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A holonic framework to understand and apply information processes in evolutionary economics: survey and proposal

A. Madureira[1] · F. den Hartog[2] · N. Baken[1,3]

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Abstract Economists unsatisfied with the basic neoclassical assumptions of rational economic actors and economic evolution towards equilibrium states founded the *evolutionary economic* approach. Their goal was to provide more realistic assumptions regarding economic agents and their institutional environments. The Modern Synthesis (MS), the current conceptual paradigm for biological evolution, was used as a source of inspiration for conceptual development. Along the biologically inspired line of thought, the Generalized Darwinism (GD) initiative relies on the abstraction of the MS to provide a unifying conceptual framework for evolutionary economics. Despite its merits, GD has been subject to criticism, particularly regarding its level of abstractness and lack of an explicit account of the social and cognitive processes that drive economic evolution. The goal of this article is to introduce and explore an alternative conceptual framework for evolutionary economics: the Holonic Framework (HF). Contrary to GD, the HF is not biologically inspired, but builds upon the

✉ A. Madureira
ajpsmadureira@gmail.com

F. den Hartog
frank.denhartog@tno.nl

N. Baken
nico.baken@kpn.com

1 Delft University of Technology, PO Box 5, 2600 AA Delft, The Netherlands

2 TNO, PO Box 5050, 2600 GB Delft, The Netherlands

3 Royal KPN, PO Box 30000, 2500 GA The Hague, The Netherlands

body of literature on the value of digital information networks. We discuss the analytical strengths and limitations of the HF relative to GD in light of several aspects pertinent to evolutionary economics (e.g. self-organization, culture, cognition, cooperation). Finally, by referring to an operationalization of the HF using Eurostat data, we show its practical strengths in comparison to GD.

Keywords Evolution · Evolutionary economics · Generalized darwinism · Modern synthesis · Holonic framework · Information networks

1 Introduction

Neoclassical economic theory based on Walrasian general equilibrium theory devised in the 19th century continues to dominate economic thinking. The general equilibrium approach produces an aggregated representation of the economy with two main assumptions [188]: 1) rational behavior of economic actors (e.g. firms as cost minimizers and households as utility maximizers) and their constraints (e.g. technological processes); and 2) a market equilibrium solution, in the sense that for each commodity and factor, their prices always adjust to a level such that demands added across all the actors do not exceed total supplies. Modern developments, such as the introduction of information asymmetries, did not involve alteration of the neoclassical theory's fundamental foundations, but, instead, resulted in more complex outcomes (e.g. multiple equilibria) [64].

Although with little initial impact in mainstream economics, the basic assumptions in the neoclassical theory of rationality and equilibrium have been questioned for decades. For example, Schumpeter questioned the economy being in a state of equilibrium: "development (...) is a distinct phenomenon, entirely foreign to what may be observed in the circular flow or in the tendency towards equilibrium. It is spontaneous and discontinuous change in the channels of the flow, disturbance of equilibrium, which forever alters and displaces the equilibrium state previously existing" [161]. Economists interested in a conceptualization of economic evolution with more realistic assumptions regarding economic agents and their institutional environments founded the *evolutionary economic* approach [19, 172]. Several recent survey articles emphasize that an agreement on basic aspects of evolutionary economics is still missing [15, 79, 182, 192]. Nevertheless, there is an almost common consensus on structuring the economic process inductively rather than towards an equilibrium, with the behavior of the collective agents characterized by bounded rationality [57, 119, 165]. Institutionalist economists focused on the impact of cultural evolution and the exercise of power [81]; neo-Austrians emphasized creativity in the presence of uncertainty [198]; post-Keynesians questioned time-reversibility present in the equilibrium setting [5]; neo-Schumpeterians investigated innovation processes and their inherent non-linearity [78, 133]; Boulding, concerned with the profound indeterminacy of evolutionary processes, questioned the applicability of the experimental method in evolutionary economics [19]; and Foster advocated the use of the self-organization approach for evolutionary economics [64]. Additionally, there is a growing body of literature on the evolution of business organizations [68, 128, 155].

All these strands of evolutionary thought provide realistic insights into the process of economic change. However, despite considerable overlaps between these strands, a widely accepted unifying analytical framework is still lacking within which each stream can be placed as a special case.

With an apparent absence of alternatives, evolutionary economists use the Modern Synthesis (MS), the current conceptual framework for biological evolution, as a useful metaphor and source of analogies for the development of theories in economics. As early as the 19th century, Bagehot, Ritchie, Veblen and others proposed that the principle of natural selection could help to explain the survival of groups, businesses, nations and even languages [7, 154, 194]. For decades, the refinements in neoclassical economics obscured the biological analogy as a valid alternative for mainstream economics [138, 162]. However, there has been a surge of interest recently into how insights from biological evolution can strengthen the conceptual foundations of evolutionary economics [56, 97, 195, 201–203]. Particularly, Generalized Darwinism (GD) has captured large attention. GD abstracts the core biological principles described in the MS of mutation, selection and genetic recombination to provide a unifying meta-analytical framework capable of inspiring, framing and organizing causal explanations for evolutionary economics [3, 32, 48, 54, 82, 83, 153]. However, the usefulness of GD has been widely questioned, particularly its level of abstractness [195], and its lack of an explicit account of social and cognitive evolutionary processes [127].

The goal of this article is to introduce and explore a conceptual framework for evolutionary economics alternative to GD. Our framework, labeled Holonic Framework (HF), provides a less abstract, more substantive departure point to study economic evolution. For example, it accounts explicitly for social and cognitive processes lacking in GD. Our framework is also relatively easy to operationalize. Therefore, it allows a relation to theoretical propositions with empirical data. Furthermore, we show that the HF is capable of accounting explicitly for other aspects considered relevant for evolutionary economics, such as self-organization. Our framework does not build upon biological sciences, but on social sciences, particularly the body of literature on the value of digital information networks. In this regard, the HF is aligned with the pleas of Schumpeter to forget biological reductionism, and instead examine economics in its own unique social, psychological and political context [162].

This article is organized as follows. In the next section, we summarize the current approach to evolutionary economics, i.e. the MS and GD. Here we assume that GD is the most advanced unifying analytical framework for evolutionary economics to date, and thus represents the state of the art reference framework. Section 2 ends with an overview of the criticisms directed at GD which serve as our motivation to search for an alternative framework. In Section 3, we use the body of literature on the value of digital information networks as a departure point to find an alternative to GD. Section 4 introduces our proposed alternative, the HF. Section 5 demonstrates the empirical power of the HF using data from Eurostat. In Section 6, we discuss the strengths and limitations of the HF relative to GD. After summarizing our conclusions in Section 7, Section 8 describes various implications and possible extensions of our work.

2 The Modern Synthesis (MS) and the Generalized Darwinism (GD) initiative

The Origin of Species appeared in 1859, introducing the new idea of natural selection [47]. Darwin observed that all organisms, even the most slowly reproducing ones, produce more offspring than can actually survive. Those individuals that are the fittest are most likely to survive and reproduce. Given that subsequent generations inherit this capability to be fitter, average fitness in the population tends to increase. However, there was a gap in the Darwinian theory: the source of variability among species. The gap was filled by Gregor Mendel's work. From the Mendelian perspective, the presumed loss of variability occurring with blending inheritance does not happen, but it is conserved by mutations.

Although satisfying in many ways, the Darwinian-Mendelian theory was in some ways unsatisfactory. The issue was the need to reconcile a theory of gradual evolution (Darwinism) with the saltationism that emerged from the new discipline of genetics born with the work of Mendel [142]. Fisher provided an answer, showing correlations between relatives on the supposition of Mendelian inheritance, convincingly demonstrating that Darwinism could be reconciled with Mendelism [63]. Subsequent work, consolidated to what has become known as the MS, a list of consensus statements that form the core of the synthetic theory of biological evolution [151]. The current MS is essentially provided in the content of six books [53, 89, 116, 152, 169, 177]. Others have made significant contributions as well [91, 92, 151]. The terms *evolutionary synthesis* and *synthetic theory* originate from the title of Julian Huxley's book in 1942: *Evolution: the Modern Synthesis*. The basic principles of the MS are the following [105]:

1. The units of evolution are *populations* of organisms and not types of organisms (i.e. *species*). A population is defined as a group of organisms of a particular species that inhabits a particular area. When a population of organisms becomes isolated from the main group by time or geography, they eventually evolve different traits. As a consequence, these organisms can no longer interbreed with the organisms from the main group. This separation creates a new species. Mayr developed the concept of biological species, which has been later defined as an interbreeding community of populations that is reproductively isolated from other such communities (see below) [116]. Natural selection acts on traits within populations that are beneficial in the particular geographical area.
2. In biology, the phenotype is the combination of the organism's morphology and behavioral repertoire that determines the way in which the organism interacts with the environment. The genotype is the genetic information that codes for the way in which the phenotype develops. Thus, the genotype both enables and constrains the organism's interaction with the environment. Genetic and phenotypic variability in plant and animal populations is brought about by genetic recombination (reshuffling of chromosome segments) resulting from sexual reproduction and random mutations along the parent-offspring sequence. Mutations are not random in the absolute sense (e.g. they are constrained by physical and chemical

rules) [43]. However, from the perspective of their usefulness for evolution, they are the source for random genetic information [178].

3. Natural selection is the most important force that shapes the course of phenotypic evolution. In changing environments, natural selection is especially important because it steers the population mean towards a novel phenotype better adapted to the changing environment. In small populations, natural selection might cause significant loss of genes from the gene pool. An illustrative example of natural selection is the development in bacteria of resistance to antibiotics. Since 1928, the year of the discovery of penicillin, antibiotics have been used against bacterial diseases. When subject to penicillin, most bacteria die rapidly. However, some may have genetic mutations that make them slightly less sensible to penicillin. If these bacteria are exposed only for a short period, they survive to penicillin. This process that eliminates maladapted bacteria from a population is natural selection.
4. Speciation can be defined as a step of the evolutionary process at which forms become segregated into two or more separate arrays that are physiologically incapable of interbreeding [53]. Speciation is preceded by selective interbreeding, which can be a result of geographical location, behavioral isolation or temporal isolation. Direct consequence of selective interbreeding is a reduced gene flow between two segregating arrays of organisms. In time, this gene flow effectively ceases when the mutations that distinguish the two arrays of organisms become fixed. Two mutations are enough to result in speciation. If each mutation has a neutral or positive effect when they occur separately, but a negative effect when they occur together, then fixation of these genes in the respective subgroups will lead to speciation.
5. Evolutionary transitions in populations are usually gradual, i.e. new species evolve from pre-existing varieties by slow processes and maintain at each stage their specific adaptation. However, there are some exceptions. For example, in cichlid fishes [120, 121], polypoid angiosperms [176] and southern African ice plants [98], reproductive isolation and the resulting origin of novel species can occur relatively faster (within a few hundred or thousand generations).
6. Macro-evolution, defined as phylogenetic development above the level of species, is a gradual step-by-step process that is nothing but an extrapolation of micro-evolution (origin of races, varieties and species). As such, the distinction between micro-evolution and macro-evolution is not a fundamental one. The only differences between them are time and scale. Comparative genomics, evolutionary developmental biology and palaeontology are among the fields of research that provide most of the evidence for the processes and patterns that could be associated with macro-evolution.

In the MS evolution is defined as the change in the frequencies of genes in a population of individuals from one generation to the next [135] and [118]: 1) gradual evolution can be explained in terms of small genetic changes and recombination, and the ordering of this genetic variation by natural selection; and 2) the observed evolutionary phenomena, particularly macro-evolutionary processes and speciation, can be explained in a manner that is consistent with known genetic mechanisms.

The appeal of evolution as a unifying theory for various sciences [4] led researchers to apply the basic tenets of the MS as a conceptual ground to explain evolution in other scientific fields. A prominent and recent example is the GD initiative, which proposes a radical abstraction of the MS from its biological evolutionary details so that *selection*, *retention* and *variation*, regardless of the very different ways in which they operate in different areas of application, provide an overall meta-theoretical framework universally applicable to various areas, including evolutionary economics [3, 48, 82, 83].

The motivation of the proponents of GD was "to derive a powerful over-arching theoretical framework in which theorists can develop auxiliary, domain-specific explanations" [3]. Darwin himself recognized the potential broader application of his core ideas upon the elements of language, and that natural selection favored tribal groups with moral and other propensities that served the common good [47]. Writers such as Keller, Veblen, Ritchie and Bagehot have argued that natural selection could explain the survival not only of individuals, but also of business firms, nations and other social institutions [7, 95, 154, 194].

Stoelhorst and Huizing described the explanatory logic of GD as follows (see Fig. 1) [181, 183]. Open complex systems consist of different components and need resources from the environment to function. To secure the necessary resources, the system needs to interact with the environment. This interaction is done by what is usually called behavior: the act of doing something to have an effect upon the outside world. The system is subjected to selection pressure because the required resources are scarce. Information regarding the way of interacting with the environment (behavior) is fed back into the system and coded in the codex of the system (an abstraction of the biological genotype) [200]. Thus, behaviors that were more

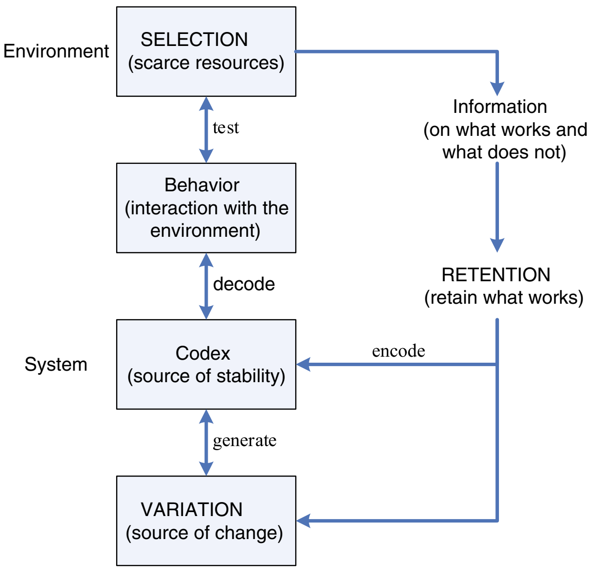

Fig. 1 A framework for Generalized Darwinism (GD) [181, 183]

successful in the past are more likely to be repeated in the future. Additionally, random changes in behaviors are more likely to negatively affect the functional integrity of the system than to improve its performance. However, in the long run, there is a need to vary behaviors to adapt to changing environmental conditions. Such variation can occur through changes in the system codex or by changing behaviors.

The mechanism of selection is an abstraction of Darwin's natural selection process, which is essentially a way of reducing the variety in a set of entities as a function of the characteristics of these entities [100, 101]. Selection operates upon multiple and different entities, and therefore a mechanism of variation is necessary that abstracts genetic changes and recombination as a mechanism that increases variety in the characteristics of the entities in the set [181]. The mechanism of retention serves the purpose of reproduction in the biological realm, which is the maintenance of the characteristics that have been favored by selection in the set of entities.

Several streams of research concerned with change in populations of firms have drawn inspiration from Darwinistic ideas, although not necessarily explicitly or addressing all three mechanisms described by GD: selection, retention and variation. For instance, population ecology focuses on the selection mechanism [77]; Nelson and Winter focused on variation and retention of firms competences as an analogue to biological genes [128]; Porter emphasized the forces that select the most competitive firms [145, 147, 148]; contingency theory investigates organizational dependence on contingencies set by the environment [124]; Burgelman [29] and Campbell [34] investigated selection within firms rather than between firms.

The importance attributed to GD as an explanatory structure sufficiently general to apply across various domains has often been stressed [3, 82, 181, 195]. For example, Stoelhorst and Huizing stated "so far, [GD] is quite simply the only fully fledged specified and logically consistent explanatory structure to account for adaptive fit that we know" [183]. Nevertheless, criticisms to GD exist, and the two main ones are as follows:

1. Its abstractness, which limits its usefulness to elaborate domain-specific evolutionary hypotheses.
2. Its lack of completeness, because the three principles that GD identifies seem not enough to arrive at full-fledged causal theories about the evolution of economic phenomena.

Stoelhorst stated "the supporters and opponents of generalized Darwinism disagree about two things: if a generalized Darwinism can adequately capture what is general about all evolution, and if a generalized Darwinism would also be able to explain what is essential about evolution in economics" [181]. For example, culture is not explicitly captured by GD, although it is an essential economic mechanism to attenuate the inherent limitations of human cognition, serving as a simplified heuristic to make good enough judgments [137]. Economic evolution constrained by cultural differences differs sharply from biological evolution [127]. For example, culture itself has a collective property that cannot be simply characterized as the aggregation of the population of traits possessed by individuals.

Because of its abstractness and incompleteness, it is difficult to see how to advance new theory using GD as a departure point. Regarding this aspect, Vromen stated that the various proponents of GD simply assume that only domain-specific auxiliary hypotheses and empirical material have to be added to the three principles and do not question the need for additional principles [195]. We thus can conclude that the potential of GD is still a matter of discussion, and the research program is still in its infancy.

As a matter of fact, the MS, which inspired GD, is under scrutiny by evolutionary biologists as well [74]. Many authors have emphasized the need to expand [36], extend [142] or replace [126] the MS. In particular, the completeness of the MS is debated. Delisle stated “evolutionary biology is still in a pre-paradigmatic state of development even today” [49]. One of the roots of this statement is the well-proven phenomenon of horizontal gene transfer between organisms, rather than vertically from their parents. Horizontal gene transfer is not explicitly accounted for in the MS, but its consequences are profound and may alter significantly the biological evolutionary process itself [26]. If the MS has limits to its explanatory power in evolutionary biology, then GD may inherently be of limited use in evolutionary economics as well.

3 An alternative approach: the value of digital information networks

In light of increasing doubts raised about the MS, Brooks and Wiley put forward a research agenda to unify various efforts in biological evolution to “expand, extend or finish the job begun by Darwin” [24]. Their conceptual theme lies in the use of energy in maintaining and transforming ordered states of matter. Using the concepts of information and entropy as a common phenomenology for a number of organizing processes in biological systems, their core hypothesis is that biological evolution is an entropic process. By expressing evolution in terms of entropy, they provided a conceptual link between biological processes and physical laws showing that biological processes are not governed by laws specific to biology. Entropy can be seen as a measure of randomness in a system. Organisms evolve by moving from states of high entropy to low entropy. The second law of thermodynamics states that over time the entropy of an isolated system that is not in equilibrium will tend to increase, approaching a maximum value at equilibrium. Stated otherwise, concentrated energy disperses over time, and consequently less concentrated energy is available to do useful work. Thus, only with a steady inflow of energy can an organism keep a separation from the environment (e.g. skin) and ordered insides distinct from disordered outsides [13].

Other authors have raised the hypothesis that, just like biological evolution, economic evolution is also an entropic process. Their justification to hypothesize so is twofold: 1) evolutionary economics uses biological evolution as an inspiration for its own conceptualization; and 2) biology is guided by fundamental physical laws. For example, Georgescu-Roegen [69] and Foster [64] argued that economic systems must be understood in terms of the second law of thermodynamics (the entropy law), and that propositions concerning thermodynamics appear to be the correct starting point in developing analytical frameworks within which economic processes can be understood. Domingos argued that the integration between economics and thermodynamics at the substantive level is of crucial importance because economic processes obey thermodynamic laws and therefore a sound economic theory must be coherent with thermodynamics [55]. This integration suggests that economic production is utterly dependent on the availability of low-entropy inputs such as natural inputs [45].

The economic process combines natural inputs (energy and matter) with information (i.e. the human input) to produce economic goods. Both types of inputs are necessary for the economic process. An economy only with natural inputs would lack information on how to use them. An economy without natural inputs would render inapplicable the information about how to use them. However, while the availability of natural inputs serves as a pre-condition for the economic process, it is the composition and stock of information that determines how efficient the natural inputs are used in creating economic value. This suggests that economic agents are best understood in terms of their information content. Economic entities maintain structural and functional integrity by processing information. Without processing information, economic systems cannot retain successful patterns of energy flow that enhance their ability to maintain order, and evolve by moving from states of high entropy to low entropy. The concept of information has been seen as general enough to encompass changes in output quality, technology, even changes in socio-economic characteristics that are concomitant with economic evolution [158].

The framework of Stoelhorst for GD, shown in Fig. 1, bases economic evolution on the selection of information about what works and what does not [181]. Ayres interpreted an economy as an information transformation system [6]. Nelson and Winter proposed *routines* containing information in the form of rules, as the units of analysis of an evolutionary theory of economic change [128]. These contemporary views do not contradict orthodox economists. For example, Solow argued that long run growth in the wealth of an economy comes from technological change, which is due to the accumulation of knowledge, a concept tightly connected to information [174]. Smith emphasized the essential role of the division of labor for the well-being of an economy, and how this division of labor is tightly connected to knowledge accumulation [170]. Common to these research streams is recognition of the fundamental role that information plays in explaining the evolution of economic activity.

Kallinikos attempted to understand the complex character of technologically sustained information processes [93]. He drew some important conclusions about the nature of information: it is self-referential and non-foundational. Self-referential means that information has value if it adds a difference to what is already known. Borgman stated "to be told that the sun will rise tomorrow is to receive no information. To learn that one has won the jackpot in the lottery is to have great news" [18]. Non-foundational means that informational differences emerge through comparison of two or more objects or items. They are not singular, but are relational entities. Due to its differential nature, information is hard to measure and conceptualize further. Nevertheless, the body of literature on the value of digital information networks and other Information Technology (IT) has shown great progress regarding this issue. A significant amount of theoretical and empirical work has been produced to address the well-known paradox "you can see the computer age everywhere but in the productivity statistics" [175].

The alternative to GD proposed in this article is a framework, labeled Holonic Framework (HF), which was first suggested for understanding, modeling and predicting the value of digital information networks [107, 111]. The HF describes a set of simple and fundamental concepts that describe how information flows are processed and from which evolutionary value is generated. Our hypothesis is that the HF is not only applicable to digital information networks, but to information networks in general. Irrespective of the technical aspects involved in the coding, transmission and decoding of information, digital networks allow humans to exchange information, just like any other transport, organizational, physical or biological network. Therefore, we hypothesize that the HF applies to information networks in general, digital or not, including economic networks.

Of all the frameworks proposed to account for the value of digital information networks and IT, the HF was chosen for two main reasons. First, it is a framework developed purely upon the premises of evolutionary economics regarding the nature and value of information, which are described in the next section. Second, the HF provides a more comprehensive view of the processes upon information. The latter is shown in [111], where we compared the HF with two other reference frameworks on the value of IT [28, 205]. This led us to the assumption, validated in this paper, that the HF could be an alternative to GD, addressing GD's key weaknesses regarding completeness and practical use.

4 Holonic Framework (HF)

4.1 Holon theory and the evolutionary view on the value of information

The term *holon* combines the Greek word for *whole* (*holos*) with the suffix *on*, which suggests particle or part [102]. Thus, the holon is a part-whole, a nodal point in a nested hierarchy (referred to by Koestler as a *holarchy*). A holon can be described in terms of its holistic and independent nature as well as its partness and dependent nature [58]. Depending on the viewpoint in a nested holarchical structure, the perception of what is the whole and part will change. Through its whole, part, dependent and independent dimensions, holon theory is capable of representing 1) nested systems as organizations or economic systems from mechanistic physical sciences, behavioral sciences, holistic system theories and sociological sciences; 2) evolutionary processes that take a holon to a different holarchical position; and 3) the individual micro-level, as well as the collective macro-level. The HF uses the concept of *holon* to refer to an entity that is part of and makes use of multi-level networks for exchange of information.

Two views can be distinguished to account for the value of information networks [28]: the *orthodox economic* approach and the *evolutionary economic* approach. The orthodox economic approach views information as an observable production input changing the uncertainty regarding the performance of an economic system. In this context, the value of information is the difference between an informed and less informed economic system. For example, in Koutroumpis, information was observed by measuring the broadband penetration rate, and economic system performance was observed by measuring economic growth. The value of information was measured with a regression between the broadband penetration rate and economic growth [104].

The evolutionary economic approach views information as procedures to change the nature of an economic system. In this context, the value of information is the difference between the results obtainable by invoking procedures from one economic system to that of another [193]. For example, recruiting agencies have multiple procedures to locate, evaluate and place job candidates. An information procedure has value if it changes the obtainable results for the better.

The orthodox view of an economic system is relatively coarse grained, being a black box transforming inputs into outputs. The evolutionary view is finer grained: modular input procedures can be rearranged to rearrange outputs. The orthodox view helps in understanding the value of information networks as facts from observations. The evolutionary view helps in understanding the value of information networks as procedures leading to changes in observations. The orthodox view applies statistical inference to the observations. The evolutionary view applies rule-based logic, and therefore extends logically to flows and information networks. Models of economic systems are typically orders of magnitude larger in evolutionary economics than in orthodox economics. Thus, it is not uncertainty, but complexity or computational costs to generate and search an enormous space state of information procedure possibilities that concerns evolutionary researchers.

Thus, the evolutionary view on the value of information is concerned with the study of procedures or intermediate processes that transform an economy. The notion that an economic system should be studied as a system of interactions and procedures is not new in disciplines such as the social sciences [70]. For example, Sambamurthy et al. argued that IT investments and capabilities influence firm performance through three significant organizational capabilities (agility, digital options and entrepreneurial alertness) and strategic processes (capability-building, entrepreneurial action and co-evolutionary adaptation) [159]. Sambamurthy et al. here define capability as an intermediate procedure [159]. Eisenhardt and Martin referred to it as "the organizational and strategic routines by which firms achieve new resource configurations as markets emerge, collide, split, evolve, and die" [59]. Particularly referring to IT capabilities, Sambamurthy et al. defined IT competence as "the organizational base of IT resources and capabilities and describes a firm's capacity for IT-based innovation by virtue of the available IT resources and the ability to convert IT assets and services into strategic applications" [159]. These IT capabilities are developed over time through a series of linked strategic decisions about investments in IT in parallel with development of organizational processes and knowledge [10]. Prahalad and Hamel defined capability as "communication, involvement, and a deep commitment to working across organizational boundaries" involving many levels of people and all functions [149]. Other authors have referred to capabilities as *routines* [44, 114, 129].

Independently of the label and definition, capabilities or routines are fundamentally processes that operate upon information. The HF defines *capabilities* as procedures that a holon can use to navigate through streams of information flowing through networks that potentially bring value. The HF identifies a set of 13 capabilities[1]:

1. Coordinatibility
2. Cooperatibility
3. Selectibility
4. Biddability
5. Adoptability
6. Creatibility
7. Brokerability
8. Normatibility
9. Trustability
10. Culturability
11. Decisability
12. Modelability
13. Perceptability

These concepts are simple and fundamental, and are the underlying principles that capture the value of digital information networks. They were derived by investigating the large amount of literature on the value of digital information networks for processes depending on information networks. These processes were then interrelated, abstracted from specific details, refined and finally conceptualized into the framework of capabilities. They are described in the next section, in no particular order.

4.2 The 13 capabilities of the HF

Coordination is a cross-disciplinary process [134]. Sociologists observe the behavior of groups of people, try to identify coordination mechanisms among them and explain how and why these mechanisms emerge. Biologists observe flocks of birds coordinating perfectly without central mechanisms and try to identify the simple rules used by these animals. Economists investigate the structure and dynamics of markets as a particular coordinating mechanism. Based upon definitions introduced in [113], the HF defines *coordinatibility* as the capability of a holon to manage dependencies between activities that are performed to achieve a goal.

Cooperation is achieved when a number of persons enter a relationship with others for a common benefit or collective action in pursuit of the common well-being [42]. Most often, cooperation is associated with coordination, but a few theorists clarify that they are distinct concepts [136]. Electronic commerce is just one example of *cooperatibility* which, based on definitions introduced in [14, 42], is defined in the HF as the capability of a holon to enter in a relationship with other holons for a common purpose.

Selection is another cross-disciplinary process. The World Wide Web (WWW) is an important source of information, and therefore, search engines are an essential

[1] To identify the capabilities of the framework, the HF mixes the action/verb/process specific to a capability (being aware that this is not always in line with the English language).

WWW selection facility. Yet, despite the pervasiveness of selection, Price mentioned that there has been no abstraction and generalization to obtain a general selection theory, and predicted the appearance of such a theory in the future [150]. Based upon definitions introduced in [28], the HF defines *selectibility* as the capability of a holon to scan for the unknown or generate courses of action that improve on known alternatives.

Through the ages, bidding has been used to determine the value of hard-to-price items (e.g. antiques). Around 500 BC, bidding was used in ancient Babylon to auction off wives, and the crown of a Roman emperor was sold by auctioning in 193 AD [37]. Objects, such as works of art, are typically awarded to the highest bidder. A contract to build a highway is usually given to the lowest bidder. Gilbert investigated bidding on cable television franchises [71]. Shubik studied bidding in dollar auctions [164]. Smith studied bidding within animals [170]. The HF defines *biddability* as the capability of a holon to influence other holons through proposals. Information networks have lowered the costs of organizing bidding auctions, which is leading to an increasing number of transactions [106]. Milgrom stated that Internet transactions reduce the state space of the negotiation to the bid alone and has the "additional advantage of being an institution [Internet] where the conduct can be delegated to an unsupervised agent" [122]. Some developments enabled the development of online-bidding: security mechanisms, improved web browsers, increasing Internet usage, etc. [11].

The capability of integrating knowledge in existing knowledge structures is a crucial step for success. In current knowledge-based economies, growth is generated from innovation [12]. Based upon definitions introduced in [189], the HF defines *adoptability* as the capability of a holon to acquire novel knowledge from other holons to be integrated in existing internal knowledge structures.

As firms struggle in competitive environments, innovation becomes increasingly important. Information networks render the firm's capabilities *amorphous* in nature, providing the ultimate potential for creation [94]. For example, they allow for flexible maintenance of networks of customers and partners inside and outside a firm. Based upon definitions introduced in [12], the HF defines *creatibility* as the capability of a holon to deliberately and purposely collate knowledge to generate new or novel ways to understand a particular phenomenon.

The combination of experiences, knowledge access, prominence and power creates inducements across actors, giving origin to information network structures [204]. Network opportunities enable an actor to create or restructure prior network structures (see Child's notion of strategic choice [38]). Network opportunities and the inertial constraints imposed by prior network structures mutually reinforce and perpetuate information structures through a structuration process [76, 179]. Hence, markets and organizations are networks of interdependent groups, in which information flows at higher speed within than across group boundaries [31]. Structural holes are network ties linking agents of separate network segments [30]. A bridging actor assumes the broker role, making a connection between different non-redundant information structures [67]. Brokerage capability across structural holes is an advantage in detecting and developing new ideas synthesized across disconnected pools of information. Based on definitions introduced in [30], the HF defines *brokerability* as the capability of a holon to act as a broker between unconnected holons.

A holon's preferences might conflict with other holons' preferences. In such a context, the importance of the concept of norms becomes apparent [51]. The development, enforcement, observation, violation, control and upholding of norms has been a topic of interest to several disciplines: philosophy, anthropology, history, sociology, political sciences, psychology, economy, law, and even biology [143]. Based upon definitions introduced in [87], the HF defines *normatibility* as the capability of a holon to share with other holons norms as rules with at least a certain degree of consensus that are enforceable by social sanctions.

Culture contains the rich fabric of religion, art, morals, customs and beliefs that diversify societies. Culture also manifests itself with tangible artifacts, such as art and technology, with visible and audible behavior patterns as well as myths, images [61], heroes [184], rituals and ceremonies [141]. In the past, most sociologists viewed culture as a "seamless web" [185], unitary and internally coherent across groups and situations [20, 84]. In contrast, recent work depicts culture as fragmented across groups and inconsistent across its manifestations [52, 115]. Based upon definitions introduced in [141], the HF defines *culturability* as the capability of a holon to share with other holons general assumptions, values and patterns of behavior emerging over time from their interaction.

Trust is an important lubricant of human relations (e.g. for friendship and economic transactions) [62]. Based on definitions introduced in [39], the HF defines *trustability* as the capability of a holon to engage in a common effort with another holon before knowing how that holon will behave.

Executives of organizations are constantly facing decision-making situations. The traditional approach to decision-making emphasizes the effects that executives can have on strategic decisions. This approach has been labeled the strategic-choice model [125]. Executives examine the firm's external environment and internal conditions and, using a set of objective criteria, decide upon the strategy [132]. The decision is then benchmarked relative to a standard [9]. An alternative perspective on decision-making argues that strategic decisions are mostly constrained by the external environment [156]. Decision-making involves a series of sequential, rational and analytical processes independent of the importance given to the decision-maker relative to the external environment [88]. A set of objective criteria are used to evaluate strategic alternatives [1, 33]. Based on definitions introduced in [1, 33], the HF defines *decisability* as the capability of a holon to evaluate and decide among strategic alternatives.

Modeling is a widely used approach in problem solving. According to the basic ideas of Gestalt psychology [103], human beings tend automatically to minimize inconsistencies in novel input information to make sense of the world and form consistent mental representations [72]. Consistency-maximizing theories have traditions in social psychology [167], with ample empirical evidence [199]. Modeling allows organisms to learn contingencies among events and actions, and therefore, it is vital in adapting to dynamic environments [132]. Based on definitions introduced in [132], the HF defines *modelability* as the capability of a holon to understand the cause-effect structure of a system, thus facilitating causal reasoning, categorization and induction.

Both decisability and modelability are limited by the fact that biological organisms have limitations on how much information can be processed [123]. A possible way to incorporate the limitations of the mind into models of cognition is to propose simplified heuristics that enable organisms to make good enough judgments [137]. Such approaches develop frameworks considering the *costs of thinking*. Limitations of the mind (e.g. memory and attention span) and limitations imposed by the environment (e.g. costs to achieve information) constrain the capability of perception [168]. Stewart argued that the nature of cognition is strongly determined by its perceptual processes [180]. In particular, they stated that "the external world can provide much of the connective tissue that integrates cognition". As an example, they mentioned the difficulty in making a proof in geometry without a diagram to inspect and mark. Traditional approaches to perception tend to deal with it in isolation from the processes of modeling and decision-making. However, due to their intricate and dependent nature, approaches have been proposed to integrate them, emphasizing their interface [85]. Still, some authors value their conceptual separation based upon

Table 1 Labels and definitions of the capabilities

Capability	Definition
Coordinatibility	Capability of a holon to manage dependencies between activities that are performed to achieve a goal
Cooperatibility	Capability of a holon to enter in a relationship with other holons for a common purpose
Selectibility	Capability of a holon to scan for the unknown or generate courses of action that improve on known alternatives
Biddability	Capability of a holon to influence other holons through proposals
Adoptability	Capability of a holon to acquire novel knowledge from other holons to be integrated in existing internal knowledge structures
Creatibility	Capability of a holon to deliberately and purposely collate knowledge to generate new or novel ways to understand a particular phenomenon
Brokerability	Capability of a holon to act as a broker between unconnected holons
Normatibility	Capability of a holon to share with other holons norms as rules with at least a certain degree of consensus that are enforceable by social sanctions
Culturability	Capability of a holon to share with other holons general assumptions, values and patterns of behavior emerging in time from their interaction
Trustability	Capability of a holon to engage in a common effort with another holon before knowing how that holon will behave
Decisability	Capability of a holon to evaluate and decide among strategic alternatives
Modelability	Capability of a holon to understand the cause-effect structure of a system, thus facilitating causal reasoning, categorization and induction
Perceptability	Capability of a holon to pick information to establish and update internal representations of the environment

empirical evidence such as *direct parameter specification* [130]. Neumann conceptualizes perception not as an activity of picking up information for the control of action, but as a specific kind of information pickup that serves to establish and update an internal representation of the environment [131]. Based on definitions introduced in [131], the HF defines *perceptability* as the capability of a holon to pick information to establish and update internal representations of the environment.

The set of capabilities previously defined is presented in Table 1.

4.3 Summary of the HF

The HF is illustrated in Fig. 2. The three horizontal planes aim to capture different levels of complexity and predictability of holons. The lower plane corresponds to less complex and more predictable holons (e.g. an individual). The upper plane corresponds to more complex and less predictable holons (e.g. a coalition). Hierarchies of holons are called *holarchies* (e.g. coalition or policy subsystem) and capture the idea that each plane is bounded to other planes in some ways and is independent in other ways. A holon constitutes itself an open-ended multi-level hierarchical construction where each level of hierarchy is a network constructed by sub-wholes connected with each other within the same level [86]. Thus, a holon is a holarchy itself. Examples of economic holons and holarchies are human beings, economic agents, firms, industries and economic sectors.

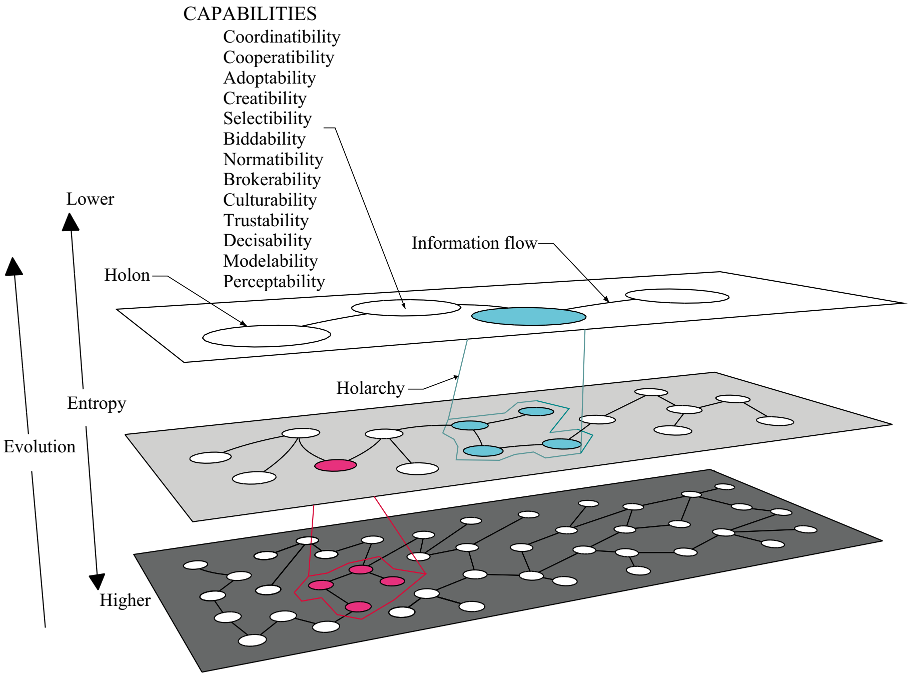

Fig. 2 Holonic Framework (HF)

The links between holons represent flows of information. Holarchies and holons evolve towards increasingly complex structures with internal and external exchanges of information. Information networks enable the expansion and growth of information. In turn, such expansion and growth of information leads to organizational changes which take increased advantage of information, feeding back again into new developments [21]. Thus, information networks reinforce the "self-propelling spiral of information" [93] towards increasingly evolved holarchies.

An important dualism in the definition of holon is the part-whole. Part is, by definition, something fragmented and incomplete, with no justification to exist by its own. On the other hand, whole implies something complete needing no further explanations. Peters and Többen relate partness of a holon to the tendency to integrate into a more comprising wholeness [140]. Wholeness is related by Peters and Többen to the stability of a holon provided by an internal canon of rules which define the possible actions and behaviors of the holon. In turn, these actions depend on observed environmental variables and are determined by the fundamental set of information processing capabilities listed in Table 1. A holon uses these capabilities to generate evolutionary value.

Evolutionary value corresponds to shifts in a system from states of higher entropy to lower entropy. The concept of entropy originated in the natural physical sciences as a measure of the number of possible microscopic configurations of individual atoms or molecules of a system that would give rise to the observed macroscopic state of the system [17]. Thus, entropy can be seen as a measure of randomness in a system [163]. The concept of entropy has been used to connect the physical sciences to various domains, namely biology [25], economy [64] and policy making [166].

On the one hand, the 13 capabilities of the HF are fundamentally different, i.e. one capability cannot be univocally identified by a subset of other capabilities. For example, coordination and cooperation are often used interchangeably, but some theorists clarify that they are distinct concepts [136]. On the other hand, these capabilities are most likely not orthogonal, i.e. they have some overlap. For example, Gual and Norgaard described how culture affects selection at various levels [75].

5 Operationalization of the HF

Operationalization refers to the process of linking the conceptual definitions to a specific set of measurement techniques or procedures [22]. In [112], we operationalized the HF with the goal of showing how two simple relations known as Metcalfe's law [119] and Briscoe's law [23] can be used to quantify how adequate the capabilities of the HF are in converting the ability to access information into economic value. All the work presented in [112] was done in the specific context of the value of digital information networks, such as optical fiber telecommunication networks. In this section, we do not intend to repeat the results presented in [112], but simply to transpose and generalize some of the results presented to the context of evolutionary economics. Our goals for this section are mainly two: 1) we want to show that it is possible to operationalize the HF, which is by itself a clear advantage relatively to GD; and 2) we want to show that it is possible to extract theoretical propositions that are interesting for evolutionary economics.

In [112], we first measured the importance of the capabilities of the HF individually in their role of proxies for economic evolutionary processes. Secondly, we measured the size of the digital information network infrastructure used by the capabilities as a proxy for the resources available to the economic agents to evolve. Finally, we investigated the correlation dependency between the capabilities of the HF and the size of the digital information network infrastructure. Our assumption that economic evolution is largely enabled by digital information networks and IT is supported by various authors who consider that we are in the middle of an economic era driven by these infrastructures. In long wave theory, this era is known as the 5th Kondratieff economic cycle [139]. A Kondratieff cycle manifests itself by a sinusoidal-like long-term cycle from approximately 40 to 60 years in length with a semi-period of high productivity growth followed by a semi-period of relatively slow growth [65].

Eurostat, the European Union (EU)'s official organization to collect statistical data, provides one of the richest data sources about the usage of IT in enterprises and households. We were allowed to use a significant part of their data set for our research. By applying some data mining techniques, we were able to relate many Eurostat variables more or less directly to our capabilities, and extract numbers representing the size of the relevant digital information network. The data spans the years 2002-2009, for various EU countries, with regional and sectoral breakdowns, for a large collection of different aspects related to the use of IT. Obviously, the Eurostat did not obtain its data with the HF in mind. Therefore, the data did not provide enough empirical variables to cover fully and perfectly each capability of the framework. The empirical variables chosen were limited by what is being measured in the Eurostat surveys, and some can better be considered to be proxies of the concepts to be measured than others. Consequently, we had some capabilities that were relatively well operationalized. For example, adoptability was proxied with the fraction of individuals that have used Internet for training and education. Others were far from optimal. For example, biddability was proxied with the fraction of individuals that have used Internet for selling goods and services (e.g. via auctions).

The first result from [112] that we would like to mention is illustrated in Fig. 3. The horizontal axis represents a normalized size of the information network measured by the Eurostat data, and the vertical axis represents a normalized value of coordinatibility, which was proxied by the fraction of enterprises using systems for managing production, logistics or service operations. A regression line is shown by the thick curve. For optimal representation of the results, a binning process was used due to the large number of samples available and their relatively large spread. Similar figures were obtained for 9 capabilities in total. It should be clear that we did not operationalize the full causal chain (i.e. digital information networks → capabilities → economic value), but only the causal chain digital information networks → capabilities. That is, the numbers we use for the y-axis do not represent real economic value in €s, but are proxies for this value. But we took care that our operationalizations of capabilities were on one hand clearly resulting from availability of digital information networks and on the other hand were closely associated with economic value creation. Future work is expected to operationalize all the HF through the complete causal chain until a notion of value (e.g. GDP). For further details on the operationalization of the HF, we refer to [112].

The regression curve in Fig. 3 demonstrates the value extracted from coordinatibility is proportional to the square of the size of the information network. This result was predicted by Metcalfe's law, which states that the value of an information network is proportional to the square of the size m of the network, relying on the observation that for an information network with m members, each can make $m - 1$ connections with the other members [119]. If all those connections are equally valuable, the total value of the network is proportional to $m(m - 1)$, thus roughly to m^2. For example, if a network has 10 members using an information network, there are 90 different possible connections that one member can make to another. If the information network doubles its size to 20 members, than the number of connections does not simply double, but roughly quadruples to 380.

If we try to transpose Metcalfe's law to the context of evolutionary economics by equating *value* from Fig. 3 with *evolutionary value* and *size of network* with *size of holarchy*, the hypothesis that evolutionary value of an economic holarchy is proportional to the square of the size of the holarchy could be raised. Taking this hypothesis to more practical terms, we could hypothesize that an economy evolves in a manner that is proportional to the square of the size of the information network that constitutes it. The implications of this hypothesis are various. For example, validating this hypothesis would provide an argument to defend that connecting isolated economic

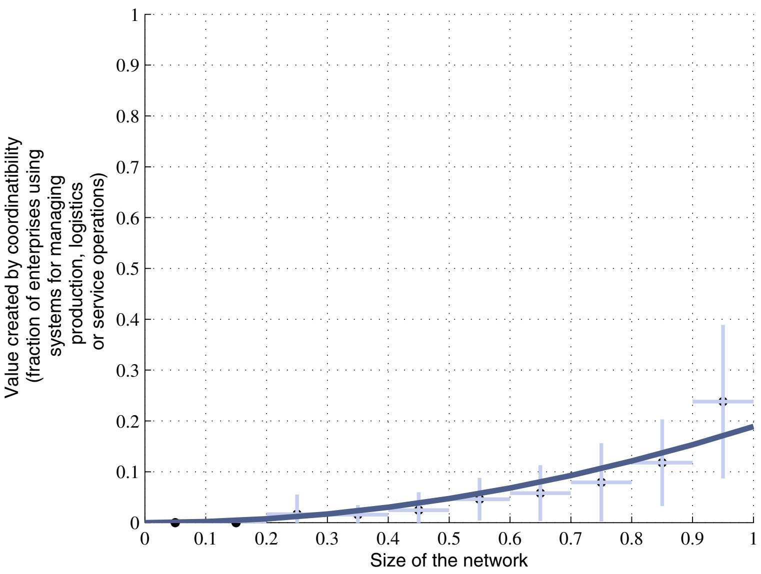

Fig. 3 Relation between size of an information network and the economic value created by coordinatibility

areas (e.g. two distant cities) would increase their joint value not linearly, but quadratically. These results could also help to explain the extent of the economic impact that transport networks had during the 20th century.

The second result that we would like to extract from [112] and transpose to the field of evolutionary economics is illustrated in Fig. 4. This result evidences limitations of Metcalfe's law, which have been pointed out by various authors [23]. Metcalfe's law assumes that each user adds equal value to the network, and this is not the case in general. For example, a connection between people communicating with different languages has in principle smaller value than within a single language domain. As an alternative to Metcalfe's law, Briscoe et al. provided an alternative which states that the value of a network of size n is proportional to $nln(n)$ [23]. Transposing this result to evolutionary economics, one could state that there are motivations to limit economic relations between different economic areas (e.g. two cities talking completely different languages).

We also demonstrated that capabilities of the HF generate value in different orders of magnitude [112]. For example, selectibility was evidenced to be more important, or at least more used, than creatibility. Quantifying and comparing the importance of the different capabilities could provide a mean to qualify and even quantify the evolutionary state of different economies in a manner alternative to current approaches (e.g. GDP), which are recurrently criticized. For example, economies with high value extracted from creatibility could be seen as highly creative economies, whereas economies with high value of coordinatibility could be seen as highly coordinated economies.

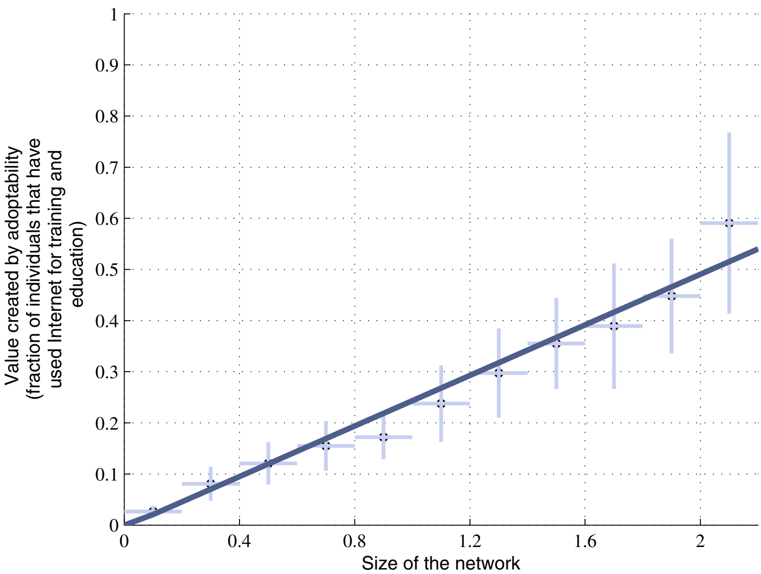

Fig. 4 Relation between size of an information network and the economic value created by adoptability

6 Strengths and limitations of the HF

As mentioned in Section 2, a critical point for frameworks such as the GD and HF is the ability to capture what is general and at the same time what is essential about economic evolution. For example, cooperative behavior is not captured explicitly in GD because it is assumed to be completely a product of Darwinian logic. Because GD leaves several relevant mechanisms obscured behind the mechanisms of variation, selection and retention, it has been seen as too general and vacuous.

Mayr pointed out that Darwinism is about explaining behavior and distinguished two forms of causation: ultimate and proximate [117]. Ultimate causation assesses *why* a certain behavior originated and it is the form of causation addressed by GD. Proximate causation explains behavior in terms of *how* the behavior occurs. For example, how is a joint venture initiated between two firms? The HF can be placed somewhere in between these two forms of causation because it concerns which behaviors evolved (the *what*). As a result of a more proximate causation than GD, the HF is less abstract, identifying explicitly several mechanisms relevant for evolutionary economics that are not explicitly identified by GD:

1. *Artificial selection*. Artificial selection is defined as "human-directed evolution" [41], and its importance for economic evolution has been stressed by various economists. For example, Commons stated that political economy explaining institutional change must be constructed as an evolutionist theory of artificial or purposeful selection [40]. The HF explicitly identifies artificial selection with the capability of selectibility.
2. *Culture*. As mentioned in Section 2, the evolution of culture and how it influences economic evolution differ sharply from the details of biological evolution [127]. The HF identifies the evolution and influence of culture with the capability of culturability, bringing culture explicitly into the economic evolutionary process.
3. *Cognition*. GD considers evolution as *blind*, and therefore does not identify explicitly any cognitive capabilities, such as self-reflection, reason, foresight or planning [82]. However, the importance of cognition for economic evolution is widely recognized. For example, Stoelhorst and Huizing stressed the importance of intentionality on the speed at which new adaptive behaviors emerge [183]. It is also well-known that often economies operate under *Knightian uncertainty*, which refers to the uncertainty that is present in many areas of economic activity, such as innovation [99]. It essentially refers to risk that is immeasurable. The impossibility of measuring risk can be explained by limited cognitive capabilities. The HF identifies three cognitive capabilities: perceptability, modelability, and decisability. Using these three capabilities, the following three hypotheses could be raised to model Knightian uncertainty:

   – Knightian uncertainty arises in the presence of limited perceptability, i.e. limits on how much information a holon can pick-up to establish and update internal representations of the environment. Consequently, under Knightian uncertainty, a holon must act with imperfect information.

- Knightian uncertainty arises in the presence of limited modelability, i.e. limits of a holon to understand the cause-effect structure of a system. Consequently, under Knightian uncertainty, a holon must act by forming subjective expectations about what the future will bring.
- Knightian uncertainty arises in the presence of limited decisability, i.e. limits of a holon to evaluate and decide among strategic alternatives. Consequently, responses in scenarios under Knightian uncertainty differ between holons.

These three hypotheses could be tested with operationalizations of the capabilities [112] and operationalizations of Knightian uncertainty.

4. *Cooperation*. Cooperation is considered a major factor of profitability and technological innovation in many industries [50]. Often, social mechanisms promote cooperation even when the return-benefits are beyond cognitive limits. Otherwise, predictability is sufficient for cooperation to succeed [90]. However, GD does not account explicitly for cooperation or for the cognitive and social mechanisms that promote cooperation. The HF, on the other hand, identifies cooperation independently and explicitly with the capability of cooperatibility.
5. *Creativity*. In GD, *variation* is understood as simply a "source of change", thus apparently purposeless regarding (ultimate) goals. The exclusion of ultimate purposefulness in the *variation* process of GD limits it applicability to economic creativity [160], which is typically assumed to be purposeful [16]. In the HF, creativity is explicitly covered by creatibility which includes in its definition ultimate purposefulness. It is important to make a distinction between creativity, covered in the HF by creatibility, and innovation, which refers to the emergence of novel information. According to the HF, innovation, i.e. novel information, arises in economies through all capabilities, not only creatibility. By proposing that economies are driven by these capabilities and that all these capabilities generate novel information, the HF suggests that exact economic predictions are impossible. Nevertheless, the HF does not preclude the possibility of making approximated economic predictions. It all depends on how far in the future the prediction is aiming at and on how much novel information the *future* brings.
6. *Self-organization*. Holarchies are nested hierarchies of self-organizing structures, the holons. The term *holon* reflects the tendency of holons to act as autonomous entities and yet cooperate to form apparently self-organizing hierarchies of sub-systems, such as the individual, the firm and the economic sector. Several authors stressed that self-organizing complex systems' dynamics might provide the conceptual framework within which Darwinism continues to evolve [197]. Contrarily to GD, which does not account explicitly for self-organization, the HF captures explicitly self-organization using the holon theory. The holon theory contains an agency-communion duality stemming from the attempt of Koestler to create a model for self-organization in biological systems [102, 190].

GD is also known to be difficult to operationalize. The difficulty is aggravated by the fact that it requires a delimitation and characterization of natural selection acting upon the economic environment. The usefulness of the mechanism of natural selection has been questioned [35, 195]. Contrarily to GD, the HF is relatively easy to operationalize (see Section 5).

The HF also has limitations. First, it investigates economic evolution only from an information perspective. Weber and Depew, for instance, stated the relevance of energy flows for the evolution of capabilities [197], and Pigliucci pled for a theory of form or matter [142]. In fact, if indeed there are five fundamental categories in nature (matter or form, energy, space, time, and information [46]), then evolution (biological or economical) should be probably studied as a convolution of the properties of these categories. Particularly interesting is the interplay between information and matter, which motivates us to look at information as data or, as Buckland put it, as a *thing* [27]. In his view, whatever information storage and retrieval systems store and retrieve is necessarily information-as-thing. In line with this perspective, the emerging discipline of Information Quality (IQ) is concerned with maximizing the value of an organization's information assets and assuring that the information products it produces meet the expectations of the customers who use them [186]. For example, Wang and Strong presented a large list of data quality attributes such as consistency, accuracy, modularity, corruption, etc. [196], and Solaiman et al. presented the following set of core Information Fusion (IF) cell functions: alignment, detection, partition, combination, truthness, estimation, and prediction [173]. Our work could benefit from clarifying the relationship between the capabilities in the HF, the data quality attributes in [196], and the IF cell functions in [173]. This clarification is most likely fundamental, lying in the difference between information as data and information as a process [27]. As mentioned in Section 3, the latter was the perspective taken in this article. Following this perspective, data is only information if it adds a difference to what is already known [93]. Consequently, the context of information is relevant as it is relatively to it that a difference may be added. The field of context-based IF systems has shown interesting progress on modelling information contexts [171]. Thus, it might add interesting insights to the knowledge presented by our article.

The second relevant limitation of the HF lies in the level of formalization and completeness of its set of capabilities. The 13 capabilities were derived by investigating the large body of literature on the value of digital information networks. In [111], we provided a review of this literature, but several other reviews can be found (e.g. [96]). This literature can be used to evaluate the 13 capabilities of the HF. For example, in [111], we compared the HF with the framework described in [28] and the one presented in [205]. Several capabilities were not present in all the three frameworks, but some capabilities were common. We cannot be sure that our framework of capabilities is complete nor orthogonal. But we are sure that these are all capabilities that can be deduced from the current literature. Alternatively and ideally, the capabilities should be derived from a unique and fundamental theory of information. Such theory does not yet exist, but its development is progressing (see e.g. [2, 191]).

7 Conclusions

The Generalized Darwinism (GD) initiative abstracts the current paradigm in biological evolution, the Modern Synthesis (MS), from its biological details so that variety generation, retention and selection, regardless of the very different ways in which they operate in different areas of application, provide an overall meta-theoretical framework universally applicable to various areas, including evolutionary economics. The two main criticisms of GD are its abstractness and lack of completeness, with a failure to capture explicitly several relevant aspects in evolutionary economics, for example, the following:

1. Artificial selection
2. Culture
3. Cognition
4. Cooperation
5. Creativity
6. Self-organization

As an alternative to GD, we developed a new framework, called the Holonic Framework (HF), to address the shortcomings of GD. In contrast to GD, the HF was not derived from biology, but from study on the value of digital information networks. The HF provides a more proximate account for economic evolution than GD, including the aspects expressly mentioned above. Additionally, by referring to an operationalization of the HF using Eurostat data, we demonstrated that the HF has a higher practical usability than GD. We finally state that the HF is not a full alternative or replacement for GD, but that both frameworks have complementary strengths and weaknesses, and could be seamlessly integrated in the future.

8 Future work

As a potential future implication of our work, the HF might serve as the conceptual framework to guide the development of Agents Based Modeling (ABM) economic models [60]. In ABM, the modeler designs classes of agents (a computational implementation of a holon), attributes these agents with certain capabilities, instantiates a population of agents, assigns initial and boundary conditions, executes the simulation for a duration of time periods, and examines the final state of the model. Broadly, an agent refers to bundled data and behavioral methods representing an entity constituting part of a computationally constructed world [188]. Among ABM's strengths, modeling flexibility is the most important. In practice, this results in heterogeneity between the agents defined in the model, facilitating a representation of the individual and social behavior of the agents.

ABM researchers argue pragmatically that agent-based tools allow modeling of cognitive agents with more realistic social and individual capabilities (hence, more autonomy). These capabilities include 1) ability to learn about one's environment (e.g. gather information, make use of past experiences, social mimicry, and experiment with new ideas) from a fixed set of options or from endogenously evolving spaces of options (e.g. strategies, performances, and preferences); 2) ability to alter expectations and preferences as an outcome of learning; 3) ability to exert some control over the timing and type of the actions; 4) ability to introduce structural changes in their methods on the basis of experience and information acquisition (e.g. in the learning method); 5) social communication (e.g. adaptively scripted messages); 6) social interaction patterns (e.g. trade networks); and others. At an abstracted level, all these capabilities are accounted for by the HF.

Contrary to neoclassical economic models, which make a system level presumption about the solution (an equilibrium state), in ABM the solution is found inductively. Rather than focusing on static or steady state paths, ABM looks for uncertain emergent properties of the agents' aggregate dynamics, often out of equilibrium. Convergence to a valid solution requires higher complexity in the definition of the agents, so that the system can develop over time solely on the basis of agents' interactions, without further interventions from the modeler (dynamical completeness). An advantage of this focus on the process rather than on ultimate equilibrium, is that modeling can proceed even if equilibria are computationally intractable or non-existent. Hence, with the HF and ABM, policy makers are now able to simulate artificial economies under different policy scenarios for a far wider range of non-equilibrium behaviors.

Finally, it is worthwhile noting that the HF is applicable to domains other than evolutionary economics. For example:

- **Service sciences** is an interdisciplinary area of study to address the challenge of becoming more systematic about innovating in services. In [108], we have explored the feasibility of using the HF to guide the development of trans-sector digital innovations [8] by taking economic sectors as innovation actors (e.g. healthcare, education, agriculture, etc.), and the capabilities of HF as innovation means. As part of a course at the Delft University of Technology, we randomly selected twenty trans-sector digital innovations from students and identified which of the capabilities were used by each innovation.
- **IT interoperability** refers to the ability of two or more systems or components to exchange information and to use the information that has been exchanged. The importance of interoperability has grown together with the adoption of digital information networks. In [110], we proposed a model to address trans-sector digital interoperability, which by definition involves interoperability across different economic sectors connected by digital information networks. Particularly, we specified how a well-known interoperability framework, the ATHENA framework, could be improved using the HF.
- **Value of IT**. Few doubt that digital information networks such as the Internet constitute the basis of a new technology-driven economic era. A large body of literature has tried to understand and quantify the value of digital information networks to help policy makers justify investments in new or improved infrastructures. In [109, 111, 112], we have applied the HF to understand the value of digital information networks. Specifically, we have used the HF to empirically validate Metcalfe's law for the first time, 30 years after it was proposed.
- **Biological evolution.** The MS is the current paradigm for biological evolution. The MS never went through a paradigmatic shift, relying on augmentations without overthrowing any of the previous foundations [73]. In [107] (chapter 5), we have explored the feasibility of applying the HF to analyze biological evolution, Specifically, we discussed the conceptual added-value of the HF regarding six

criticisms pointed to the MS: abstractness, altruism, cognition, self-organization, horizontal gene transfer and empirical power.

- **Policy making.** The Advocacy Coalition Framework (ACF) has gained a good reputation as a policy analysis instrument. However, several limitations of the ACF have been identified. In [107] (chapter 4), we introduced a new framework for policy making labeled the Capability-aware Policy Framework (CaPF). The CaPF was derived by integrating the ACF with the HF. We demonstrated the conceptual added value of the CaPF in light of six criticisms previously directed at the ACF. Furthermore, we illustrated the practical value of the CaPF with a case study on the development and implementation of an electronic identification management system in Austria.
- **Strategic management.** Strategy is the act of aligning a company with its environment, and is required because senior management cannot participate in all decision making and directly ensure the consistency of the myriad of individual actions and choices that make up a firm's ongoing activity [146]. Perhaps the most important framework for strategy is Porter's *competitive-five-forces* framework [144]. The competitive-forces approach views strategy as essentially determined by the industry structure (environment), and it helps firms to find a position in an industry from which it can best defend itself against competitive forces or exert influence in its favor. Porter's framework has been explored, contributed to and tested by many practitioners and theorists. Porter himself acknowledged a few limitations in his framework in [146]. He recognized that the success of a firm should be centrally concerned with the creation and exploitation of its so-called *distinctive competences*. To compensate for this limitation, a few streams of research developed [157, 187]. From these perspectives, firms are heterogeneous with respect to their capabilities, and strategy is both constrained and shapes these capabilities. Helfat et al. mentioned that capability-based approaches continue to inform strategic management theory because they acknowledge the importance of time and historicity in economic decision making by referring to organizational paths [80]; they explain why every organizational entity is equipped with specific resources and an identity; and they shed light on internal factors such as tacit knowledge, social complexity, organizational routines and competences [66]. The HF identifies a set of capabilities that determine the evolution of holons. Therefore, it would be interesting as future work to position the HF within the literature on strategic management.

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