires from the non-participants at the group meeting (Q_C)

THE PILOT STUDY: DATA ANALYSIS

The data analysis was carried out with a qualitative strategy, which was iteratively implemented so as to build up an overview of what happened and to interpret it by recognising criticalities, trends and behaviours during the intervention (Anfara, Brown & Mangione, 2002; Denzin & Lincoln, 2005). The analysis was designed to address the two following research questions: RQ₁) *What is the initial state of scientific and epistemological knowledge of citizens about the concepts of science of complex systems?* RQ₂) *Do citizens use the scientific competences developed by the activities in*

decision-making processes concerning societal issues? If so, how do they connect and integrate them with other competences, knowledge and experiences? In the current section, the methods and the main results of the analysis are clearly divided into two subsections, one for each RQ.

The Initial State of Knowledge

To answer RQ₁, the 34 interviews and questionnaires Q_A of citizens about Bauman's pamphlet were considered as data sources. In order to elaborate a qualitative approach to organize their answers into categories and interpret them, we carried out a triangulation survey with experts¹ (Anfara et al. 2002; Denzin & Lincoln, 2005). Four physicists were involved in the study: three of them are specialists in science of complex systems (Antonio, a professor author of many essays and books about complexity; Nicola, a researcher in Computational Physics; Maria, a secondary school teacher with a PhD in Anthropology and Epistemology of Complexity) while the final participant, Emanuele, is a researcher in History of Physics with an epistemological background.

These four experts were asked to read Bauman's text and the questionnaire Q_A that we had given to citizens, after which they were required to comment on the scientific content communicated by the text and, more in general, the whole argumentation developed by the sociologist. A semi-structured individual interview was carried out with each expert.

Although every specialist gave his/her own personal answer in which many idiosyncratic elements can be observed, analysis of the four interviews highlights four recurrent attitudes toward the text: technical, epistemological, personal and communicative/educational; in Table 3 a short description and some quotes from all the experts are set out. These four attitudes make the specialists' discourses authentically *rich and thick* (Levrini, Fantini, Tasquier, Pecori & Levin, 2015): the four metacognitive dimensions that interlaced in their answers confirmed indeed a deep understanding of the text.

Table 3. The four dimensions that coexist in specialist's discourses

	Brief description	Quotes
Technical dimension	Recognition and critical analysis of scientific terms and concepts in the text	<p>"Complexity arises from the inadequacy of a unified description, from the ability to privilege different variables, different indicators, different space-time levels, and the relationship between these different worlds we create through descriptions." (Antonio)</p> <p>"The main meaning of Laplace's claim lies in the fact that the evolution of a system is determined; studying the evolution of a system means defining the initial conditions and the laws that govern it, the differential equations whose integration allows to determine the trajectories and so the evolution of the system. This is, as Baumann says, «a pre-determined future»" (Maria)</p> <p>"The concept of turbulence is correctly connected [in the text] to deterministic chaos and refers to systems with an extremely limited time horizon. [...] There is a strong distinction between possibility and plausibility." (Nicola)</p>
Epistemological dimension	Recognition of the metaphorical and epistemological meaning of scientific terms, as well as the emerging view of nature of science	<p>"According to Bauman, [irreversibility] is a property: «physics has proved that it is an ontological property of the world.»" (Antonio)</p> <p>"What science or scientific vision is there at its base?" (Emanuele)</p>
Personal dimension	Recognition of the sociological thesis and personal evaluation of the argumentation	<p>"The point is to learn how developing <i>formae mentis</i> [mindset] to avoid being inflexible toward eventualities. [...] The risk is to vehicle the message that scientific uncertainty causes a global uncertainty in society and influences what happens at every level." (Emanuele)</p> <p>"It would be a good idea to encourage reflection to look for more information and widen horizons." (Nicola)</p>
Communicative educational dimension	Recognition of the general goal of the text and suggestion of inputs to strengthen its message	<p>"In the section related to mixophilia and mixophobia, I read between the lines some characteristic elements of complexity that could be made more explicit, but I understand that the goal of the author was surely different, more sociological." (Maria)</p>

To develop the analysis of citizens' interviews and questionnaires, we searched for the previously identified dimensions in their answers. The result was that, contrary to the richness and in-depth quality of the specialists' discourses, the citizens focused on only one perspective in their answers; moreover, the communicative-educational dimension was missing in the citizens' answers. In Table 4 the three types of answers, the number of people (out of 34) who displayed each attitude, their description and some quotes are set out. The predominance of answers based on common sense is evident; regarding the four technical answers, it is important to mention the fact that they come from four professionals with a technical-scientific education (e.g. engineering). A comment is provided in the discussion of the results.

¹ All the names in the transcripts are gender-indicative pseudonyms.

Table 4. The three types of citizens' answers (out of 34 total answers)

	Brief description	Quotes
Technical answer		<i>"Laplace and the determinists [...] believed that, in the universe and in life, nothing is left to chance, everything is governed by precise laws, everything has a cause and an effect: if we understand the laws, we can come to the certain knowledge of the future."</i> (Paolo)
4 answers	Focus on scientific terms from a technical perspective (correct basic definitions; scientific dimension disconnected from the sociological thesis)	<i>The world of becomingness, characterized by turbulence and probability is introduced... a world that irreversibly evolves not only according to clear and established laws, but also by virtue of random elements. Randomness is its characteristic, while causality is less defined, since it can arise from several unpredictable factors."</i> (Carlotta)
Epistemological answer	Recognition of scientific terms and their epistemological meaning (correct explanations; understanding of the role of science within the sociological argumentation)	<i>"I agree with Bauman's interpretation about the complex world... The fact that we cannot get rid of the uncertainty of the future and at the same time we know that even the action of an individual can provoke epochal changes is an extraordinary thing!"</i> (Marinella)
2 answers		
Personal answer	Good sense based answer (missing recognition of the scientific origin of terms like probability, uncertainty, system; approach guided by personal experience or good sense)	<i>"I would say that the significance of Laplace's claim is stimulating, because uncertainty, in the right measure, is something that stimulates us to search for the condition of certainty, which, in my opinion, even when we think we have achieved it, must and can always be improved"</i> (Martina) <i>"The seductive view [of Laplace's claim] is when, having surpassed the uncertainty, the whole arouses a general well-being. Conversely, the vision is less seductive when it creates a war."</i> (Grazia) <i>"The world of becomingness is characterized by the fact that the world is no longer ordered by imposed rules, structures and laws."</i> (Livio)
28 answers		

The Competences Put into Play

To answer RQ₂ and study the correlation between scientific skills developed through the second phase of the intervention and citizenship skills displayed in the third phase, we considered as data sources the audio-recordings of the group discussion about the second set of activities, and questionnaires Q_B and Q_C of the focus groups about Irene. Four types of correlation have been recognised and identified in terms of alignment between scientific/technical competences and decision-making competences:

- **successful alignment:** the scientific concepts (e.g. feedback, equilibrium) are used in non-scientific contexts to analyse a situation and to evaluate future scenarios. *"If the number of enterprises grows, as well as the agenda of cultural events, families become richer and attract other families and, thus, other enterprises... this is a positive feedback because it is a self-perpetuating mechanism!"* (Cristina, 46)
- **semi-successful alignment (awareness):** there is an explicit acknowledgment of the distance between "emotional" ways of thinking about citizenship issues and scientific competences which have not been consciously acquired. *"I am totally disengaged from science and I don't have any skills, but what I use to reason and decide is the emotional component and the idea of a sort of equilibrium"* (Lucia, 52)
- **unsuccessful alignment (no citizenship skills):** explicit refusal to use hard scientific knowledge acquired during the second set of activities to address a "soft" problem of urban planning, where there is no exact solution. *"I have technical competencies but, as a specialist, I am of service to policy makers and their political decisions. [...] I cannot decide with technical competencies about political problems"* (Carlo, 65)
- **unsuccessful alignment (common sense):** absence of scientific competences and use of an approach based on common sense when the problem of urban planning is addressed. *"I don't have any technical skills but I reason with common sense to evaluate the pros and cons of a decision and to find the best solution for everyone"* (Marco, 40)

The latter attitude was predominant; we can conclude that, for these citizens, the second set of activities was not effective in building a significant knowledge about the science of complex systems. In particular, they encountered difficulties in understanding the correct meaning of scientific terms (e.g. *negative* and *positive* feedback loops were perceived as *bad* or *good* mechanisms respectively, according to their common meaning in everyday language) as well as problems in grasping the methodological and epistemological value of simulations not as mere games but as tools for approaching the science of complex systems. Yet, the presence of successful cases represents a strongly positive sign since the activities were very innovative and they have a large margin for improvement. The most worrying result is the third type of reaction that, as we will describe more comprehensively in the next

section, comes from scientifically educated citizens who did not feel comfortable in applying hard knowledge to “soft” and citizenship problems.

DISCUSSION OF THE RESULTS

The citizens’ initial state of knowledge about the concepts of science of complex systems was not only very patchy from a theoretical point of view but also revealed a lack of explicit reflection on the epistemological contribute of science in general. This is particularly evident in the answers provided by professionals with a technical-scientific education: they gave correct technical definitions of the scientific terms used in Bauman’s argumentation, but this did not lead them to reflect on the methodology and epistemology of the scientific content. An epistemological perspective, even though quite accurate from a technical point of view, can be recognised in just two cases where the citizens had no scientific education at all. The ample frequency of answers based on common sense bears witness to the discomfort of citizens concerning a text that was perceived as “too scientific” and therefore out of their reach; this is confirmed by the absence of educational or communicative perspectives in their answers. While the specialists, having understood the content of the text from scientific and sociological perspectives, felt authorized to assume a critical point of view towards the text, expressing opinions about its argumentative strengths and weaknesses, the citizens did not feel qualified to do so, often underlining their own inadequacy in reading such kinds of text. The triangulation with experts also allowed us to identify a common characteristic of all the citizens’ answers: in approaching the text, they did not integrate different dimensions (correct conceptual understanding, epistemological critique and personal reflection and interpretation) but remained anchored on only one of these aspects. This attitude contrasts with the richness of experts’ discourses in which they display an acquisition of content knowledge which is organized in harmonious ways, through the overall epistemological perspective and the personal evaluation of the text in general, reflecting a deep understanding of the topic. This difference we observed is consistent with research on expert and novice differences in general (Chi, Glaser, & Farr, 1988; Larkin, McDermott, Simon, & Simon, 1980; NRC, 2000; Wu, Wen, Chen & Hsu, 2016) and about science of complex systems in particular (Hmelo-Silver & Pfeffer, 2004; Jacobson, 2000a, 2000b, 2001; Jacobson & Wilensky, 2006).

The second important finding concerns the effectiveness in some cases of scientific activities in developing citizenship skills (e.g. taking into account multiple perspectives and joint participation in public decisions) that were supposed to be fostered by our activities along the intervention.

Although not a majority, the successful cases of alignment between scientific-technical competences and decision competences show that it is possible to design activities based on authentic scientific concepts in order to develop citizenship skills. Such cases of successful alignment showed, in their answers, the same pattern of reasoning: i) decoding of the scientific apparatus of the science of complex systems; ii) application of those scientific concepts to personal contexts; iii) use of those concepts for the analysis of a complex civic situation and to take the decision. This pattern is based, first of all, on the traceability, in the citizens’ discourses, of epistemological ideas and scientific concepts typical of the science of complex systems. For instance, a renounce to linear causality can be observed in favour of an embracing of circular patterns of complex relationships between causes and effects, showed in the use of feedback loops to reason about future scenarios of the town Irene. This is an example of how hard-scientific skills (e.g. the ability to recognise a feedback loop) were applied in a context that goes beyond science and, in particular, to analyse an urban problem and make a decision on that, that are citizenship skills.

We consider significant also the attitude of semi-successful alignment. These citizens, at the end of the third phase of the intervention, clearly recognized the value of the scientific concepts and the related epistemological ideas, even if they considered the level of knowledge they reached not solid enough to use it for reasoning about a complex problem. We can interpret the data concerning patterns of successful and semi-successful alignment using our theoretical framework, as follows.

The main concepts of science of complex systems (non-linearity, high sensitivity to initial conditions, feedback loops, emergent properties), grasped thanks to the activities of set B, provided those citizens with lenses to look at complex scientific, environmental, social and economic phenomena. For example, the reported quote by Cristina shows that the crucial term “feedback” was exported from the native scientific field to the evaluation of future scenarios for the town of Irene, recognised as a complex system; in other people’s discourses, similar sentences refer to the concept of “equilibrium”. As we anticipated in our theoretical framework, considering a specific system as complex requires it to be approached with an appropriate attitude and a suitable conceptual, technical and epistemological framework. In these cases, citizens showed to have started to adopt this approach in their ways of reasoning about problems.

Finally, the activities triggered interesting social dynamics that were appreciated by citizens: most of them recommended repeating the experience in the form of training activities in town councils, since they recognised and appreciated their value as tools for developing citizenship skills.

Alongside these elements of success, the study also revealed some weaknesses. Some citizens, in the cases of unsuccessful alignment (no citizenship skills), explicitly refused to use scientific knowledge to address a problem of urban planning. This problem was not recognised as a complex problem that requires to be addressed with a new epistemological attitude inspired by the conceptual apparatus of the science of complex systems. As we have pointed out in our theoretical framework, this can be interpreted as an example of the gap between science and citizenship (Jacobson & Wilensky, 2006).

The numerous cases of unsuccessful alignment (common sense) confirmed the well-known difficulties in learning about the basic concepts of the science of complex systems and their counterintuitive character (Casti, 1994; Wilensky & Resnick, 1999): the common sense remained, in these cases, the only basis for their reasoning about complex problems. A similar difficulty can be traced in the cases of semi-successful alignment, since the citizens were aware that they had not completely understood the scientific concepts and, then, continued to use their common sense. These cases indicate that our educational approach has to be improved and reinforced in order to contribute, in a more significant way, to fill the mentioned gap between science and citizenship.

As another criticality of the intervention, the activities of the third phase (The Fishback Game and the Town Irene) activated forms of resistances from the citizens with a technical-scientific education, since the activities conflicted with their image of "science for specialists"; even the simulations, largely used in the second set of activities, were not perceived in some cases (particularly by older individuals) as authentic scientific tools used to make visible the mathematical modelling of the real situation but only as mere games. The playful dimension, which we predicted able to foster engagement and interest, resulted in distancing the older participants in the study.

CONCLUSIONS

Our work in the pilot study presented above addressed the issue of scientific citizenship, providing an example of how appropriate scientific and mathematical contents typical of science of complex systems can be reconstructed from an educational perspective, taught and organized in the form of activities aimed at developing citizenship skills.

Approaching complex systems requires an intrinsically interdisciplinary modelling that moves from the mathematical equations to the physical, biological, economic and social situations; this modelling makes large use of tools, such as simulations, which are becoming increasingly important at decisional, economic and political level, but are very rarely taught at school and, usually, are not part of the school education of current adult citizens. In our intervention, the explicit reflection on disciplinary concepts like equilibrium, system, feedback and causality allowed in some cases a more conscious approach to a civic and political problem, as urban planning is.

The innovative contribution of this paper can be traced mainly in its approach: the idea that STEM disciplines themselves may have a transformative power to encourage citizens to develop skills. This process starts from teaching the core ideas and ways of thinking of the science of complex systems (non-linearity of the models, systemic vision, circular causality, concept of self-organization as an emergent property), without getting trapped in technical and mathematical aspects: this approach helped the citizens to interpret and manage complex social dynamics in an authentically complex way, both from a conceptual and an epistemological perspective. As we already mentioned in the theoretical framework, our approach is different from the classical ones in which there is more emphasis on the methodological aspects of science and less importance is given to the conceptual knowledge (Osborne, 2010): we have not only given a general idea of the scientific methods but we have introduced also specific scientific concepts as bases to scaffold citizenship skills. Even though this approach showed some criticalities, it demonstrated to have some potential.

The cultural and political value of the experimentation was recognised by almost all the citizens; in particular, one council member participant in the study suggested that the Mayor "*organize the same course with the whole municipal council, because it was a wide-ranging project for the community: a project in which the community is reinforced and democracy realized*" (Franco, 54). For these reasons, we consider this study as a basis for further reflection on the potential relevance of STEM disciplines in sustaining an informed and, thus, healthy and vibrant democracy (Millar & Osborne, 1998), as required by many reports in the field of citizenship education.

The results of this pilot study led to a revision of the activities (specifically in the second and third phases of the intervention) for a second pilot study that involved voluntary secondary-school students as part of a project (*National Scientific Degree Project*) hosted by the Department of Physics and Astronomy of Bologna. This context allowed a more intensive focus on the technical contents of the discipline of complex systems; therefore, the second set was re-designed framing the activities within a lecture in which the mathematical and formal dimension was also introduced through the Lotka-Volterra predator-prey model (Volterra, 1926). The third phase of the intervention was also modified, in that the wide span of citizenship skills was restricted to a specific set of competencies of imagination and projection into the future: future cities, future professions, future societies, future

worlds. These skills, within the I SEE European Erasmus+ project (I SEE, 2016), have been classed as future-scaffolding skills. The results of this pilot study were particularly successful (Barelli, 2017).

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