Green Energy and Technology

Ioan M. Ciumasu

Eco-cities

Scenarios for Innovation and Sustainability

Springer

Green Energy and Technology

Climate change, environmental impact and the limited natural resources urge scientific research and novel technical solutions. The monograph series Green Energy and Technology serves as a publishing platform for scientific and technological approaches to "green"—i.e. environmentally friendly and sustainable—technologies. While a focus lies on energy and power supply, it also covers "green" solutions in industrial engineering and engineering design. Green Energy and Technology addresses researchers, advanced students, technical consultants as well as decision makers in industries and politics. Hence, the level of presentation spans from instructional to highly technical.

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Preface

Even as the cover title opens a wide horizon, the sub-title indicates a practical scope: generating options in concrete eco-city projects. The initial idea of this volume came from editor Anthony Doyle who invited me to consider making a book proposition that would develop further the method from a research paper using a Delphi-based approach to generate eco-city scenarios [1]. As so often with issue-driven works, this book took a decade to generate, so it incorporates the knowledge and the experiences that have been accumulating during all this time. Some of those include my own works within science, epistemology, sustainability, eco-innovation management and science-business relations (also outlined in a chapter of another Springer book, focused on smart cities and societies [2]). But more importantly, the book comes out in a world that is a lot different. Back then, long-term consequences of the 2008–2010 financial crisis loomed in the dark. Today, we are witnessing a shift: aggravating climate changes and the broad unsustainability crisis manifested through sets of sets of interconnected eco-socio-economic issues and emergencies, and an insufficient response capacity that persists in spite of thick specialist expertise existing in most areas. Ever since the end of the Cold War, true worldwide shocks were thought to be unlikely because global financial-industrial interdependencies had become the norm and geopolitical-economic negotiations emerged as a default approach. But for those who study complex dynamic systems (by sheer necessity in problem solving-oriented research), such cascading events do not surprise: they simply signal that some criticality thresholds (i.e., tipping points between alternative internal equilibrium configurations of those systems) have been reached. Humanity needs options and postponing again isn't one of them anymore.

Many books and papers touch on cities-and-sustainability. But few, if any, do more than informing about some of the problems and eventually proposing laundry lists of 'should' and 'must' advices or making sets of narrow-cover specialist suggestions that leave (knowledge gaps and/or) operational integration towards real solutions to some undefined 'others', or naively presume that integration comes by itself. Meanwhile, real-world crises keep multiplying and aggravating, and the still-rare (difficult but right) holistic projects afield keep lacking operational instruments.

This book needed time precisely because it took on the challenge of solving the methodological puzzle of necessary conditions that precede gap-bridging between what we know and what we do. In order to be an honest author, I wanted to develop a minimal working base of hitherto-missing integrative knowledge-action models, and thus truly assist real-world eco-city projects in spite of the traditional divisions between academic disciplines and between science, business and government.

Based on direct experience in pioneering projects, in-depth literature reviews, and generalized models, this book offers a way for working together productively.

Versailles, France Ioan M. Ciumasu
December 2022

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Main Idea in 100 Words

Teaser Nutshell

The world is not some big-but-ultimately-predictable clockwork. It is a complex dynamic system, i.e., it includes not only order but also thresholds, tensions, unpredictable paths, and surprises. Today, the multiplication of not-just-local crises shows that we have already entered a deep, systemic phase transition to a new long-term structural and functional equilibrium—for better or worse. Like all societal transformations in the past, this one too may last for decades, it will be predominantly disordered, and its end outcome will remain uncertain for a long time. This book offers a practice-oriented tool for learning what matters and staying on course towards a great future.

Contents

Module 1
Definitions and Introductions

1.1 Premises

As a civilized society, we need to become operationally aware that *Homo sapiens* is part of nature and that Humanity depends on the integrity and the proper functioning of our planet's natural bio-physico-chemical processes. At present time, we have lost and need to reestablish a long-term balance with those. But (a) competent action requires preparation and (b) cities, as communities of people, are key to it. This gives the practical reason of the book: to close the gap between what we know and what we do collectively.

This volume is not some vain attempt to capture "all there is to know" on this hard topic or to lure you with "silver bullet" solutions. The book comes from an extended effort beyond armchair 'guiding principles'—at the bleeding edge of pioneering projects that cut across the traditional boundaries dividing academia, business and government, and it offers a hands-on method for efficient orientation, organization, and management eco-city projects. As I am first and foremost a scientist, the book relies firmly on research and science, academic references being used steadily throughout the text. But the book also regards every city as a living space-and-time, a unique combination of attributes and potentials that are uniting minds and destinies, a place with a character and soul of its own: "cities, like dreams, are made of desires and fears, even if the thread of their discourse is secret, their rules are absurd, their perspectives deceitful, and everything conceals something else" [69].

While acknowledging contexts and respecting identities, I started from within my own 'experience as horizon' [328] and took the operational perspective of a project manager seeking to connect science and society through the 'imperative of problem solving' [225]. I gave myself the task of making the right distinctions as justified by experience and knowledge at hand, and I aimed at distilling a set of knowledge-action models for those of us who undertake to solve the 'riddles of planning' [111] without naivety [102, 153] and to navigate between the Scylla and Charybdis of eco-city projects.

I. M. Ciumasu, *Eco-cities*, Green Energy and Technology,
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This book includes three autonomous but complementary modules that can be read and re-read separately. The first introduces the central notions grounding any eco-city scenario and project work. The second describes a procedure for generating coherent and evidence-based sets of scenarios as a basis for eco-city programs (i.e., sets/strings of interrelated projects that are needed for generating relevant solutions for cities). The third presents a set of generalized models that I deemed necessary in the preparation and the course of eco-city projects: main ideas for managers, plus technical details, and some small mathematical 'plug-ins' for experts.

Throughout the book, whenever a technical concept is mentioned for the first time, it is explained in plain words right away. But I encourage you to look it up and to maintain a healthy critical spirit at all times: the professional literatures and networks are brimming with work results that wait to be integrated into new solutions.

I hope that this book will serve as a conversation starter and as a common think-and-do platform for teams that include both non-technical and technical people.

1.2 What Is Sustainable Development?

The Challenge

There are at least two ways to concisely define sustainable development. The first is the general statement in the well-known Brundtland Report of the United Nations' World Commission on Environment and Development [440]: the kind of development that satisfies the needs of the present generation without compromising the possibility of future generations to satisfy theirs. This definition follows the prior emergence of key notions like 'ecology' [179], 'ecosystem' [403, 404], and 'ecosystem ecology' [299]; an understanding that we must protect the long-term socioeconomic value of nature, and related optimistic versus pessimistic takes [52, 75, 165, 170, 183, 233, 265, 308].

The second is directly through the applied systems perspective on sustainability, which points out that any economic system is a sub-system of a social system, itself being a sub-system of a natural/bio-physical system [167, 169, 439]. This nested systems perspective and model links straightforwardly with sustainability studies and with evidence from research, development and innovation (RDI). Crucially, it helps us visualize and understand correctly the unsustainability crisis as an unresolved conflict of priorities between humans and nature (Fig. 1.1), manifested across 'coupled human and natural systems' (CHANS) (Fig. 1.2), i.e., all functional interdependencies between human socio-economic systems and nature as a whole [147, 239, 240].

Because survival is the real top priority of people, human concerns begin with the economic issues, continue with the social issues and end up with the environmental issues. This order largely overlaps short-, medium-, and long-terms, except for emergencies and imminent threats, which trigger the "default crisis management" mode. So, the strength of support for any policy follows this order: economy now > society

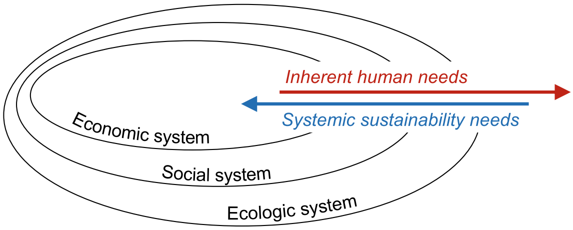


Fig. 1.1 The nested inclusion relation between economic, social, and natural systems. The arrows pointing in opposite directions illustrate the unsustainability crisis as an unresolved conflict of priorities identifiable in humans versus natural systems. Adapted after [99, 103, 167, 169]

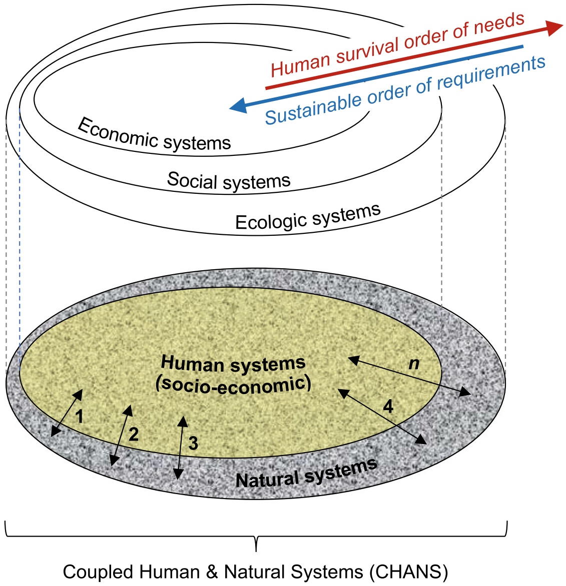


Fig. 1.2 General representation of virtual CHANS case studies (sustainability issues) mapped on the systemic perspective model. Human systems can have various sizes: from a few people to a city to humanity itself. Black double arrows denote interdependencies (couplings)

later > environment later on. But, to be compatible with sustainable development goals, proposed solutions must verify the objective space of possibilities allowed by the natural life-support systems ergo must follow the opposite order of priorities: environment as start basis > society (as next condition) > economy as end outcome.

From an epistemic perspective (also including information science and knowledge organization), the category mapping in Fig. 1.2 can serve as an operational start basis for purpose-driven knowledge integration across disciplines and professions, i.e., knowledge-action models. Seen through the lens of CHANS, "sustainability can be defined operationally as a feasible, desirable set of flows (material, currency, information, energy, individuals, etc.) that can be maintained despite internal changes and changes in the environment" and "sustainable development can be defined as the process by which CHANS can be moved towards sustainability" [257].

In theory, the nested relation between systems opens the way to concrete scenarios and operations [99, 103], in ways that respect both ecological complexity across scales (e.g., [398]) and humanity's aspirations. But can we? Will we? Earth existed without humans for most of its time and will continue to exist if humans disappear, but humans cannot exist without our planet's life-support system. We trust human ingenuity [334], but, even if we colonize other planets, the Earth's "Biosphere 1" (or Technobiosphere [414]) remains necessary and irreplaceable [114, 292].

Importantly, the concept of sustainability as-we-know-it has only gained social traction in recent decades, especially after the United Nations Conference on Environment and Development (UNCED; the so-called Earth Summit in Rio de Janeiro in 1992) [174, 364], but with two important observations. The first is that the core principles of sustainability, namely that (a) we must look beyond short-term interest and that (b) we must insure intergenerational fairness, are in fact part of common-sense wisdom since the dawns of human civilization. One could make a long list of human practices that embody de facto the principle of anticipation and avoidance of collapse by overuse or overexploitation—from the domestication of plants and animals and the multi-annual (long-term) management of those resources since Neolithic, fast-forward to modern day psychology which explains how small children learn (on their individual path to maturity) to refrain from immediate gratification in order to obtain a superior benefit later.

And, the core meaning we now give to the notion of sustainability has been documented for centuries. In 1713, Hans Carl von Carlowitz, a government-appointed manager of natural resources (mines and the forests as wood source for burning in mines) in German Saxony, used the word '*Nachhaltigkeit*' (the German word for Sustainability) with the same meaning that we have today. His book *Sylvicultura Economica* (i.e., forest economics)—which you probably noticed was published 63 years before 1776, the year when (1) Adam Smith's book *The Wealth of Nations* was published (largely regarded as the beginning of modern economics), (2) James Watt built his new steam engine (a key technological event in the Industrial Revolution), and (3) the American Declaration of Independence was made (in a revolution started as an objection to taxation without representation)—can be read today without difficulty and many parts of it are as relevant today as they were then. This is already remarkable. What is even more, when he refers to sustainability, von Carlowitz actually cites other authors (many of which he knew from his professional travels across Europe) that were using this idea for the management of natural resources on the continent for centuries before his time, for example the management of forests in France [173, 373]. And, the history of human civilization in every world region is replete with examples that illustrate the importance of the long-term view and the necessity of understanding the big picture.

In short, the notion that the socio-economic and overall development of Humanity needs to be sustainable (so that we do not undermine ourselves) is really a matter of common sense rediscovered across different sectors of activity, even if this comes in different forms and shapes, after some long and winding roads of history.

'Planetary Boundaries Framework' analyses based on the 'Earth System' approach to modeling of anthropogenic impacts show that 6 out of 9 main boundaries are transgressed (biogeochemical flows; freshwater change; land system change; biosphere integrity; climate change; novel entities (anthropogenic materials))—meaning the loss of 'safe operating space for humanity' (the 'still OK' others are: stratospheric ozone depletion; atmospheric aerosol loading; ocean acidification) [348].

In Principle, Is there a Logical Way Out of this Conundrum? Yes

The unsustainability crisis may appear unsolvable, leading to our "self-organized extinction" [170]. The particular cases (local solutions) when a depletion of local common resource pools have been avoided [9, 308, 309, 310, 311, 312] might be too peculiar to repeat in most other local contexts and across scales; this path is probably only a small part of the story. But an analytic regard at the nested systems model reveals a general knowledge-action model, i.e., a logic direction to follow. Namely, if the two conflicting ordered sets of priorities are projected against the series of phases and steps that are known from the overall process of problem resolution in complex situations [99, 375] it becomes obvious that the two series pertain to two distinct sub-processes inside the full-length cycle of problem resolution (Fig. 1.3).

In other words, the two arrows/ordered sets of priorities (1) occur at different moments of the evolution of the typical in-project conversation taking place in those projects that apply a truly systemic approach (i.e., projects that are complex-enough to cover the entire spectrum of basic domains of expertise), and, therefore, (2) they are actually in a relation of operational complementarity, not reciprocal exclusion. Respectively, they describe the requirements of two functionally distinct halves of a full cycle of problem definition and resolution: the "economy first" set of priorities expresses the order in which different types of concerns need to be assimilated during a holistic, "all-inclusive" definition of a problem faced by people, while "natural environment first" set of priorities shows the order in which knowledge and expertise from different domains must be considered by any project or program seeking to generate evidence-based solutions that can be, objectively speaking, sustainable on the long term [97].

The abstract model above can also be formulated as a set of principles (Box 1.1).

Box 1.1 Basic principles for solving the humans/nature conflict of priorities

- Short-term economic incentives do determine human priorities and the public business agendas
- Longer-term prosperity and economic-business competitiveness do depend specifically on those solutions which increase system sustainability
- Holistic approaches enable new action models. Therefore, short-term/economic priorities of people must be recognized as top incentives to act. This provides the necessary public basis for mobilizing professional networks and projects

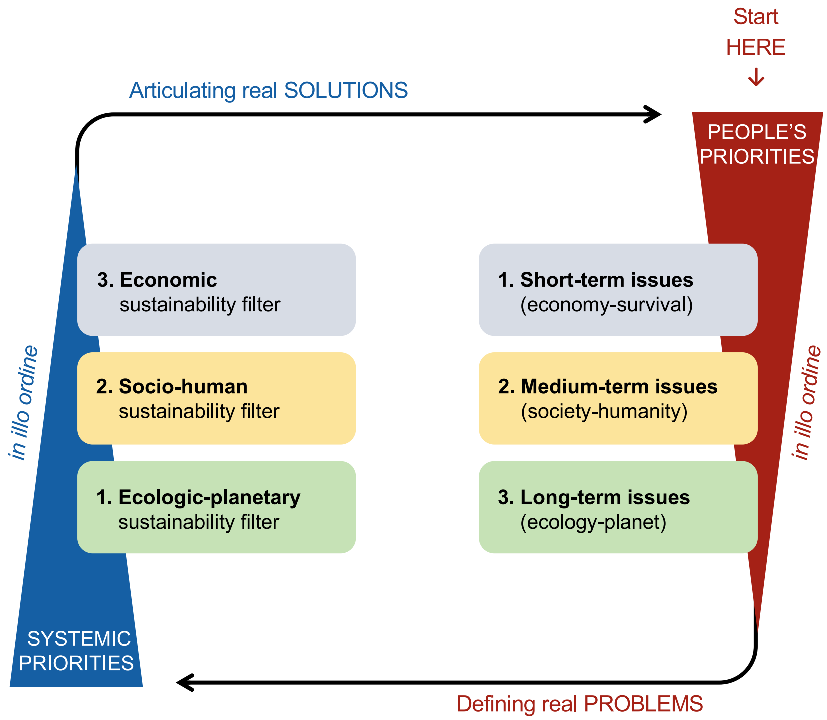


Fig. 1.3 Resolution cycle for the conflict of priorities between human livelihood and sustainable development. The two large arrows chasing each other explicate the conflict of priorities from Fig. 1.1 through projection on different but complementary planes of knowledge representation inside a full iterative (cyclical) process of problem resolution and updating. Numbered boxes indicate steps derived from the nested inclusion relation between economic, social, and natural systems, operationalized as knowledge filters, i.e., lists of domain-specific expert-determined indicators that must be met ("passed") along the process in their order of application inside the two cycle halves. The Latin expression *in illo ordine* means 'in that order'

This model along with its underlying principles represents the start-basis for the methods and scenarios that are being presented in the rest of the book.

Why Hasn't this Solution of Principle Been Applied Yet? ... or, has It?

The short answer is that some progresses are being made, but breakthroughs take time. This systemic nested inclusion relation between nature, society, and economy is not new. To use a beautiful and famous example, Elinor Ostrom (1933–2012), a pioneer of sustainable solution developments and recipient of the Nobel Prize for economic sciences (in 2009), already used in her own work the practice-oriented vocabulary of nested complex dynamic systems and CHANS, such as 'nested sets', 'nested ecosystems' and 'nested enterprises' (e.g., [312]), expressions not unrelated to the so-called 'problem of embeddedness' of economy [172]. Originally trained as a political scientist, she learned whatever it was necessary to better understand the problem and articulate appropriate solutions, thus using sociology, economics, anthropology, and mathematics and donated her Nobel Prize money to the lab she helped establish at her university for the study of local communities in their relation with their natural resources (e.g., [19, 309]).

But, even today, this vocabulary and the systemic perspective on sustainability as a whole is still new—even to the relatively small number of people that know about it (this is the best of cases); or it is simply ignored (this is the case in most fields outside sustainability studies and in society at large).

(As a telling example between brackets, some people, in particular those who see sustainability not as problem to solve but as a fashion to join or/and exploit, still use the logically incorrect representation of sustainability as a small area of "triple overlap" between environment, society, and economy (Fig. 1.4)—as if some part of the economy could exist outside social systems, and, respectively some part of human society could exist outside nature. Such a superficial (non-critical; often opportunistic) regard on sustainable development promotes falsehood and undermines functional science-society relations, thus creating more harm than good).

We Need Adequate Knowledge Representation and Integration

Far from being anodyne, the difference between a correct and an incorrect model is fundamental because the respective sets of definitions of categories and the logical relations between them are semantically and mathematically non-identical. Adequate and correct representations of real systems make the difference between success and

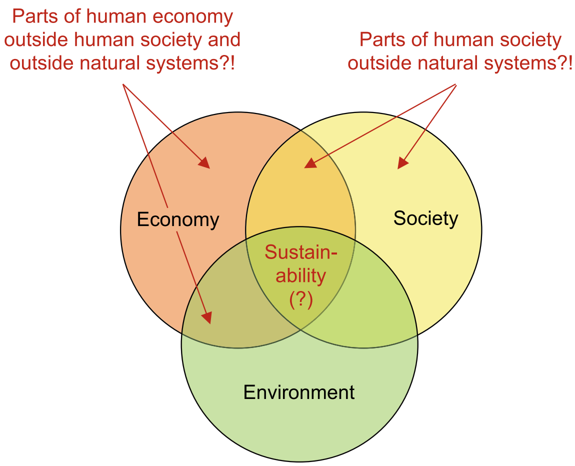


Fig. 1.4 Incorrect representation of sustainability. This now-outdated model had the merit that it recognized the problem of unsustainability, but then it used a vague definition (the initial, necessary compromise lowest common denominator between competing political views in the 90's). Science-wise, it fails to see humans as part of nature and tries to imagine the solution ("sustainability") by using the very same mindset that created the problem in the first place (i.e., incongruous representations of reality coming from previously separate fields) combined with the scientifically naive idea that nature is the environment "out there" instead of a physical reality everywhere

failure. Admittedly, the comparatively incorrect model shown above is a technically correct illustration of the mistaken views that characterize unsustainable development because it shows well the problem of knowledge fragmentation. This issue is important because misrepresentations may induce people to think that sustainability is a “nice-to-have” (not a “must”) and will prevent them from seeing the “world of options” behind the problem [312]. Worse, such mistakes can trigger adversarial attitudes and scientifically unjustified beliefs, e.g., that sustainability was an impractical concept to be dismissed as an eccentricity or luxury.

Science works with proofs: it provides a basis for coherent action but also evolves with time. Bibliometric analyses (i.e., the study of trends in science reports) show that the field of ‘sustainability studies’ is not monolithic. It is actually a constellation of topics that reflect a multitude of perspectives that also changes in time: as our needs evolve and knowledge accumulates, new questions are being asked and thus science moves to a next logical stage. Figure 1.5 shows that the root label ‘system’ only emerged in the sustainability studies landscape by 2014, probably due to a growing need for operational integration of all the knowledge that has been accumulating.

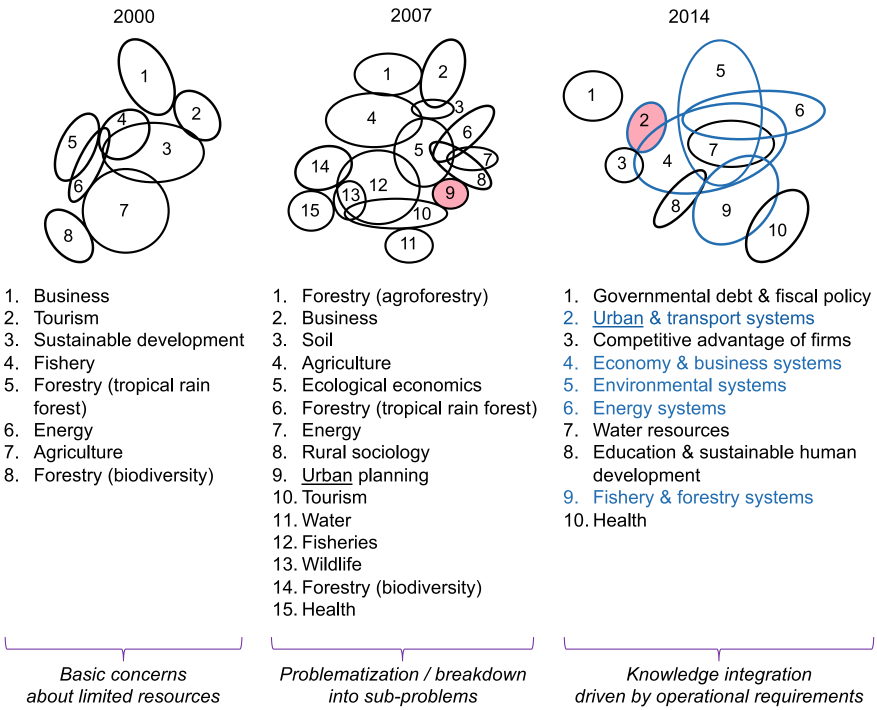


Fig. 1.5 Evolution of the main themes in the literature on sustainability studies. Ellipses reflect the size (volume) and distances (and overlaps) between sub-domains identified in research publications. Blue outlines mark the presence of the category ‘system’; rosy fills signals ‘urban’. *Source* Redrawn based on the bibliometric method (citation network analysis; topological clustering of terms identified in the titles of published sustainability studies) used by Kajikawa et al. [215, 216]

In this analysis, one notices the central place of the year 2007—in many respects, a peak of activity. Interestingly, 2007 is also when sustainability studies begun to be officially recognized as an established field: a historic moment in time when it ceased being just an eclectic area of shared concerns across (and with contributions from) traditional disciplines and actually gained "a room of its own" in academic institutions, notably in terms of dedicated funding [106]. Of course, that recognition does not imply that the integration of knowledge across (older or/and newer) fields had been achieved. It only shows (a) that this recognition came after efforts to problematize sustainable development in specific real-word contexts (after a decade-long period of societal introspection and intellectual redefinition of the relation between Humanity and its home planet) and (b) that operational integration (driven by concrete problem-solving) had become the next logical phase.

One also observes that 2007 is the year when 'urban' emerged as a core designation within the broad picture of sustainability studies. Arguably, this is more than just a coincidence, and the next sub-section of this book will focus on the place of cities in the whole challenge of sustainability. But before doing that, one last important question must be asked in this introduction: *How do the 'human and natural system couplings' (HANSC) from Fig. 1.2 translate into operational requirements?*

As explained below, all real systems (natural, human, or man-made) are complex dynamic systems (CDS), and agent-based modeling (ABM) is the usual way to represent them. In short, a core answer to the question above, and a starting point for further elaborations, is provided in Fig. 1.6.

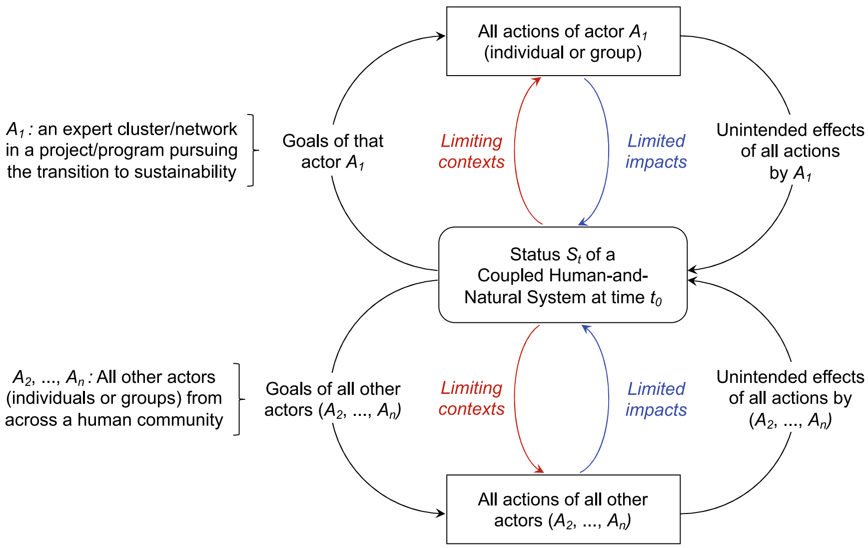


Fig. 1.6 General ABM model of the coupled feed-back loops involved in CDS: an abstract representation of the sum of sums of interdependencies, constraints, and uncertainties connecting actors and CHANS overall or chosen target HANSC inside CHANS. *Source* Redrawn based on [230, 396]

In practice, CDS are called just ‘complex systems’ or just ‘systems’, as near all real systems are complex and dynamic (bar the simplest) (Fig. 1.7); or the term ‘complex adaptive systems’ (CAS; CDS that are able to change based on learning from experience) is used instead (see, e.g., [76]). Examples come from all domains: the biosphere, the ecosystems, the colonies of social animals (insects, birds, mammals, etc.), the immune system, the brain, the developing embryo and the living cell itself; social organization of people (cultures, political parties, communities); stock markets, manufacturing, businesses, supply chains, and innovation systems (for a review, see, e.g., [384], also [270]); cities (e.g., [150]), urban health and wellbeing (e.g., [161, 241, 358, 411]), and so forth.

This complex causality means that realistic (ergo sustainable) solutions can only (1) come from a good understanding of the target systems and (2) be multi-purpose. The general problem-resolution cycle in Fig. 1.3 already reflects this reality.

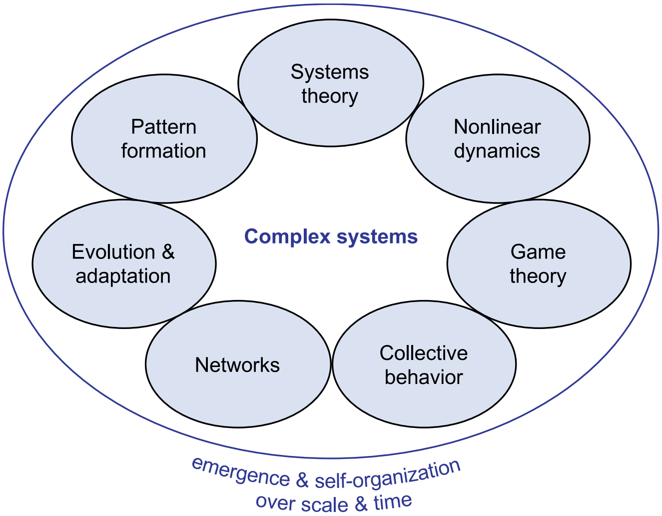
At the wider societal level, we need to reach the point where most of us understand that we all live in CDS, not in some deterministic world-as-a-clock “machine”. The mechanistic predictions based on Newtonian physics are but particular cases of the physical world and only apply in the “easy world” between certain boundaries. This is why experimental physics works by isolating some phenomena (eliminating all the rest) in laboratory. This reductionist approach helps us in the search for mechanisms (when and where they exist), but it always comes together with specifications about the boundaries within which every mechanism exists. When more parameters from the real-world are added, human planning quickly loses realism. Instead, we must understand and operate with the attributes of the CDS (Table 1.1).

To paraphrase a famous quote, preparing for the future is 1% planning and 99% learning. That is, we must build capacity to learn and to act based on learned lessons.

Indeed, the whole discussion about successful eco-city projects is about everyday relentless development of competence to carry out such projects and thus becoming better and better at it—in short, learning-by-doing and doing-by-learning [91, 92]. And, the same applies to sustainability transitions in society in general [163, 244, 245, 268].

Surely, learning our way towards a goal does not mean that everyone must become an expert in natural, social, and economic complex systems. Instead, a truly holistic project (1) must include enough expertise from different fields (even if that means very many people and organizations) so that the project team as-a-whole can cover all needs and (2) must find/develop enough common grounds by openly discussing their differences and agreeing on a minimum core of shared values and knowledge. This learning means also that we must work with nature, not against it. This starts with facing complexity instead of pretending it isn’t there just because it’s difficult, and continues with building the means for addressing that complexity—through a perpetual exercise of cultivating visibility (via realist scenario set iterations) while integrating knowledge as it comes, and as developed, in practice via disciplined experimentation ([96]; details discussed in Chap. 3, Sect. 3.8; see also the discussion at the end of Sect. 1.3 about cities as loci of experimentation).

These being said, it becomes clear that objective systemic ‘complexity’, a demonstrable physical reality, must not be confused (like it is often the case in daily life)



Systems theory	Feedback loops, entropy, homeostasis, autopoiesis, information, computation, cybernetics, self-reference, sense-making, complexity measurement
Pattern formation	Partial differential equations, fractals, dissipative structures, reaction-diffusion, self-replication, percolation, cellular automata, geomorphology, spatial ecology
Nonlinear dynamics	Ordinary differential equations, time series analysis, phase space, attractors, iterative maps, stability analysis, chaos, bifurcations, population dynamics
Evolution & adaptation	Evolutionary computation, artificial neural networks, machine learning, natural computation, viable system theory, artificial intelligence, genetic algorithms
Game theory	Bounded rationality, rational vs. irrational decisions, social dilemmas, n-person Prisoner's Dilemma, evolutionary game theory, networked games
Networks	Graph theory, scale-free networks, small-world effect, social network analysis, community identification, motifs, dynamic/adaptive networks, systems biology
Collective behavior	Agent-based modeling, collective intelligence, swarm behavior, ant colony optimization, synchronization, self-organized criticality, phase transitions

Fig. 1.7 A basic cloud-of-clouds model of (a selection of) topics in the study of complex systems. *Source* Modified after [67]

with perceived situational 'complicatedness'—a managerial contingency. In short, complexity and complicatedness are in fact not interchangeable (unless everybody in the conversation is known to be familiar with the difference between the two).

In business environments, there are heuristic tools for orientation in daily works and help with making the right distinctions, at least at a basic "sense-making" level. For example, the Cynefin framework use 'complicated' and 'complex' as labels for two successive stages on a gradient between what is 'simple' ('obvious' or 'clear') and what is identified as 'chaotic' situations (e.g., [286, 390]). Although this kind of tool is not real science-based knowledge management methods, it has the merit that

Table 1.1 Key features of complex systems

Attribute	Short definition (main idea)
Complexity	A property that cannot be inferred from system components; this is qualitatively different from complicatedness/multiplicity. Models that ignore this property (even if motivated by the need to gain mathematical-operational tractability) or choose to treat it as noise will inevitably be inaccurate and therefore useless in the real-world
Network character	Operational representability as networks: sets of sets of objects (and relations between them) coded as mathematical graphs (dots/vertices connected by links/edges; more technical details in Chap. 3, Sect. 3.2, Box 3.1). This allows the detailed study of individual and collective properties and interactions between systems components
Emergent properties and behaviors	A unique property of a system that cannot be explained as a (or reduced to the) sum of its components, as it does not exist in those components, and only appears when these components interact as a system. Sometimes, they can be modelled/visualized as network effects
Self-organization	Order resulted as emergent property (unforeseen or unplanned); called 'self-organization'/'spontaneous order' in natural/social sciences
Nonlinear dynamics	Thresholds, steady-states between them & less ordered ("chaotic") transitions between those; feedback loops, inherent uncertainty, 'power law' (fractal) patterns; self-organized criticality, i.e., non-manifest accumulation of tension behind equilibrium thresholds followed by sudden re-equilibration events, e.g., "the straw that broke the back of the camel"

it can contribute to some extent (at least at the beginning, for starting conversations and some exploratory works) in the managing the uncertainties of planning in various areas that involve science and society alike, from ecosystems [34] to infrastructure safety [194].

1.3 What Is a City?

The Different Perspectives

What is a city? The simple definition from human geography is: a large human settlement (smaller ones being towns, villages, and hamlets). Urban geography studies urban processes, thus bringing together aspects from the biophysical, social, and economic systems. Different fields of study have different perspectives, reflecting their particular questions of interest (Table 1.2), but ultimately, a city is its people.

In this sense, some historic details stand out as cultural references for the present, but a holistic perspective is a logical next step in our quest to truly understand what is a city. This is not just a matter of intellectual curiosity: looking deep into this matter is to look deep into the soul of Humanity to see its past, present and future. To this

Table 1.2 Domain-specific perspectives upon cities (a non-exhaustive list)

From the view point of:	A city is …
Physics	A complex system in space–time; flows of matter-energy/information
Engineering	A built environment, with all related infrastructures and appliances
Biology; ecology	A colony of species *Homo sapiens*[a]; a disturbance of local ecosystems
Chemistry; geology	A source/sink in biogeochemical cycles; a feature of *Anthropocene*[b]
Physical geography	A form of landscape modification, covering about 3% of Earth's land
History; archaeology	A location of events and material records thereof; a culture and power hub
Business; lifestyle	A hub of knowledge, learning and innovation; an engine of progress
Economics	A place of production, exchange and consumption of goods and services
Sociology	A social construct, a place of high diversity and density of interactions
Politics	A constituency, a spectrum of organizational preferences and choices

[a]In the usual terms of anatomical modernity and behavioral complexity, humans begun to exist approximately 300,000 years ago although the technical discussion is more nuanced (for a recent summary, see [368]). On a geological time-scale, this means:
… 0.18% of the history of mammals (which emerged ca. 168 million years ago);
… 0.05% of the existence of animals on Earth (earliest evidence from 580 million years ago);
… 0.008% of the existence of life on Earth (earliest evidence from 3.7 billion years ago);
… 0.0066% of the existence of Planet Earth (which formed 4.54 billion years ago);
… and knowing that less than 1% of all species that ever existed on Earth are still alive
[b]Because humans started to be a geological force with impacts on the planet's geosphere, hydrosphere, biosphere/ecosphere, and atmosphere, and generate an anthroposphere (or 'technosphere', i.e., that part of the environment that is made or modified by humans for their habitation and activities, including all artifacts, e.g., artificial satellites), geologists are debating whether we are in a distinct geological epoch (sub-division of geological time) called 'Anthropocene' [117, 141, 297, 395]. To date, an official decision has not been made, but 'pro' arguments keep accumulating. In any case, current evidence suggests (a) that behavioral changes connected to lithic technology goes back to 3.3 million years ago, at the origin of genus *Homo*, i.e., before the emergence of species *Homo sapiens* 2.8 million years ago [60, 184, 435], see also [16, 189, 204, 277, 376] and (b) that human exploratory behavior and "learner-driven innovation" was at the origin of lithic cultures already [445]. All in all, because (1) tools and tool-users co-evolve in a virtuous circle of success and capability and (2) as tools are known from hominids preceding *Homo sapiens*, one can logically argue that tools made us human [289]

aim, I will briefly evoke three moments in the existence of humanity before going on to the other managerial aspects that matter for current and future projects.

Firstly, after the defeat of the Greeks at Thermopylae in 480 BCE (by the Persians led by Darius, "the King of kings") and in the expectation of a decisive confrontation which they could only hope to win by strategically retreating on land and engaging the enemy at sea, Themistocles persuaded the Athenians to abandon their old city, essentially because "a city is not its stones but its people". Afterwards they saw their city burned to the ground but they also won the war and returned to rebuild Athens to an even greater glory and as a major socio-economic, cultural and political hub. This episode reminds us that a city is much more than what meets the eye.

Secondly, cities actually appeared in the history of humanity when a great number of people came together, i.e., gravitated around and concentrated at a given location, this spatio-temporal movement generating (a) complex forms of organization which were necessary to insure co-existence in a crowded area and (b) a sophistication of life which was not possible in scattered agricultural populations and which further promoted demographic growth and attracted other people. In this historical process, candidates to the status of proto-cities making the transition from rural to urban (or as "social experiments"; presumably different from a city-proper by a lack of planning and centralized rule) are known *inter alia* from:

- the Middle East, with settlements starting since ca. 9000 BCE but distinguishable as proto-cities especially since ca. 4000 BCE, notably the Ancient Jericho in Palestine (Tell es-Sultan; in Hebrew and Arabic, 'tell' means mound or hill), Brak (Tell Brak) and perhaps also the low-density, special purpose (manufacturing) settlement of Khirbat al-Fakhar, both in North-Eastern Syria, and Çatalhöyük in Central Anatolia. All of these predate the indisputably urban settlement of Uruk, from ca. 3100 BCE in Southern Irak (see, e.g., [262, 296, 421]).
- and Central Europe (the Cucuteni-Trypillia culture, ca 5500–2750 BCE overall, with large settlements known from the Middle Period of this culture, ca. 4000–3500 BCE) (see, e.g., [20, 77, 130, 273, 397, 412], see also [441]).

For the purpose of this book, I will illustrate the following short discussion mostly with details from the latter region (because I am familiar with it, as a native).

While the debate is still ongoing about which large settlement(s) from the dawns of human urbanity can be considered essentially a city or only pre-urban, a comparative ("traditional") disciplinary versus ("modern") holistic perspectives is interesting and informative for the fundamental question "*What is a city?*" that needs to be asked by the manager(s) of any project aiming at improving our cities today.

From the disciplinary historical and archeological perspective (also included in Table 1.2), the main tentative cut-off criteria tend to relate to whether or not the researcher can distinguish in the remains (or in the technical reconstitutions) of such settlements the presence of any form of 'division of labor' and especially 'social stratification', as these two aspects are regarded as proxy indicators of a complex civilization.

Through these lenses, the urban-or-not decision relies almost exclusively on the interpretation of the material evidence discovered so far at the study site and every gap in the used data, information and knowledge can hamper the recognition of an urban character in large settlements. However, understanding the beginnings of urban life requires that the (perfectly legitimate) disciplinary perspective mentioned here can and must be complemented by other disciplines and view angles, in a holistic concert of science. Concretely, from a current complex systems perspective, it is physically impossible that very large numbers of people (often up to 5, 10, 20 thousand inhabitants or more) known from the Neolithic and the transitional Chalcolithic a.k.a. (Eneolithic or Copper Age, i.e., agriculturalists with some influence from hunter-gatherers,) could actually co-exist without a 'next-level' complexity of social organization, regardless of how "peaceful" these populations might have been. (And the Cucuteni-Trypillia culture is thought to have been peaceful, because of a lack of archaeological evidence of abundant remains of weapons and warfare). On the contrary, based on our current understanding of Humanity, the archaeological evidence of the long-time coexistence of such a huge number of Neolithic-Chalcolithic people at one single site simply indicate either that (i) some inexplicable lack of evidence (some 'unknown unknown') completely distorted our image about warfare in that civilization or that (ii) warfare was not needed much because people had other ways to deal with each other, i.e., a functional complex socio-economic structure.

Technically, any student of the 'urban phenomenon' that would choose to ignore the simple observation summarized above (and easily verifiable in the literature and in real life) would not practice science but merely some naive form of empiricism (for a discussion about the Scientific Methods, see the summary provided in Sect. 3.7 and the references therein). In the following paragraphs, I will try to just briefly show why, starting from existing archaeological evidence about proto-cities, placed in context and in the big picture. I do this because I think this kind of exercise is useful in two ways: in the true study of cities (as a basis for improving cities), there is nothing healthier and more necessary than questioning given assumptions; and, in so doing, we actually arrive at some of the core questions and methodologies that can help us do what we preach: the holistic approach.

Let us start with the obvious observation that some arguments against the urban character of large Neolithic settlements often point to certain key factors may have actually favored a peaceful coexistence: (a) contrary to some present myths, those people (at least in the Cucuteni-Trypillia culture used here as lead example) actually experienced an abundance of food in their natural environment (not scarcity), so there was no need for a cut-throat battle for it, and (b) abundant archaeological evidence exists which can be interpreted as proof that those were matriarchal societies (which are presumed to be less prone to war), and, moreover, weapon remains are not particularly abundant in these archeological sites. However, these arguments (even if accepted as complete, which is not a given) might perhaps be enough to explain peaceful coexistence in the small-size settlements of that culture, also knowing that this culture included settlements of all sizes, but such explanations do not hold for large and densely populated settlements: there, we have a very different discussion.

We already know that people from Neolithic already had general anatomical and psychological modernity (these features have already been achieved about 50,000 years ago, and here we are talking about people from 5000 to 10,000 years ago). Given this simple fact, assuming that life in a settlement of 10,000 individuals was essentially the same as life in a settlement of few tens of individuals would be naive (and therefore such an argument would be flawed from the beginning). Quite on the contrary, the fact that such high concentrations of people were possible at all is in itself a hard proof under our eyes that people in such large settlements had already achieved a certain, different level of social organization. In addition, not all Neolithic sites had the same level of connectivity with other sites, the most connected ones (in a regional network of sites) having the conditions for more sophisticated social life than the sites that would be more marginal in (lesser connectivity) with a given Neolithic culture. Realistically, these factors cannot be assumed as irrelevant.

On top of that, recent studies using remote sensing technologies are already bringing material evidence for the presence of economic and social status differences between inhabitants, along the internal structure and organization of the settlement.

For example, here is a very telling extract from a study using remote sensing technologies that enabled full-picture study of a newly discovered Cucuteni small site in Romania [20]:

> This internal village structure linked with the topography of the site, with well-defined buildings and open spaces, pathways to the fortifications, fortified elements, etc., involved an impressive amount of labor which clearly emphasizes the existence of a well-established social organization, following the rules established within Cucuteni communities. The results of this study, together with those obtained by our team at other Cucutenian sites such as Ripiceni–Holm, Brătești–Dealul Chicera, Fulgeriș–La Trei Cireși, Hândrești–Dăiceni, etc., with their varied typology of documented internal organizations, shows how they anticipate the later evolution of the mega-sites and giant settlements seen in the Republic of Moldova and Ukraine.
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> The existence in our case study of a fortified enclosure with semi-circular ditches and palisades in the core area, and the presence of exterior habitations surrounded by three narrow curvilinear ditches, shows a clear distinction that should be made between defensive elements and ones with a symbolic purpose. In other words, our study documents a novel situation that could provide clarifications regarding the functionality of these construction works, a topic that divides the scientific community and offers occasional ungrounded opinions that are intensely debated in the professional literature. (…) In view of these results, the use of non-invasive investigations in researching Eneolithic sites belonging to the Cucuteni-Trypillia cultural complex now seems mandatory. They permit creation of integrated research results that can significantly contribute to prioritizing the main directions of future work and a reassessment of archaeological excavation strategies.

Then, a second study on a large Cucuteni-Tripillia mega-site in Ukraine (called Maidanetske) [327] indicates significant difference in social and economic status between the dwellings located in different structures of the same settlement (on top of the many interesting details known from that culture, like a rich material and spiritual life and the deliberate burning of the houses at the end of a cycle of 75–80 years and new houses ae being built on top of those). Here are two snippets from that study:

> About 2300 house remains are visible in the magnetic map (...). The magnetic anomalies of the burned buildings are arranged along concentric ellipses around an inner vacant space. A corridor, which is free of houses, divides the settlement into an inner and outer part. The houses that are directly located along this corridor belong to the so-called “ring corridor”. Inside this free space are the megastructures, buildings with a different architecture than houses. North, outside of the outermost ellipse, remains of an older settlement are visible.
>
> The buildings are arranged along concentric ellipses around an inner vacant space and a vacant ring. Buildings along this ring corridor have increased total magnetic moments. The total magnetic moment indicates the remaining building material and therefore the architecture. Lastly, architecture can reflect economic or social status. Consequently, the increased magnetic moment of buildings along the ring corridor indicates a higher economic or social status.

This echoes an earlier one [199], which argues based on available evidence (difference between building types and how these evolve in time) that these mega-settlements look like they might have harbored precisely the transformation of social organization from more egalitarian to more centralized and more socially stratified, with potential social consequences in the complex dynamics in the subsequent eras.

Furthermore, even the great similarity between houses (which is sometimes hastily interpreted as a sufficient proof of an egalitarian society), when it occurs, is not necessarily an indication of similarity in social status: it is also a matter of efficiency based on the construction technology available at the time and is to be expected if there is a division of labor where specialized builders lead the constructions (the same way, specialized potters do the pottery at the high level of refinement and extent known from this culture): serial production of buildings by (or under the supervision of) specialized builders which use some general templates (for basic shape and spatial patterns) to facilitate their work and then add or not more features and/or details depending on context (today, we call it “customization”).

More broadly, and as argued elsewhere by Blanke and Walmsley [46], in order to properly understand systemic features of a city in given culture (specifically, the resilience and evolution capacity of the cities in the region known as ‘Decapolis’, i.e., “Ten Cities” in Greek, in southern Levant), archaeological evidence must not be interpreted strictly within the narrow confines of one discipline but needs to be corroborated with evidence from other fields of investigation.

For instance, in our example from Central Europe, we also know that one of the precursors of the Cucuteni-Trypillia culture mentioned above was the Vinča culture (or Vincea in Romanian), which is well-known for the *Tărtăria Tablets* (ca. 5300 BC; present day Romania). These objects display the world’s first known and undisputed example of a Proto-writing System, i.e., visible marks communicating limited information, using ideographic and symbolic systems (in this case, along symbolic traditions from early Neolithic).

Although Cucuteni-Trypillia culture itself is sometimes described by archeologists as “static” because of its remarkable continuity, it shows abundant proofs of abstract thinking and great material achievements. One example is the emergence in this culture of the earliest forms of potter’s wheel, and the wheeled toys (miniature models of animals and cups) discovered in this culture indicate the clear knowledge that objects can be pulled on wheels, which further suggests this mechanism was used in daily practice (although no evidence conserved well-enough to be discovered in modern times—most likely because these objects were made of wood, and we know that the local climate does not favor the conservation of wood artifacts). The very same is true about textiles: their existence is known in this culture from imprints on pottery, but their perishable nature made that they didn’t conserve. And the pottery itself (one of the most important type of evidence from Cucuteni-Trypillia settlements) is one of great complexity of shapes and chromatics. Interestingly, some of the substances/materials used in this pottery are rare and can only be obtained from very few places across this entire area (of over 300,000 square kilometers) and needed to be brought from neighboring cultures further away.

When taken together and placed in a holistic context, such details indicate not only a remarkable diversity of ideas and practices but also specialized skills, which logically implies a division of labor and trade across large geographic areas. Basically, we talk about a complex society which cannot be artificially reduced to local rurality and agricultural subsistence—even though agriculture did (inevitably) play a big role in the sustenance of all known proto-cities and 'first true cities'.

Indeed, the high homogeneity known from the Cucuteni-Trypillia culture is to be expected if local settlements across the entire region are regarded as nodes that are communicating with each other in a network of settlements spanning the culture and further communicating with neighboring cultures. And there is no reason whatsoever to presume that they did not communicate; quite the opposite is true: there is evidence of communication capacity. We know that individuals from hunter-gatherer societies were capable of long-rage walking covering very long distances (hundreds of kilometers) in a relatively short period of time (weeks and months), i.e., humans can do that. Also, the Cucuteni-Trypillia culture was also close to the area where horses have been domesticated (in fact there is evidence of horse remains in this culture but it is not clear whether they were already domestic or just wild horses hunted for food) and we know that they were already using wheels. And, we are talking about a civilization that lasted for thousands of years. In short, communication and interactions (between the settlements located inside a regional civilization) must be recognized as a factor.

Once this recognition is made, any simple network analysis (based on current, well-established methods; see Table 1.3 for a brief introduction) or just a mental exercise using the principles of network analysis predicts right away that (1) some settlements are more central than others and in time they will gradually become more influential (i.e., they will gain a 'higher centrality' within the network), which will further stimulate their growth and influence, and (2) the most influential settlements will serve as cultural diffusion centers facilitating (and speeding up) exchanges and the spread of innovations across the entire culture. In other words, the simple network mechanics results in (1) a "horizontal" gain in homogeneity across the network and (2) a "vertical" gain in heterogeneity inside the strongest nodes of the network. Additionally, each settlement anywhere anytime is a network of individuals interacting with each other; in time, some individuals (or groups of tightly linked individuals, called "cliques" in network analysis) which are more central (i.e., have the highest numbers of connections) will inevitably become more influential because their centrality makes them looked-for because they serve as "shortcuts" between any two individuals in that network of person-to-person interactions. And, logically, the larger a settlement is/becomes, the more structured it will become internally, which makes inevitable role specializations and division of labor between individuals and between groups (i.e., social differentiation).

In this sense, another aspect was observed in the literature precisely about Cucuteni-Trypillia mega-sites: larger population sizes logically imply higher collective computational abilities of these settlements [278]. This is important, because we also know that major innovations and societal changes (the Industrial Revolution from the eighteenth century included) happen in situations where there are many

Table 1.3 Some general approaches to modeling cities as whole systems or/and units

Model type	Main idea
Adaptive cycle	A repeatable sequence of phases ("reorganization, exploitation, conservation, release"; or "transformation, golden age, decay, crisis") as a basic pattern of change-and-stability in the evolution of a city in its context, usually represented as a Möbius band (or a large infinite sign) [129, 176, 202, 444]
Nested networks	These are mathematical graphs: sets of vertices/dots (agents) and edges (links), as briefly mentioned also in Table 1.1; for more about graphs, see also Chap. 3, Sect. 3.2, Box 1.9). Thus, a city can be modeled as a high-density subnetwork (cluster) within wider (regional and global) networks while itself including smaller networks. (e.g., [182, 229, 281, 282]). Many real-world interactions between groups of agents cannot be described only as sums of pairwise interactions, but mathematics give us further tools, e.g., higher-order interactions involving groups of 3 or more vertices: hypergraphs, which are graphs in which an edge can simultaneously join any number of vertices (so, explicit pairwise relations are not needed), and simplicial complexes which include units like vertices, edges and triangles (they are more constrained than the hypergraphs, providing an intermediate level of structuring) (for a discussion on mathematical and physical basics, see, e.g., [26, 27]) Given the huge amount of data and information involved, also relevant is the notion of 'smart city', which refers to computer-aided automation and optimization of functions and processes within cities, which is part of the discussion on eco-cities when reasonable [41, 47, 118, 276, 285, 300, 443], [209] So, in the systems perspective on sustainability described above, each sustainability filter (SF) is definable as a hypergraph, and different interactions within or between SFs can be represented using classical network graphs, simplicial complexes or hypergraphs; then, periodic processes and temporal dynamics can be represented as coupled oscillators
Urban metabolism (practice-oriented metaphor)	A bounded system model (with in-/outputs) which identifies and quantifies relevant fluxes of matter-energy (and therefore also information). This makes a city system describable by basic and applied science (physics, chemistry, biology/ecology) and mathematics as a basis for the further research on various questions of interest (from sociology, economics, engineering, etc.), and for generating knowledge-action models and solutions to multi-dimensional problems. Recently, a related notion integrates smart city ideals: smart urban metabolism [42, 43, 121, 380, 381]

human agents interacting with each other, i.e., an "*emerging social brain*" [405]. In other words, Cucuteni-Trypillia mega-sites and other proto-cities or first cities had a major role in the evolution of humanity to urbanity because they represented "places where things happen". For what this book is concerned, namely system-level urban transformations, this is probably the most important aspect of proto- and first cities.

Put together, the two dynamics mentioned above (internal and external to a given node-settlement), one easily sees how population size and social structuring go hand-in-hand, generating a "next level" type of social organization (see also [441]). Mathematically, one can easily notice about this reasoning that "it's elementary!" Then, in research practice, this same reasoning can help explain the the remarkably persistent cultural commonality (a shared local Hellenistic culture of Eastern Mediterranean) across the Decapolis network of cities studied by Blankey and Walmsley [46] mentioned above, and their common hinterland.

Finally for this second aspect, the point with all this discussion (and in light of the different debates going on in the literature) is not whether a certain ancient human settlement is to be declared "urban" or not. After all, the more we go back in history towards the origin of cities, the harder it is to find abundant evidence (and the more tempted we are to apply present time (and methodological contingent) criteria to those very different contexts) (for a discussion about the issue, see, e.g., [162]). The point (from a system, operational, and holistic perspective, as taken in this book) is that the becoming of a city is about a process of transformation that is led by both internal and external forces in a complex nonlinear dynamic that can see situations of long-term stability and (relatively) fast change at historical scales. It is less about "officially" pinpointing a specific moment-and-location and more about understanding the process of evolution of human settlements in their context because this is what makes a city (and any human settlement) what it is. In this sense, this discussion made here is more in line with the *Functional Model* used in modern archaeology for (1) understanding a city in relation to its hinterland (and context in general) and (2) "to study urban sites from the point of view of evolving social networks" ([274], see also, [44, 388, 433]). For a modern social network analysis of ancient proto-cities see ([156, 157], for the networks of settlements in pre-Roman Central Italy) and ([259], for a case study of internal networks inside a proto-city—Çatalhöyük, Turkey). For reviews of social network analysis (and related complexity science) methods in archaeology, see [61, 269]. For a modern Big Picture perspective of the evolution of cities ("*Where do cities come from and Where are they going to? Modelling past and present agglomerations to understand urban ways of life*"); see [158].

For concrete illustration of the point made above with the example of Cucuteni-Trypillia 'mega-sites', I find it particularly useful to put here an extract from the conclusions from [157] in their study of the evolution of a regional network of settlements which resulted in the emergence of the city of Rome as dominant in its region (*Latium Vetus*) and beyond:

> This work has enabled the definition of a unified index combining all the useful information from infrastructure network topology in a compact expression that provides a single criterion to rank the settlements we have represented as the nodes of a system of connections. (…).