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RESEARCH ARTICLE

Types of Technological Innovation in the Face of Uncertainty

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Abstract

Technological innovation is almost always investigated from an economic perspective; with few exceptions, the specific technological and social nature of innovation is often ignored. We argue that a novel way to characterise and make sense of different types of technological innovation is to start considering uncertainty. This seems plausible since technological development and innovation almost always occur under conditions of uncertainty. We rely on the distinction between, on the one hand, uncertainty that can be quantified (e.g. probabilistic risk) and, on the other, deep forms of uncertainty that may resist the possibility of being quantified (e.g. severe or fundamental uncertainties). On the basis of these different ingredients of uncertainty in technological innovation, we propose a new taxonomy that reveals the technological nature of innovation. Unlike previous taxonomies employed to handle different types of technological innovations, our taxonomy does not consider the economic value of innovation alone; it is much more oriented towards societal preferences and forms of technological uncertainty. Finally, we investigate the coherence of our proposal with the dual nature of technological artefacts, showing that innovation can be grounded on structural and functional factors and not just on economic ones.

Keywords Uncertainty · Technological innovation · Philosophy of technology · Philosophy of innovation · Dual nature of technology

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1 Introduction

Given its pervasiveness, innovation—particularly technological innovation—is a hallmark of modern society (Nowotny, 2008). The scientific literature on technological innovation is dominated by the economic approach, which considers innovation as a process to produce commercial goods, possibly focusing on making innovation processes more acceptable and responsible (Bourban & Rochel, 2021; von Schomberg & Blok, 2021a, 2021b). There is no comparable amount of research investigating the intrinsic nature of such processes (as clearly acknowledged in von Schomberg & Blok, 2021a and 2021b), and philosophical investigations of innovation are still in their infancy (Blok, 2021).

Different modes of classifying types of technological innovation may lead to severe inconsistencies (Garcia & Calantone, 2002), affecting both the theory and the practices of innovation. This article aims to fill this gap by providing a philosophical explanation and conceptualisation of various technological innovations. We believe that the acknowledgement of the interplay among different types of uncertainty in connection with societal preferences is a crucial factor in understanding different types of technological innovation. The article is organised as follows. Section 2 critically reconsiders certain well-known taxonomies concerning technology. Section 3 stresses the importance of an undervalued issue, that of severe uncertainty. Section 4 proposes a new taxonomy that takes uncertainty seriously into account. Section 5 discusses the dual nature of technological artefacts in relation to our typology. Section 6 concludes by highlighting the main findings.

2 Varieties of Technological Innovation: Existing Taxonomies

Investigating the intrinsic nature of technological innovation is essential for understanding the contemporary world. This section introduces certain theoretical aspects of technological change and innovation. It critically discusses some of the fundamental and most influential classifications of technology innovation, highlighting their limitations.

Theories of technological change have a crucial role in understanding different types of innovation. As an example, according to van de Ven and Poole (1995), technological change can be handled by the following four "ideal-type development theories", also called "motors of innovation".[1] The first is the *life cycle theory*, that is, a theory of change that uses the metaphor of organic growth; the main idea is that change is achieved by means of a "compliant adaptation" to some regulatory standards, usually expressed in the form of successive steps. This is the case, for instance, of the development of new drugs that must comply with the well-known preclinical and clinical phases of the FDA (Food and Drug Administration) in the USA or the EMA (European Medicines Agency) in Europe, or

[1] See also Ellwood, Williams, and Egan (2022).

with other national regulatory agencies. The second is *teleological theory*, which, unlike life cycle theory, is not about prescribing specific phases or sequences to be accomplished in order to provide change and innovation. Instead, it focuses on the goal of the innovation process that is pursued in order to achieve a specific objective. The third is *dialectical theory*. This is a perspective on change and innovation that assumes the existence of a plurality of different and even contradictory values and opinions of multiple actors: that is, a dialectical process that in some cases may lead to a creative synthesis. The fourth and final theory is *evolutionary theory*, which propounds a change model based on a continuous process of variation, selection, and retention resulting from minor changes.

It seems that this proposal is much better suited to understanding different forms of (economic) organisation than to understanding different forms of technological innovation. Van de Ven and Poole (1995) pointed out that combinations of these "motors" may create different composite change theories. However, it seems that the very same innovation process can be interpreted by all these motors since compliance with a regulatory agency, goal achievement, dialectical inconsistencies, and evolutionary growth due to small changes may be present in many different types of innovation processes.

Technological innovation is almost invariably analysed as an economic phenomenon. The definition and classification of innovations have been a continuous endeavour in economics (Coccia, 2006; Schumpeter, 1942). The purely economic view is primarily directed at interpreting innovation in light of market- and company-oriented considerations. For example, Chessbrough (2003, p. ix) writes that "by innovation I mean something quite different from invention. To me, innovation means invention implemented and taken to market". This emphasis on the market and companies is reflected in virtually all attempts to describe different forms of innovation. Chessbrough (2003, p. 43) distinguishes *open* innovation from *closed* innovation, stating that open innovation "means that valuable ideas can come from inside or outside the company and can go to market from inside or outside the company as well", whereas closed innovation is internal to an organisation.

More widely, extant taxonomies in economics often classify technological innovations along two dimensions: the market dimension and the technological one. The market dimension concerns the impact of the new technology on the existing market (e.g. Coccia, 2006). The technological dimension concerns the relationship between the new technology and other existing technologies (e.g. Coccia, 2006). The market dimension is considered an essential factor and a necessary condition to classify technological innovations.

To cite an influential example, Clayton Christensen (1997) distinguishes between *sustaining* (or incremental) technologies and *disruptive* technologies (or radical innovations). Sustaining technologies produce small improvements in products, and they impact on already existing markets, consumers, and users (e.g. introducing an automatic braking system into a car can produce an incremental improvement in the vehicle's performance). Disruptive technologies, by contrast, may produce a leap forward in the product and can create a new market by attracting new consumers (e.g. implementing an autonomous driving system, like that of Tesla, radically changes the nature of the technology itself and can open a new market for the product).

Clayton Christensen's classification combines the technological dimension, which concerns the relationships between the old and the new technology, with the market dimension, which concerns the economic impact or value of the technology. Both these dimensions are necessary to classify technology as sustaining or disruptive. However, neither of them is sufficient: there can be innovations that are disruptive from the technological point of view (because these technologies represent a huge leap forward in the development of the product), but not from the market point of view (because they fail to impact on the market as expected).

Market-based classifications are often uncritically taken for granted even though they suffer from severe limitations. As remarked by Gobble (2016, p. 66), "when everything is disruptive, and all innovation is open, [we are] left with no tools to distinguish what may be important about a new tool, a new approach, a new concept". We agree with this observation and maintain that a conceptual clarification of innovation types is essential for clearing the field of possible misunderstandings.

Another perspective on types on innovation has been proposed by Henderson and Clark (1990), who focused on the product of innovation understood as a system consisting of a set of interrelated components. They distinguish between *incremental innovation* (which involves minor changes in the already existing components of the product) and *radical innovation* (in which the result of innovation is a product with new components and new relationships among them). For example, gradual improvements in the quality of the film in analogue cameras were incremental innovations, but digital cameras, which replaced film with electronic image sensors, were a radical innovation (Henderson, 2021).

Henderson and Clark also assume that there are two other types of innovation: *modular innovation*, which involves the introduction of new technologies that change the core design concepts of individual components while leaving the relationships among components untouched, and *architectural innovation*, which assembles components in new ways without necessarily introducing any significantly new component technologies. A case of modular innovation is replacement of the analogue keypad of a mobile phone with a digital keypad, whereas a case of architectural innovation is the inclusion of digital cameras in mobile phones, which "changed not only the architecture of the product but also the architecture of the entire industry" (Henderson, 2021, p. 5480).

We now highlight some potential limitations of the taxonomies that we have just considered, which mainly rely on the economic dimension of technological innovation and, in some cases, are not able to cope with the importance of societal preferences.

First, the distinction between open and closed innovation may neglect those aspects of innovation that extend beyond economic considerations or are related to innovation elements that are not solely internal to a company nor solely external or even uncertain.[2] Indeed, one can imagine the existence of a continuum between

[2] For a critical discussion of the open innovation model, see Benezech (2012).

open and closed forms of innovation (Dahlander & Gann, 2010; Lazzarotti & Manzini, 2009).

Second, any taxonomy based purely on a technology's impact on the market is an ex post rather than ex ante classification. For example, to determine whether a given technology is disruptive, one needs to consider the impact of that technology on the market; that is, a technology may have the potential to be disruptive but fail to do so (e.g. because it fails to break through the market). Furthermore, it may be impossible to establish in advance whether a technology is disruptive before that technology enters the market. This aspect can be a limitation if one wants to employ Clayton Christensen's classification to handle technological innovations. Autonomous driving is a case in point (Arfini et al. 2022). Fully autonomous vehicles may be considered "disruptive" from the technological point of view. However, until they are brought to the market, it is impossible to determine their impact. It is possible that most people will not trust the new technology and consequently decide not to switch to fully autonomous vehicles in the future; examples of innovative technologies that failed in the market abound in the history of technology. Therefore, partially autonomous vehicles may be more disruptive from the economic point of view, even though fully autonomous vehicles may be more disruptive from the technological point of view.

Third, Henderson and Clark's perspective is based on the introduction of new components into a technological product and on possible reconfigurations of the components. There is no acknowledgement or explanation of the societal preferences and values associated with a new technology that may clarify the reasons why a new component is introduced and/or why a different relationship between technological components has been created. What is missing in Henderson and Clark's classification is thus a clear acknowledgement of the peculiar normative aspects of technologies that extend beyond the simple interplay among components.

Finally, and more generally, all the proposed classifications do not take into account the severe uncertainty that is commonly related to the complexity of productive technological systems and their social impacts.[3] As stressed by Nowotny (2008, pp. 120–121), "From an empirical standpoint, processes of innovation are the result of specific activities that aim at introducing new products or at altering production processes. At any rate, they cannot be understood as something routine, whose results are foreseeable in detail. The theoretical problematic lies in the fact that the success of innovative procedures is unforeseeable and in the resulting problem of discontinuous change". For example, autonomous vehicles base their driving decisions on a risk calculation performed by the system and that system often integrates data shared by other autonomous cars on the road. Therefore, it may be impossible even for the company that produces the vehicle to anticipate how it will

[3] The social and political control of new technologies, especially highly innovative ones, is indeed subject to the so-called Collingridge dilemma (Collingridge 1980): "we cannot predict the eventual shape or effects of complex technologies as they emerge and, by the time we know, it will be too late to change direction" (Stilgoe 2019, p. 9). See also Rosenberg (1996).

behave in a particular situation, which may have consequences also for the allocation of responsibility in the case of an accident (Taebi, 2020).

In conclusion, we think that a more convenient approach consists in starting with uncertainty and using it to develop a new taxonomy of technology innovation.

3 Crucial, Undervalued Issue for Technological Innovation: Uncertainty

Since the nature of technological innovation is permeated by uncertainty, we claim that a focus on it provides the proper basis on which to understand different types of innovation. On the one hand, technological innovation may face uncertainties and ambiguities due to a lack of knowledge about the future. The future, in particular the distant future, is an obvious reason for uncertainty (Jalonen, 2012). On the other hand, without uncertainty, there would be no need to innovate (Bernasconi et al., 2013; Julien & Marchesnay, 1996). This means that uncertainty poses, at the same time, constraints as well as opportunities for technological innovation.

It has been recently argued that uncertainty can change the nature of the innovation process itself (Furr, 2021). However, both uncertainty and innovation come in many different forms and their mutual relationships may be used to dismantle their dynamics, especially in the technological field. The role of uncertainty in technological innovation is significant to the point that predictions are almost always unjustified and incorrect (Hansson, 2011). Therefore, we need to think about possible scenarios and alternative futures for technological innovation (Sarpong and Maclean, 2011). This means that stories are not always repeated in technological innovation. This fact has been recognised to be due to the intrinsic uncertainty of most contemporary technology. The main reasons for this uncertainty are the lack of complete control over technology and the possible coordination problems among all the different players involved in the process of technological innovation (Bernasconi et al., 2013).

However, clear acknowledgement of the forms of uncertainty is almost always lacking in technological innovation studies. This is unfortunate because the interplay among uncertainties can better explain different types of technological innovation and may help to envisage possible alternative futures for different technologies rather than providing empty or unjustified predictions. Furthermore, recognising this interplay may help public actors to take decisions regarding the regulation of technology.

Uncertainty comes in different forms. A classic way to consider uncertainty is to talk about "risk". However, the concept of risk may have different meanings and conceptualisations among different disciplines and even within the same field.[4] At

[4] For instance, in those disciplines interested in disaster risk mitigation methods, "risk" is usually defined in terms of hazard, vulnerability, and exposure (UNISDR 2015). These components of risk make sense from a policy-oriented perspective since risk can be mitigated (when possible) by reducing the hazard, the exposure, or the vulnerability. More generally, a comprehensive source for the philosophical and social aspects of risk is Roeser (2012). For some informal definitions of risk that go beyond technical definitions, see Chiffi and Chiodo (2021).

any rate, a probabilistic and consequentialist definition of risk is usually adopted in probabilistic risk assessment. Risk is considered in this case to be the probability of an adverse event evaluated in conjunction with its consequences in a specific lapse of time (Royal Society, 1983). When one can be confident of one's probabilistic estimations, and when consequences can be easily predicted and evaluated, this can be a viable definition. However, as we have already underscored, this is not always the case when considering technological issues, given the intricacies of possible severe forms of uncertainty.[5]

The non-probabilistic form of uncertainty is usually termed "severe", "fundamental", "radical", or "deep" uncertainty, and it is differentiated from probabilistic risk (Hansson, 1996; Kay & King, 2020; Keynes, 1973; Knight, 1921; Langlois, 1994; Shackle, 1961; Simon, 1947). The technical meanings of risk and uncertainty can become distant from their everyday use, and the dichotomy between probabilistic risk and other forms of uncertainty is not always accepted. A common view is that a subjectivist interpretation of probability can be meaningfully attributed to any event, so that decisions can be based on the (expected) utility obtained by summing up the values to the agent of all possible outcomes, each weighted by the probability (expressing the agent's belief about) of that outcome. This is basically the view that "all human behaviour can be regarded as involving participants to maximise their utility from a stable set of preferences and accumulate an optimal amount of information and other inputs in a variety of markets" (Becker, 1978, p. 14).

We do not want to reignite the old controversy regarding the possibility of applying probability to all kinds of events and for all types of uncertainty.[6] Nevertheless, in line with Hansson (2022), we think that not all forms of uncertainty can be easily handled by probabilities, or even formalised or quantified. For instance, forms of interactive uncertainty involving the mutual behaviours occurring between individuals or between institutions and individuals can be at least qualitatively assessed and formalised with epistemic game theory (Chiffi & Pietarinen, 2017; Perea, 2012), while we do not possess any way to formalise or quantify forms of agential uncertainty related to the behaviour of one's own future actions (in particular about whether one will implement the decision that one makes) or structural uncertainty, which concerns the structure and the proper delimitations of decisions, including uncertainty about which options are really available to people, and uncertainty about the spatial and temporal boundaries of their decisions (in particular, how far in the future the outcomes considered will occur).

[5] There may be other ways to distinguish between risk and uncertainty. For example, risk may seem more related to an objective dimension, whereas uncertainty may seem more akin to an epistemic condition. We thank an anonymous reviewer for raising this point. For a political and question-answer view on uncertainty, see (Floridi 2015).

[6] Charles Peirce wrote, for instance, that when referring to plausible or abductive inferences in science, there is no need to assign probabilistic value to such inferences before they are empirically tested. He pointed out that "not only is there no definite probability to the conclusion, but no definite probability attaches even to the mode of inference. We can only say that […] we should at a given stage of our inquiry try a given hypothesis, and we are to hold to it provisionally as long as the facts will permit. There is no probability about it. It is a mere suggestion which we tentatively adopt" (Peirce 1898 [1992], p. 142).

Unlike empirical uncertainty, agential uncertainty and structural uncertainty are impossible to quantify in probabilistic terms.

Even when accurately taken, evidence-based decisions may face the inherently problematic limitations of the aforementioned types of uncertainty. This does not mean that probability theory and other tools used to formalise or measure uncertainty are useless, but only that there are forms of uncertainty that are somehow intractable and seem to be resistant to quantification and measurement with current formal methods in decision theory, such as probabilities, credal sets, and belief functions. More generally, resolvable uncertainty is uncertainty that can be removed: this is more likely to happen in the case of quantifiable uncertainty (Kay & King, 2020), while in the case of severe uncertainty, we simply do not know, for instance, the statistical distribution of the phenomenon of interest, and a method to mitigate such uncertainty may be difficult to find.[7] Moreover, when uncertainty is quantifiable (as in the case of probabilistic risk), there is the assumption that all relevant events are somehow listable ex ante before the decision (O'Driscoll & Rizzo, 1985). This is the case of gambling at a casino; in this case, expected utilities can be easily computed since the gambler knows all potential outcomes in advance and can compute the probability of a specific outcome, as well as its potential consequences. In the case of more mundane forms of uncertainty, this is not always possible, and there may be impediments to knowing the set of all alternatives that may occur (O'Driscoll & Rizzo, 1985). There is, in this case, always room for unpredictable events (Moroni, 2012).

From a methodological perspective, we maintain that distinguishing probabilistic forms of uncertainty from others is still analytically coherent and fruitful. As we have seen, on the one hand, uncertainty is assumed to be something negative that people want to mitigate. This is, of course, true. On the other hand, technological innovation is, indeed, hardly conceivable in a context devoid of any form of uncertainty. Briefly put, uncertainty triggers innovation, and many contemporary forms of technological innovation are often linked to highly uncertain contexts in which contingencies may help people to "think outside the box" and explore new scientific and technological paths.[8]

In the next section, we will focus on empirical forms of uncertainty, notably probabilistic risk and severe uncertainty and their impact on innovation.

4 Types of Technological Innovation and Uncertainty: a New Approach

Most existing taxonomies of technological innovations are purely market-based. These taxonomies tend to neglect the severe uncertainty that is related to innovation processes and their societal impacts. Moreover, these taxonomies cannot be applied

[7] Woods (2019) critically discusses the three following perspectives on how to deal with semantic knowledge and uncertainty: *subduance* (new knowledge is acquired that solves the problem), *surrender* (the agent in question removes this unmet target from his/her current cognitive agenda), and *abduction* (a semantically formulated hypothesis is abductively inferred).

[8] The ability of a system to take advantage of a shock has been called "antifragility" (Taleb 2012).

to products that have not yet been marketed. In this section, we will claim that these limitations can be overcome.

Inspired by the seminal works of Thompson (2003) and Karen Christensen (2007), we propose a new framework in which to classify and handle technological innovation. This framework is based on situations of quantifiable empirical uncertainty (with the use of probabilities or other methods to measure uncertainty) and on situations of severe empirical uncertainty (which is usually difficult to quantify). Thompson's (2003, p. 134) taxonomy acknowledges that in decision-making "there could either be certainty or uncertainty regarding causation, and certainty or uncertainty regarding outcome preferences", whereas Karen Christensen's (2007) taxonomy points out that the technologies used in planning can or cannot be known and that the planning goals can or cannot be agreed upon. Each taxonomy generates four prototypical alternatives. Both of them have a special meaning for a planning approach, whereas our taxonomy is used to identify and understand different types of technological innovation. In other words, Thompson's and Christensen's taxonomies were intended to be used in planning theory, while, in interpreting innovation in itself, we deem it better to consider societal preferences rather than the goals of planning decisions. Our contention is that different forms of technological development require distinct views based on the nature of the uncertainties and societal preferences involved. Furthermore, given the pervasiveness of the concepts of risk and severe uncertainty in technological innovation, we propose a taxonomy that does not include rationalist approaches to decision-making in which technologies and goals are certain and shared (as in Thompson (2003) and Karen Christensen (2007)).

We propose a new taxonomy based on different forms of empirical *uncertainty* (i.e. quantifiable uncertainty or severe uncertainty) and on societal *preferences*[9] (they may exist prior to the creation of the technology, or they may be fostered by the technology itself). Many traditional technologies were created to satisfy some societal preferences that existed before the technology. However, this has not always been the case. When in 1984 Jeep launched one of the first SUV models, there was no societal preference for this type of car. We could say that Jeep also created societal preferences for this technology. Our thesis is that the interaction of quantifiable and non-quantifiable empirical uncertainty with the satisfaction of pre-existing societal preferences or the institution of certain preferences is essential to understanding alternative approaches to technology development and innovation.

Hence, the taxonomy that we propose comprises the following four types of technological innovation:

i. *Incremental type*, i.e. a simple extension of previously existing technologies in order to satisfy pre-existing societal preferences; in this case, there is quantifi-

[9] By "preferences", in a very broad sense, we mean any desire, interest, and predilection that someone might have. The adjective "societal" merely alludes to preferences in a certain society. In cases in which societal preferences exist prior to the creation of a new technology, these preferences are, strictly speaking, preferences for the opportunities and performances that the new technology is able to provide.

able empirical uncertainty and societal preferences pre-date the creation of the new technology

ii. *Adaptive type*, i.e. a technological development in which there are no pre-existing societal preferences, but an existing technology may be easily adapted while generating new societal preferences; in this case, there is quantifiable empirical uncertainty, and societal preferences are created along with the new technology

iii. *Radical type*, i.e. a development of a brand-new technology occurring under severe uncertainty but with clear pre-existing societal preferences to be satisfied; in this case, there is severe empirical uncertainty, and societal preferences pre-date the creation of the new technology;

iv. *Frontier technology type*, i.e. a technology developed in highly uncertain contexts with a clear potential to create a multitude of not-yet-specified societal preferences; in this case, there is severe empirical uncertainty, and societal preferences are created together with the new technology.[10]

We now consider these four types of technological innovation in detail.

i. *Incremental Type*

Incremental innovation introduces relatively minor improvements or simple adjustments to current technology. It exploits the potential of the established know-how and often reinforces the dominance of established firms. Although it draws from no dramatically new science, it often requires remarkable technological skills (Banbury & Mitchell, 1995; Dewar & Dutton, 1986). This is a weaker form of innovation, in which all potential future developments of a technology are somehow conceivable in advance, and uncertainty can be easily quantified and resolved. More importantly, the main societal preferences related to this (incremental) technology are stable and clear. This means that it is known how to extend the technology, and in which direction, to meet specific societal preferences.[11] An incremental innovation is, for instance, a new model of an established brand of smartphones (e.g. iPhone), which clearly improves and extends the functions of the previous models but does not alter the core functions.

ii. *Adaptive Type*

The adaptive situation implies the possibility of supporting a range of possible future configurations of a technology based on conditions for development and innovation. These conditions generate "possibility spaces" and reflect a set of desirable objectives to be achieved through the adaptive process. The idea here is that potential

[10] We are not assuming that this is the only way to characterise technological innovation. Nevertheless, we believe that our characterisation of different forms of technological innovation may go beyond the standard economic view on innovation because it encompasses issues related to uncertainty and societal preferences.

[11] Unlike Henderson and Clark (1990), we use the term "incremental innovation" in relation to the type of uncertainty and the nature of social preferences.

future alternatives can still be listed ex ante, and radically new possibilities are not envisaged. Nonetheless, adaptive technologies in general show complexity, non-linearity, and dynamic behaviour (Harkema, 2003). They are characterised by forms of uncertainty that are not severe, even if they may be significant. The structure of adaptive technology is modifiable to promote different configurations, thus meeting new societal preferences that may change over time. An adaptive innovation is, for instance, the introduction of different driving modes of the engine control unit of a car (in-city mode, sport mode, eco mode, etc.) which leaves it to the driver to choose according to the conditions of the road. Adaptation is indeed a teleological notion, because it generally requires an adaptation to something new. Without a clear formulation of new societal preferences, it is difficult to imagine how technology can be adapted. The notion of resilience seems particularly connected to the adaptive view. A technological system can be considered resilient if it can withstand, recover, and adapt after an external shock. For instance, "the (electric) power system resilience is the ability of this system to withstand disasters (low-frequency high-impact incidents) efficiently while ensuring the least possible interruption in the supply of electricity" (Raoufi et al., 2020, p. 2). In this case, the possible scenarios associated with a potential shock are clearly listable in advance, and the power system may adapt itself for the emergency situations of a scarcity of electricity.

iii. *Radical Type*

Radical innovation is a type of innovation which is highly discontinuous and with a revolutionary nature. It is a type of innovation that improves a product or service in an unexpected way. In this perspective, the societal preferences to be satisfied can be clear and fixed, but there is (or there was) severe uncertainty concerning the possibility of developing a new suitable technology. When a radically new technology is introduced, it is likely to face severe uncertainty, particularly at the beginning. This type of technological innovation either disturbs or imposes a major change on an existing technological system. This is the case, for instance, of smartphones, cryptocurrencies, drones, and self-driving cars. After reaching mainstream users, technologies implying radical innovation can be considered "disruptive" if they grow exponentially in the market (Christensen, 1997). In our view, the notion of disruptive technology usually involves two dimensions: it is radical, and its growth in the market is exponential. Unfortunately, quite often, these two dimensions are not demarcated; and as a result, the notion of disruptive innovation (and technology) has an unclear interpretation. It is for this reason that we prefer to consider disruptive those radical technologies that have already shown their deep impact on the market. However, unlike Markides (2006, p. 21), we do not claim that there are "two specific types of disruptive innovations—namely, business-model innovations and radical (new-to-the-world) product innovation"; rather, we claim that being disruptive[12]

[12] We are thus differentiating what is defined simply as "disruptive" from other phenomena called "social disruption" or "moral disruption". See Nickel (2020), Hopster (2021), Nickel, Kudina, van de Poel (2022), and van de Poel (2022).

without any other qualification is just a market-oriented notion, while being radical is a strictly technological one. For example, fully autonomous vehicles might be considered a radical innovation from the technological point of view, but they are not disruptive because they are almost entirely absent from the market.

iv. *Frontier Technology Type*

Frontier technologies are technologies based on interdisciplinary research that have been developed but have not yet been adopted or are at least scarcely accepted.[13] They may "alter the way people live and work, rearrange value pools, and lead to entirely new products and services" (Ramalingam et al., 2016, p. 16). Examples of frontier technologies based on advanced scientific research include advanced robotics, quantum computers, and reusable rockets. This means that even if this type of technology may show a high level of efficacy at an experimental level, its impact on society may be still unclear, and its pragmatic implementation (effectiveness) may be problematic.[14] This implies that severe uncertainty exists concerning the adoption of certain technologies at the social level and that there are no societal preferences that pre-exist them. There is room in this case for many unknown technological scenarios that may conflict with individual or social values and recommendations. Taking decisions about these technologies is therefore complex. Frontier technologies, indeed, exhibit absolute novelty and uncertainty, and their potential applications and connected societal preferences are somehow instituted by the creation of the technology in itself. Indeed, in addition to severe uncertainty, there is no shared vision concerning potential achievements and regulations of this kind of technology and its ethical and social impacts. Economic-based approaches treat the uncertainty related to innovation mainly from the perspective of the social adoption of the new technology. However, the societal impact of a new technology may also include its effects on the labour market, the disruption that it may cause to social institutions and environmental damage (Hansson et al., 2021). On the one hand, frontier technologies can be extremely complex, but, on the other hand, they possess the highest level of innovation potential since they may dramatically impact on society. Consequently, decision-making in regard to frontier technologies can be challenging.

5 Innovation and the Dual Nature of Technology

A remarkable feature of our framework for types of innovation is that it is coherent with an epistemological reading of the functional representation of technologies. Bonaccorsi (2011) points out that innovation can be characterised by considering

[13] To be noted is that we do not assume that there is a strict correspondence between pre-existing technologies and quantifiable uncertainty, on the one hand, and new technologies and severe uncertainty on the other, even though it is easier to quantify the uncertainty related to products that merely improve on already existing technologies (Taebi 2020). We are grateful to an anonymous reviewer for encouraging us to clarify this point.

[14] The distinction between efficacy (experimental internal validity) and effectiveness (external validity in a target population) is standard in clinical research and for medical technologies. See Rothman, Greenland, and Lash (2008).

the dual nature of technology, meaning that technological artefacts can be of course physically produced, but unlike other types of physical objects, they are created in order to achieve specific human goals: this is their aim or function (Dipert, 1993 and 1995; Kroes & Meijers, 2006; Vermaas & Houkes, 2006; Lorini et al., 2021). This means that an artefact can be described as a designed physical structure and in terms of the functions related to human intentions.[15] Likewise, technological innovation may be conceived in terms of structural and functional factors.

The "dual nature" of technical artefacts has both ontological and epistemological aspects (Kroes, 2010). From an ontological perspective, technical artefacts are mind-dependent entities different from physical objects,[16] while, from an epistemological perspective, the knowledge of artefacts pertains to two different kinds, in the sense that *functional* and *structural* descriptions of artefacts are logically distinct. This means that from an artefact's functional description, we cannot logically infer its structural properties, and vice versa, coherently with the well-known is-ought dichotomy. Different functions can be realised in the same structure, and artefacts with the same structure can be implemented in order to perform different functions. However, as said above, this does not mean that functional and structural descriptions are not related to one another.

In our taxonomy, we consider the different levels of empirical uncertainty as constituting the main structural factor explaining technological innovation, whereas the adherence to or the influence on societal preferences is considered the main functional factor. As acknowledged by Kroes (2010, p. 56), "two specific contexts of intentional human action are of particular interest, namely the engineering design context and the user context". Even if from an ontological perspective, the design context can be viewed as the most important functional factor since it is somehow constitutive of the artefact, from our epistemological perspective, sensitive to technological innovation, the function of a technical artefact is mainly related to the aims of human action and social preferences.

This means that focusing on economic factors alone does not allow one to handle the multifaceted dynamics of innovation, which also require structural and functional factors coherently with the dual nature of technologies. A crucial limitation of most economic taxonomies, indeed, is that they cannot be applied to innovations that have not yet been marketed. These classifications are therefore ill-suited for policy-making, which must take decisions in advance on how to regulate emerging technologies. Our classification, by contrast, is based purely on different types of uncertainties (quantifiable or severe) and different types of societal preferences (pre-existing or created) that are connected to the new technology.

[15] Functions in technology may convey different meanings and require alternative types of formalisation. See Carrara, Garbacz, and Vermaas (2011). A classic distinction between structural and functional descriptions of objects was introduced by Polanyi (1958).

[16] See Masolo and Sanfilippo (2020) for a recent framework in which it is possible to analyse and compare selected theories about technical artefacts present in the literature.

6 Concluding Remarks

Technological innovation is almost always investigated from the economic perspective, with a focus on creating commercial value. With very few exceptions, the specific technological nature of innovation is rarely considered.

In this article, we have argued that a novel way to characterise and make sense of different types of technological innovation is to start considering (the intricacies of) uncertainty. This seems to be a plausible approach since technological development and innovation almost always occur under conditions of uncertainty. We have distinguished empirical uncertainty that can be quantified (e.g. probabilistic risk) from severe and empirical forms of uncertainty that may resist being quantified. Relying on these different ingredients of uncertainty in technological innovation, we have proposed a new taxonomy that may reveal the nature of innovation.[17]

Unlike previous taxonomies used to handle different types of technological innovation, our taxonomy does not consider solely the economic value of innovation (which of course cannot be neglected) and is much more oriented towards societal preferences. This is especially true in the case of the radical view and the frontier technology view of innovation, where societal preferences related to a new technology are created by the technology itself. This means that future changes in the values and societal preferences associated with these two types of technological innovation may induce new forms of social and individual experimentation (Van de Poel, 2016; Moroni & Chiffi, 2022) and require a reformulation of the design and the implementation strategies of the technology. But this is precisely the dynamic of genuine innovations, which have influence on societal preferences and may involve social experimentation. Finally, we have investigated the coherence of our proposal with the epistemological reading of the dual nature of technological artefacts, showing that innovation can be grounded on structural and functional factors, not just economic ones. In particular, changes in the function of technology may enhance different forms of innovation.

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[17] In future research, we would like to investigate the impact of uncertainty in technological innovation on different stakeholders.

Declarations

Ethics Approval Not applicable
Consent for Publication Not applicable

Competing Interests The authors declare no competing interests.

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