Journal of
Innovation, Technology and Knowledge Economy
econsciences.com

Volume 1 March 2025 Issue 1

Invasive technologies: Technological paradigm shift in generative artificial intelligence

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Abstract. This study proposes a new concept that explains the modern technological change: technology invasiveness that breaks into a scientific and technological ecosystem, with accelerated diffusion of massive quantities of products leading to main change in the innovation ecotone that transfers knowledge and know-how in businesses and markets. Invasive technologies conquer scientific, technological, and business space of alternative technologies and expand the knowledge space of adjacent possible by introducing radical innovations that support dynamic interactions between new technologies and emerging development and applications. This theoretical approach is empirically verified in emerging path-breaking technology of transformer, a deep learning architecture having unsupervised and semi-supervised algorithms that create new contents and mimics human ability (Generative Artificial Intelligence). Statistical evidence here, based on patent analyses, reveals that the growth rate of transformer technology is 55.82% (over 2016-2023) more than double compared to 23.02% of all other technologies, such as Convolutional Neural Network: it is force that is revolutionizing the way societies interact with machines. Hence invasive technologies are considered as one of the major causes of global technological change and this study offers a profound exploration of how invasive technologies drive technological change, significantly contributing to our understanding of technological evolution's dynamics and its societal and industry impacts.
Keywords. Technology invasiveness, Technological change, Innovation ecotone, Generative artificial intelligence, Patent analysis.
JEL. C55, O31, O33.
SDGs. SDG8, SDG9.

1. Introduction

The goal of this study is to suggest a new concept the drives technological and social change: accelerated invasiveness of new technologies that is a characteristic hardly known. Invasion is anything that breaks into a place, occupying it or spreading in enormous quantities in the short run. In nature there are different aspects of invasion: in botany the invasive plants invade lands and human habitats (Walker & Smith, 1997; Gholizadeh et al., 2024); in biology the invasive organism is not indigenous to a particular area and causes environmental harm (Pelicice et al., 2023); in medicine, the invasive cancer navigate in different tissue microenvironments of the body (de Visser & Joyce, 2023; Krakhmal et al.,

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2015). This study extends the scientific concept of invasiveness, in a broad analogy, to explain the dynamics of technological change in a theoretical framework of generalized Darwinism (Hodgson & Knudsen, 2006; Wagner & Rosen, 2014). The principal goal is to propose in science the invasive behaviour of technologies to analyze the dynamics of path-breaking technologies that destroy established technologies, occupy their space, and become dominant technology supporting technological and social change. The proposed concept of technology invasiveness is supported with a technological and statistical analysis of the innovative technology of transformers (a neural network) that drives Generative Artificial Intelligence (AI). The invasive behaviour of new technology is especially relevant in a world of rapid technological change with aspects of 'creative destruction' in existing products and competences in science, technology, markets, and society (Teece et al., 1997; Tripsas, 1997). Invasive technologies pave the way for development of many inter-related technologies by ''expanding the adjacent possible'' in science and technological fields (Coccia, 2018; Coccia & Watts, 2020; Kauffman, 2000, 2016, 2019; Kauffman & Clayton, 2006; Kauffman & Gare, 2015; Lehman & Kauffman, 2021; Wagner & Rosen, 2014). In addition, the analysis of the technology invasiveness can create the framework within which a synthesis of basic properties on evolutionary pathways could be worked out, extending lines of research to explain technological evolution in modern economies. The behaviour of invasive technologies can extend the theories of technological evolution and diffusion with a new conceptual approach to explain modern scientific and technological change for a better theory that supports effective science and technology policy implications for societal benefits. Hence, this study offers a profound exploration of how invasive technologies drive technological change, significantly contributing to our understanding of technological evolution's dynamics and its societal and industrial impacts.

2. Current approach to disruptive technologies

One of the fundamental problems in technological studies is the behaviour of drastic technology in economic system and society (Dosi, 1988; Rogers, 1962; Sahal, 1981; Utterback et al., 2019; Utterback, 1994). One of the most important frameworks is based on disruptive technology that significantly alters established industries and markets, creating new sectors and business models (Colombo et al., 2015). A technology that generates radical innovations that radically change the way the market structure and how products and services are yielded and consumed. Disruptive innovation by Christensen (1995) causes a relevant change and abruptly interrupts the way in which industries, firms, and consumers operate.

One of the characteristics of destructive technology that generates radical innovations, based on new products and/or processes, is high technical and/or economic performance directed to reduce market share or destroy the usage value of established technologies/products/processes previously used (Christensen, 1997; Christensen et al., 2015; Tria et al., 2014). Calvano (2007) maintains that "Destructive Creation" is the deliberate introduction of new and improved generations of products that destroy, directly or indirectly, current products inducing consumers to change their habits with consequential economic and social change. The dynamics of disruptive technologies generate technological, industrial, economic, and social change (Coccia, 2020). Adner (2002, pp. 668-669) claims that: "Disruptive technologies . . . introduce a different performance package from mainstream technologies" (cf., Adner and Zemsky, 2005; Calvano, 2007; Coccia, 2019). Abernathy and Clark (1985, pp. 4ff and pp. 12-13) clearly mention that: "An innovation is . . .. derived from advances in science, and its introduction makes existing knowledge in that application obsolete. It creates new markets, supports freshly articulated user needs in the new functions it offers, and in practice demands new channels of distribution and aftermarket support. In its wake it leaves obsolete firms, practices, and factors of production, while creating a new industry.... innovation that disrupts and renders established technical and production competence obsolete, yet is applied to existing markets and customers, is … labelled 'Revolutionary'. It thus seems clear that the power of an innovation to unleash Schumpeter's 'creative destruction' must be gauged by the extent to which it alters the parameters of competition, as well as by the shifts it causes in required technical competence. An innovation of the most unique and unduplicative sort will only have great significance for competition and the evolution of industry when effectively linked to market needs".

Christensen (1997) argues that disruptive technology has specific characteristics: a) higher technological performance; b) provide products/processes that satisfy the needs that are demanded by mainstream market. Christensen et al. (2015) claim that disruptive technologies can be generated by small firms with fewer resources that successfully challenge established incumbent businesses (e.g., the case of OpenAI for ChatGPT, funded in 2015). Innovative firms, generating disruptive technologies and innovations, grow more rapidly than other ones (Abernathy & Clark, 1985; Tushman & Anderson, 1986, p. 439). Christensen's (1997) approach also shows that disruptive technologies or innovations (these terms are used here interchangeably) generate significant shifts in markets and society (cf., Henderson, 2006). In general, technological and market shifts of path-breaking technologies embody competence-destroying because these technologies destroy the competence of established technologies existing in industries (cf., Hill & Rothaermel, 2003; Tushman & Anderson, 1986). Moreover, disruptive innovations undermine the competences and complementary assets of existing producers, and change habits of consumers, fostering economic changes in many sectors (Christensen & Raynor, 2003; Garud et al., 2015; Markides, 2006; cf., Coccia, 2005). The diffusion and growth rate of disruptive innovation are also important drivers to create and sustain competitive advantage of firms and nations amidst rapidly changing business environments (Kessler & Chakrabarti, 1996, p. 1143; Porter, 1980). Disruptive technology also generates a process of actual substitution of a new technique for the established one and, consequently, affects the behaviour of manifold inter-related technologies generating a new technological paradigm with different technological trajectories in industries (Sahal, 1981; Fisher & Pry, 1971).

In this context, the study here proposes that the concept of invasive technology in order to develop the approach of disruptive technologies to explain rapid technological change in modern economies. Next section presents the research philosophy, methodology and study design to structure the theory and empirical evidence of basic predictions.

3. From disruptive to invasive technologies

3.1. Research philosophy of the study

The proposed theoretical framework here is developed with an evolutionary perspective of technological change guided by generalized or universal Darwinism (Dawkins, 1983; Nelson, 2006; Levit et al., 2011). Hodgson (2002, p. 260) maintains that: "Darwinism involves a general theory of all open, complex systems". In this context, Hodgson & Knudsen (2006) suggest a generalization of the Darwinian concepts of selection, variation, and retention to explain how a complex system evolves (cf., Hodgson, 2002; Stoelhorst, 2008). In the economics of technical change, and in Science of Science (Sun et al., 2013) the generalization of Darwinian principles ("Generalized Darwinism") can assist in explaining the multidisciplinary nature of scientific and technological processes (cf., Hodgson & Knudsen, 2006; Levit et al., 2011; Nelson, 2006; Schubert, 2014; Wagner & Rosen, 2014). In fact, the heuristic principles of "Generalized Darwinism" can explain aspects of scientific and technological development considering analogies between evolution in biological systems and scientific-technological systems (Oppenheimer, 1955; Price, 1986). Arthur (2009) argues that Darwinism can explain technology and science development as it has been done for the development of species in the environment (cf., Schuster, 2016, p. 7). Kauffman & Macready (1995, p. 26) state that: "Technological evolution, like biological evolution, can be considered a search across a space of possibilities on complex, multipeaked 'fitness,' 'efficiency,' or 'cost' landscapes". Schuster (2016, p. 8) shows the similarity between technological and biological evolution, for instance technologies have finite lifetimes like biological organisms. In general, technological, and scientific evolution, such as biological evolution, displays novelty, radiation, stasis, survival, adaptation, extinctions, etc. (Bowler & Benton, 2005; Kauffman & Macready, 1995; Solé et al., 2013). However, the invasive behaviour in the domain of science and technology is hardly investigated in social studies of technology but it can be basic to explain important characteristics of technological evolution. The general theoretical background of "Generalized Darwinism" (Hodgson & Knudsen, 2006), described here, can frame a broad analogy between science and technology processes and similar ones in botany and biology that provides a logical structure of scientific inquiry to analyze invasive behaviour of technologies in economic systems and society (Coccia, 2019; Ziman, 2000).

3.2. Theory of invasive technologies

Invading organisms or elements play important roles in ecology (Wang & Kot, 2001). However, the role of invasive behaviour in the study of technologies and innovations is unknown but its examination is basic for uncovering new basic aspects of technological diffusion, evolution, and change.

Some basic concepts structure the proposed theoretical framework:

- Invasion is an element that bursts and spreads in space, occupying the position of other elements in system.
- Invasive technologies can replace, in a specific system, other technologies in several life cycles, producing new technologies and innovations that have the potential to spread in different domains and sectors leading to technological, economic, and social changes in the invaded environment (impacts')

Postulates

- Invasive technologies are a driver of technological and social change.
- Invasive behaviour ◎ technological evolution
- Invasive technologies change systems and have an adaptive behaviour to different systems and at the same time eliminate the less suitable technologies, leaving the more suitable ones to survive.

Predictions of the theory of invasive technologies

Testable implications of the theory of invasive technologies are:

◎ Technological change =f(invasive technologies)

◎ Rate of growth of invasive technology i in a system S is > 2 ◎ rate of growth in alternative technologies j, j=1, …, m

◎ Invasive technology (i) is better adapted than alternative technologies (j) in S, if and only if (i) can spread, survive, and produce new innovations in S than is (j) over time.

Figure 1 shows the interrelationships of invasive technologies in innovation ecosystem.

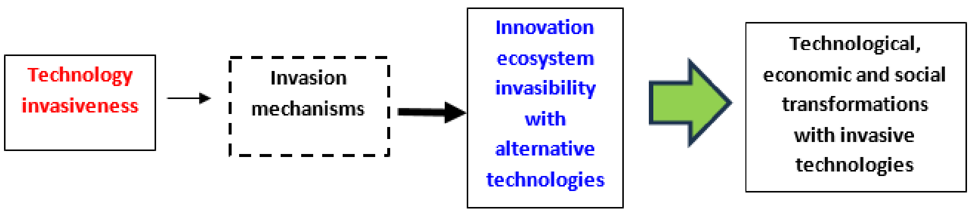

Figure 1. A Schematic diagram of invasive technologies

3.3. Research setting to evaluate the theoretical prediction of invasive technologies: case study of Transformers Technologies

The predictions of proposed theory of invasive technologies are verified empirically in some main technologies. In the context of R&D of new products and processes in Artificial Intelligence (AI), this study focuses on new technology of transformer architecture, a new type of neural network, described by Vaswani et al. (2017). Transformer architecture from 2018 is developing pretrained language models (Generative Pretraining Transformers, GPTs), such as OpenAI's GPT series and Google's Bidirectional Encoder Representations from Transformers (BERT) model with radical innovations of ChatGPT introduced in 2022 and Microsoft Copilot started on February 2023.

Before transformer models, established Recurrent Neural Networks (RNNs) are powerful technologies, but they have limitations, such as slow training, do not retain old connections well, etc. Instead, new architecture of transformer technology is based on three powerful elements: a) self-attention; b) positional embeddings and c) multi-head attention. Unlike traditional RNN models, transformer models are designed to learn contextual relationships between words in a sentence or text sequence by the mechanism of self-attention, which allows the model to weigh the importance of different words in a sequence based on their context (Menon, 2023). Transformer models have revolutionized some research fields, such as Natural Language Processing (NLP) for tasks of language modeling, text classification, question answering, sentiment analysis, computer vision, spatial-temporal modeling for video analysis or time series data, and other ones (Menon, 2023). A critical advantage of transformer model is the ability to process input sequences in parallel, which makes this technology faster than RNNs for many NLP tasks (Dell, 2023). One of the main radical innovations in transformer technology is the development of large-scale, pretrained language models, referred to as Generative Pretraining Transformers (GPTs), such as OpenAI's GPT series, from GPT-1 in 2018 to ChatGPT-4 in 2023 capable of generating human-like content (OpenAI, 2015, 2022); Google's Bidirectional Encoder Representations from Transformers (BERT) model (Devlin et al., 2018); Microsoft copilot (Mehdi, 2023), etc. These pretrained models can be used for specific NLP tasks with reduced additional training data, making them highly effective for a wide range of NLP applications, such as (cf., Assael et al., 2022; Kariampuzha et al., 2023): machine translation, document summarization, document generation, named entity recognition, biological sequence analysis, writing computer code based on requirements expressed in natural language, video understanding, computer vision, protein folding applications, etc.

Overall, then, science advances in computer sciences have generated the advent of the large language model (LLM, Bowman, 2023). In this domain, new technology of transformers is directed to model some activities of the human brain with the generative AI — software that can create plausible and sophisticated text, images and computer code at a level that mimics human ability (Pinaya et al., 2023; Tojin et al., 2023). Transformer architecture has revolutionized the field of LLM with main applications in NLP by with radical innovation in GPTs directed to shape the landscape of generative AI. Transformer models are a main case study to explain pervasive and invasive behaviour of technologies that support technological change in society (Dosi, 1988).

3.4. Study design

The proposed theory of invasive technologies is evaluated with a patent analysis in emerging transformer technology (a type of deep learning model used in natural language processing-NPL- and in generative Artificial Intelligence). We also analyze a previous technology, the Convolutional Neural Networks, in short CNN, for a comparative analysis of these main technologies in Large Language Model to explain characteristics and properties of the invasive technologies that can explain technological evolution and change.

- Logic structure of search string

In order to detect accurately the science dynamics of transformers in the library database Scopus (2024), we define General Domain D with following search string directed to detect patents over time:

D= ("machine learning" OR "data science" OR "artificial intelligence").

After that we refine the Domain for two technologies under study: Transformer and CNN.

- Transformers, period under study 2017-2023

Domain Restricted for Transformers is called DTR.

DTR= ("machine learning" OR "data science" OR "artificial intelligence")

AND

("large language models" OR "LLM" OR "Natural Language Processing" OR "Natural Languages" OR "Sentiment Analysis" OR "Text Mining" OR "Question Answering Systems" OR "Semantic Web" OR "Chatbot" OR "Knowledge Representation" OR "Natural Language Understanding" OR "Text-mining" OR "Opinion Mining" OR "Topic Modeling" OR "Word Embedding")

Or

DTR= (D) AND ("large language models" OR "LLM" OR "Natural Language Processing" OR "Natural Languages" OR "Sentiment Analysis" OR "Text Mining" OR "Question Answering Systems" OR "Semantic Web" OR "Chatbot" OR "Knowledge Representation" OR "Natural Language Understanding" OR "Text-mining" OR "Opinion Mining" OR "Topic Modeling" OR "Word Embedding")

To detect the impact of Transformers (TRF) on science that is also used with other terms, the search string is given by:

TRF= (DTR) AND ("bert" OR "chatgpt" OR "transformer" OR "attention mechanism"). This set TFR includes the technology with invasive behaviour.

The complement of the set TRF is TRF^{C}:

TRF^{C}= (DTR) AND NOT ("bert" OR "chatgpt" OR "transformer" OR "attention mechanism").

This set included the technologies that have been predated by invasive technology of TRF.

Of course, TRF+ TRF^C=DTR

- Convolutional Neural networks, in short CNN, period under study before 2017, year of the emergence of Transformers

The general domain is D, as defined above, but in order to detect the science dynamics of CNN, we refine the search string with a restriction considering the field in which CNN operates. The keywords are stopped when the restricted set has a marginal increase in documents.

Domain Restricted for CNN is called DCNN

DCNN= ("machine learning" OR "data science" OR "artificial intelligence")

AND

("computer vision" OR "image recognition" OR "Image Processing" OR "Object Detection" OR "Image Segmentation" OR "Image Enhancement" OR "Object Recognition" OR "Image Analysis" OR "Image Classification" OR "Images Classification" OR "Face Recognition" OR "Machine Vision" OR "Image Interpretation" OR "Gesture Recognition" OR "Machine-vision" OR "Augmented Reality")

Or

DCNN= (D) AND ("computer vision" OR "image recognition" OR "Image Processing" OR "Object Detection" OR "Image Segmentation" OR "Image Enhancement" OR "Object Recognition" OR "Image Analysis" OR "Image Classification" OR "Images Classification" OR "Face Recognition" OR "Machine Vision" OR "Image Interpretation" OR "Gesture Recognition" OR "Machine-vision" OR "Augmented Reality")

In order to detect the impact of CNN, the search string is given by:

CNN=(DCNN) AND ("convolutional neural network" OR "CNN"). This set CNN includes technology with invasive behaviour.

The complement of set CNN is CNN^C is:

CNN^C = (DCNN) AND NOT ("convolutional neural network" OR "CNN"). This set included the technologies that have been predated by technology CNN.

Moreover, CNN+CNN^C=DCNN

- Measures and sources of data

This study uses the number of patents concerning research topics and technologies under study. Data are from online library database Scopus (2023), downloaded on 9 November 2023. 2024 is not considered because it is in progress.

- Samples

The study considers the following sample of data, detected using the previous logic of search strings with a combination of specific keywords and Boolean operators for the search box of search engine Scopus (2023):

- Set of Transformers TRF: 8,908 patents (all data available from 2016 to 2023).
- Complement of set TRF, TRF^C: 79,268 patents (all data available from 2016 to 2023).
- Set of CNN: 69,599 patents (all data available from 1995 to 2023).
- Complement set of CNN, CNN^C: 181,231 patents (all data available from 1995 to 2023).

- Data and information analysis procedures

One significant way to understand the invasive behaviour of technologies TFR is to estimate the rates of spread in technological space having different and alternative technologies, such as CNN.

Let Patents (TRF) =number of patents of Transformers, having invasive behaviour

Let Patents (TRF^C) =number of patents in other technologies in domain of TRF

Let DTRF = Patents(TRF) +Patents(TRF^C), total number of patents in the domain of technologies of Large Language Models

$$\alpha = \frac{Patents(TFR)}{DTFR} \quad \beta = \frac{Patents(TFR^C)}{DTFR} \qquad \alpha + \beta = 1$$

Let Patents(CNN) =number of patents of CNN, have invasive behaviour.

Let Patents(CNN^C) =number of patents of other technologies in domain of CNN

Let DCNN = Patents(CNN) +Patents(CNN^C), total number of patents in the domain of technologies of Large Language Models

$$\delta = \frac{Patents\,(CNN)}{DCNN} \quad \varepsilon = \frac{Patents\,(CNN^C)}{DDCNN} \qquad \delta + \varepsilon = 1$$

These shares of the spatial growth of invasive technologies in the domain are calculated over time and visualized graphically.

After that, the temporal growth of these technologies is analyzed with a rate of growth compound continuously: r. In this case, the function of patent development is exponential:

$$Patents_{\,t} = Patents_0 e^{rT}$$

Hence, $\frac{Patents\,t}{Patents\,0} = e^{rT}$ where e is the base of natural logarithm (2.71828…)

$$Log\frac{Patents_{\,t}}{Patents_0} = rT$$

$$r = \frac{Log\,\frac{Patents_t}{Patents_0}}{T}$$

Where
r= rate of exponential growth of technology from 0 to t period
P_0 is the patents to the time zero.
P_t is the patents to time t.
T= t–0

Trends of invasive technology i at t are analyzed with the following log-linear model:

$$Log_{10}\, y_{i,t} = a + b\ time + u_{i,t} \qquad (1)$$

y_t is patents of invasive technologies.
t=time
u_t = error term
(a = constant; b=coefficient of regression)

4. Empirical evidence: Test of prediction in invasive technologies

4.1. Pattens of temporal and morphological change in technologies

Table 1 shows a regression analysis of estimated relationship based on patents over time, using a linear model. R^2 is remarkably high in all models, showing a high goodness of fit. F-test is significant with p-value <.001. Estimated coefficient of regression suggests that transformers, as invading technology, have a growth rate of 0.30 (p-value 0.001) that is more than double than other alternative technologies operating in the same domain (0.13, p-value 0.001). Moreover, the most interesting finding is that the growth rate of invading transformers in the space of science and technology compared to other previous radical technology of CNN is almost double (0.16, p-value 0.001).

Table 1. *Parametric estimates of relationships based on patents*

Dependent variable Publications	Constant α	Coefficient β	R^2	F	Period
Log10 Patents Transformers technology	1.30***	0.30*** (0.016)	0.98 (0.105)	339.95***	2016-2023
Log10 Patents not Transformers technology	3.34***	0.13*** (0.017)	0.91 (0.107)	57.71***	
Log10 Patents CNN technology	–0.87***	0.16*** (0.010)	0.92 (0.431)	292.05***	1995-2023
Log10 Patents not CNN technology	1.61***	0.10*** (0.003)	0.98 (0.125)	1227.66***	

Note: *** p<0.001; Explanatory variable: time; period is from the starting year of the patent to 2023 (last year available); In round parentheses the Standard Error. *The F-*test is based on the ratio of the variance explained by the model to the unexplained variance. R^2 is the coefficient of determination.

This result suggests that the invasive power of transformers is of a high intensity, having a pervasive diffusion and more drastic impact to generate the conditions for a main radical scientific and technological change (for visual representation see figures 2 and 3).

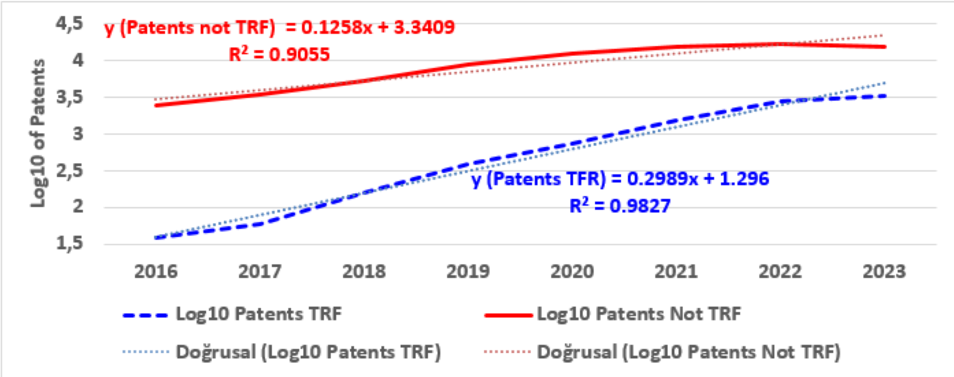

Figure 2. *Estimated relationships for temporal evolution of Transformers technology compared to overall domain of large language models (Patents), 2016-2023 period. Dotted line indicates the dynamics of invasive technology; Continuous line indicates the dynamics of other alternative technologies predated.*

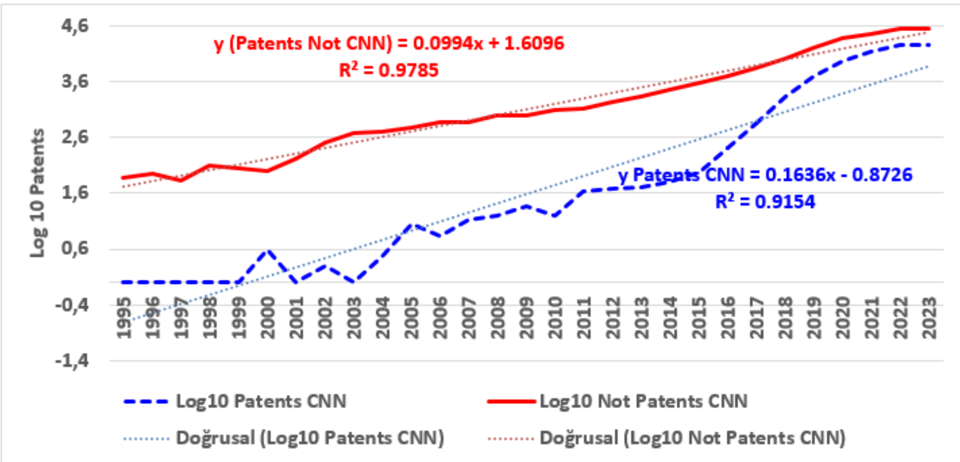

Figure 3. *Estimated relationships for temporal evolution of CNN technology compared to overall domain of large language models (Patents), 1995-2023 period. Dotted line indicates the dynamics of invasive technology; Continuous line indicates the dynamics of other technologies*

Table 2. *Exponential rate of growth in large language models of invading and predated technologies*

	Transformers	Domain excluded Transformers
Patents	Rate%	Rate %
r TRF = Exponential growth 2016-2023	55.82	23.02
r'' TRF = Exponential growth 2021-2023	25.81	0.76
	CNN	Domain excluded CNN
Patents	Rate%	Rate %
r' CNN = Exponential growth 1995-2023	33.84	36.11

Using the exponential equation to calculate the growth rate of technologies under study, it confirms that the growth rate of invading technology of transformers is about 56% versus 23% of alternative technologies in space (more than double), and it is considerably higher than previous technology of CNN having about 34% (Table 2). This result confirms the invasive behaviour of transformer technologies in the space of LLM, based on rapid and strong diffusion. Moreover, the invasive dynamics of transformers in about 7 years, based on share of patents of transformers on total, shows a rapid diffusion invading the space of other alternative technologies in the related domain, changing the ecosystem of LLM with pervasive application of manifold radical innovations in generative AI that generate technological and social change (Figure 4). The share of patents in CNN technologies in 2023 is higher than transformer technology but the accumulation of knowledge started in 1995, compared to Transformers that started in 2017 (Figure 5).

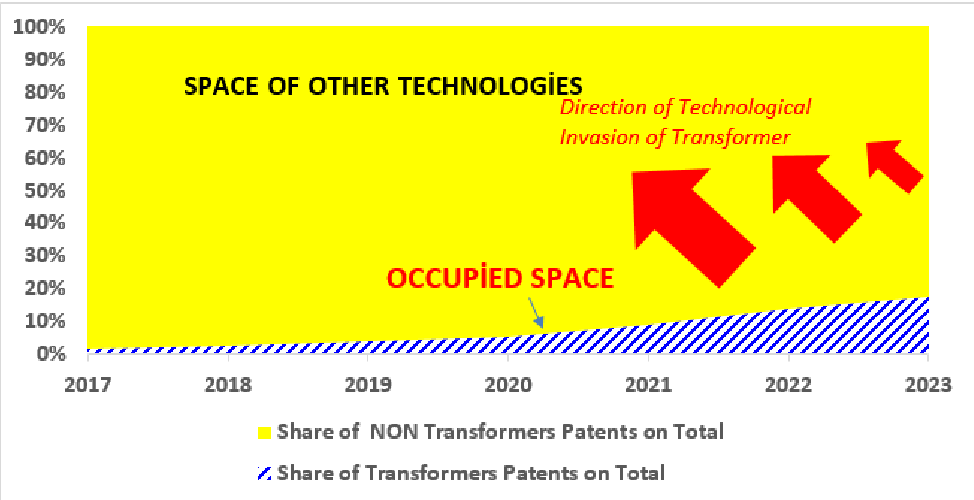

Figure 4. *Patterns of morphological change in domain of large language models generated by emerging technology of transformers (Patents). Large arrows indicate the direction of technological invasion*

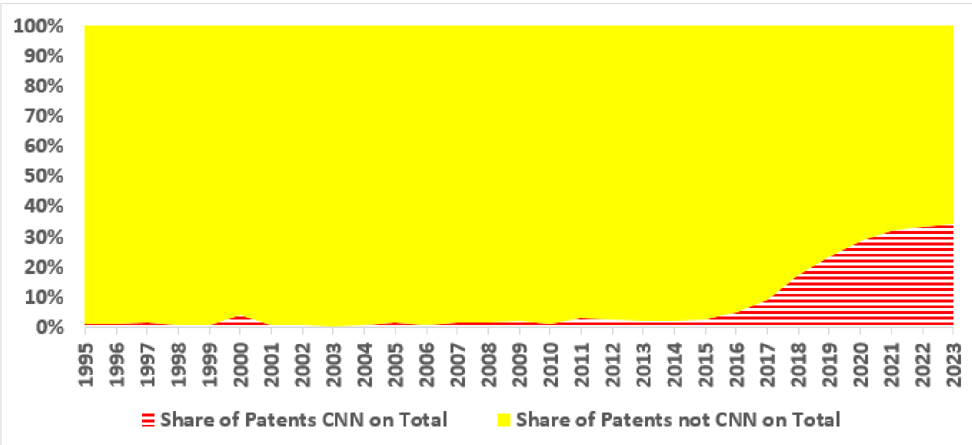

Figure 5. *Patterns of morphological change of CNN in domain of large language models generated by (Patents)*

5. Analysis of findings

Technology analysis of the specific dynamics of invasive behaviour that generates radical changes in a brief period provides critical information to explain scientific and technological development directed to progress of human society (Bettencourt et al., 2009). Table 3 shows the comparison between the two technologies under study with high rate of growth by

Generative Pretraining Transformers show powerful invasive behaviour in the short run compared to CNN.

Table 3. Comparative analysis of invasive technologies

	Generative Pretraining Transformers 2016-2023	Convolutional Neural Networks CNN 1995-2023
Rate of Exponential growth (patents)	55.82	23.02

5.1. Explanation of empirical evidence of invasive technologies

The emergence of transformer technology is due to the interaction and convergence of competencies from mathematics and model design in neural networks. Transformer architecture was introduced in the context of natural language processing (NLP), revolutionizing it, but it has shown to be versatile and powerful technology, finding new applications in diverse fields such as computer vision, speech recognition, etc. Before transformers, recurrent neural networks (RNNs) had many limitations, but a main breakthrough is the introduction of self-attention mechanism which intuitively mimics cognitive attention, such that transformers in large language models removed the recurrent neural network and relied heavily on the faster parallel attention scheme (Tyagi, 2023). The speed at which the invasive technologies expands its range is a fundamental parameter to predict their ability to invade the scientific domain of alternative technologies to be a dominant one in a short run (cf., Schreiber & Ryan, 2011). In fact, temporal, and spatial models of technological evolution here, based on data of patents, reveal the highest rate of growth in invasive technologies compared to other technologies. A basic driver of invasive behaviour in transformers is the interaction with different research fields and technologies, such as in autonomous driving, remote sensing images, etc. (Chen et al., 2023; Coccia, 2019, 2019a; 2020, 2020a,b,c; Coccia & Watts, 2020; He & Li, 2022). Scholars have shown that interaction among technologies, as just mentioned, can support technological evolution, and the result here is consistent with the multi-modes interaction of Utterback et al. (2019). In the case under study of transformers, the technological interaction is generating high growth rates and a symbiotic-dependent evolution in which each technology benefits from the activity of the other one (cf., Coccia, 2019; Coccia & Watts, 2020). In particular, technological interaction of transformers with other technologies generates synergistic combinations and fosters major innovations, which are currently progressing at a rapid rate, such ChatGPT and similar ones, opening completely new opportunities in markets (such as AI, Burger et al., 2023; Chen et al., 2023; He and Li, 2022; Krinkin et al., 2023; Roco & Bainbridge, 2002).

Moreover, transformers have invasive behaviour because they have the characteristics of General-Purpose Technology (Coccia, 2020). Lipsey et al. (1998, p.43) define a GPT as: "a technology that initially has much scope for improvement and eventually comes to be widely used, to have many users and to have many Hicksian and technological complementarities." (cf., Lipsey et al., 2005). Invasive technologies, such as GPTs, exert a pervasive impact across firms and industries and permeate the overall economy of nations in the short run. Bresnahan & Trajtenberg (1995, pp.86–87) show that GPTs have a treelike structure, radiating out towards every industry of the economy. In fact, transformer architecture, such as GPTs, generates clusters of innovations in several industries because they are basic processes/components/technical systems for the structure of various families of products/processes that are made quite differently supporting co-evolutionary pathways, such as in autonomous driving (He & Li, 2022), very high-resolution remote sensing image change detection (Chen et al., 2022); etc. The manifold applications of transformers such as GPTs are driven by firms (such as Open AI, Microsoft, Google Brain, etc.) to maximize profit and/or to exploit the position of a (temporary) monopoly and/or competitive advantage in industries (Calvano, 2007; Coccia, 2015, 2016). In general, transformers are invasive technologies having the characteristics of disruptive technologies and general-purpose technologies characterized by: "pervasiveness, inherent potential for technical improvements and 'innovational complementarities,' giving rise to increasing returns-to-scale" (Bresnahan & Trajtenberg, 1995, p.83, original emphasis). Many characteristics of invasive technologies are like general purpose technologies (GPTs) such as (Jovanovic & Rousseau, 2005, p.1185):

1. Pervasiveness to propagate in many sectors
2. Technical improvement that reduces costs in products and processes
3. Product and process innovation spawning

Lipsey et al. (1998, p.38ff) describe other similar characteristics of GPTs, appropriate to describe invasive technologies, such as: the scope for improvement, wide variety, and range of uses and strong complementarities with existing and potential modern technologies (cf., Coccia, 2012a, 2012b, 2017a, 2017). Overall, then, transformers with invasive behaviour are complex technologies that support product/process innovations in several sectors for a corporate, industrial, economic, and social change (cf., table 4; Coccia, 2015; cf. Coccia, 2012, 2012a, 2014, 2014a, 2016, 2017).

Table 3. Differences between disruptive and invasive technologies

	Disruptive technologies	Invasive technologies
Technological type	General Purpose Technologies	Disruptive + General Purpose Technologies
Technical characteristic	Pervasiveness and cost reduction	Pervasiveness and innovation spawning
Business strategy	Exploitation	Exploration and exploitation (ambidexterity)
Evolutionary patterns	Mutualistic interaction	Symbiotic interaction
Rate of growth	Rapid	Accelerate
Period of diffusion	Medium run	Shot run
Current Example	5G technology	Generative Pretraining Transformers

5.2. Most important drivers of technological invasion

A list of putatively relevant drivers for technological invasions can be grouped into broader categories:

(a) scientific and technological advances and interaction between fields

(b) socio-economic activities

(c) environmental turbulence and threats (wars, conflicts, emergencies, etc.)

(d) societal awareness, values, lifestyle

(e) cooperation, legislation & agreements, technological strategies at national and corporate level.

6. Concluding remarks

Advances in information sciences are generating recent technology with main changes in economies and societies. This study proposes, for the first time, the invasive behaviour of technologies. Successful technological invaders can have devastating impacts on human society and the structure of modern economies. The proposed theoretical framework of invasive technologies can clarify the main characteristics of on-going technological change for supporting R&D management and innovation policy in emerging technologies having a high potential impact in every sphere of human activity in the current information and digital era (Hicks & Isett, 2020). This study assesses the theories of invading technologies focusing on transformer technologies in generative AI that has an unparalleled growth at expense of other technologies creating basic conditions to generate a drastic scientific change in LLM and consequential radical innovations with main effects on economic and social systems in a not-to-distant-future. This specific behaviour of invasive technologies fosters a rapid diffusion, destroys other technologies, and captures their scientific, technological, and commercial space. This dynamics between different technologies is based on competition of performance and effectiveness in problem solving activities. Fisher and Pry (1971) modeled the diffusion of innovative technology becoming a substitute for a prior one (cf., Utterback & Brown, 1972). Other scholars have explained this competition as a predator and prays, the new product is a predator of current products (pray; Utterback et al., 2019). This study suggests the main concept of invasive technologies that have the power to disrupt, destroy and make obsolete established competences with a high pervasiveness in manifold industries over a short run with long run impacts (Christensen et al., 2015, 1997; Coccia, 2020). What this study adds is that the invasive behaviour of new technology is more drastic than disruptive technology having also main characteristics of general-purpose technologies as verified here with transformer architecture in generative artificial intelligence. What is the cause that drives Transformer architecture to be an invasive technology? One of the possible explanations is a specific interest of scholars, analysts, etc. to solve complex and difficult problems in different contexts (Sun et al., 2013; Coccia et al., 2024; Guimera et al., 2005; Wagner, 2008; Kargı, & Coccia, 2024c; 2024d). In this context, the rapid evolution of invasive technology paves the way for the development of other technologies in spatial-temporal fields in science and technology by ''expanding the adjacent possible'' (Kaufmann, 1996).

6.1. Theoretical implications

The predictions of our theoretical framework of invasive technologies are borne out in the phenomena investigated, paving the way to a better understanding and control of innovation processes in a knowledge economy.

Properties of invasive technologies

Invasive technology IT*i* in the domain D is when from t to t+*n:*

- IT*i* has a very rapid growth, acceleration.
- IT*i* disrupts the use of other technologies.
- IT*i* invades and captures the scientific space of other technologies.
- IT*i* creates new dynamic capabilities (the organization's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments; Teece et al. 1997)

Moreover, other characteristics of invasive technologies are:

– Pervasiveness over time and space in the short run
– Adaptation to a wide range of market applications and environmental conditions
– Interaction with manifold technologies
– Associations with different activities in science and society

These results can be the basis for an emerging science of invasive technologies that can explain technological, economic, and social change in three main scientific directions:

1) invasiveness of technologies
2) invasibility of innovation ecosystems and

3) recurrent (patterns of the technologies) × (ecosystem interactions) that may support a technological invasion syndrome based on a set of concurrent aspects that usually form an identifiable pattern.

A science of invasive technologies can encompass 'typical recurrent associations of technologies and invasion dynamics with particular invasion contexts such as an invasion phases, invaded environment and socioeconomic context' (cf., Kueffer et al., 2013). We expect that a resulting theory of technological invasions will need to be conceived as a somewhat heterogeneous conglomerate of elements of varying generality and predictive power: laws that apply to well-specified domains, general concepts and theoretical frameworks that can guide thinking in research and management, and in-depth knowledge about the drivers of particular invasions of technologies in specific industries or across sectors.

6.2. Managerial and policy implications

Invasive technologies tend to have similar patterns emerge based on two contrasting forces that can have managerial implications: the tendency of retracing already explored avenues (exploit) and the inclination to explore new possibilities. Policymakers and R&D managers can use the findings here to make efficient decisions regarding the sponsoring of specific technologies having a high rate of growth (invasion) to foster technology transfer with fruitful effects for boosting up next economic and industrial change. These managerial approaches can be explained in the framework of the expansion of the adjacent possible, in which the restructuring of the space of possibilities conditional to the occurrence of radical innovations. Proposed theory and empirical findings can guide an ambidexterity strategy for invasive technologies based on:

a) exploration activities when rate of growth, and uncertainty in research fields and technology is higher. However, organizations that focus only on exploration face the risk of wasting resources on research topics and emerging technologies that may fail and never be developed, so a stage to gate model can reduce failure risk and foster the development of new technology in these contexts (Coccia, 2023);

b) an exploitation approach to innovation strategy when rate of growth is lower with consequential more stable technological trajectories.

Ambidexterity strategy of innovation management by balancing exploration and exploitation approaches in invading technologies allows the organization to be adaptable to turbulent environments and achieve and sustain competitive advantage (Duncan, 1976; March 1991; Raisch & Birkinshaw, 2008; Kargı, & Coccia, 2024a; 2024b).

6.3. Limitations and development of future research

This study shows for the first time, to our knowledge, the behaviour of an invasive technology to explain some technological and social changes in knowledge economies. However, these conclusions are, of course, tentative. This study provides some interesting but preliminary results in these complex fields of emerging technologies, but some limitations to deal with future studies can be summarized as follows. Many fundamental questions in the science of invasive technologies can only be answered through integrative studies such as, a research that encompasses comprehensive studies of invasive behaviour of a particular technology in a specific fields, comparative studies of invasive behaviour of the same technologies across multiple fields and industries, in short, to analyze invasive behaviour of technologies with context-dependencies. In this study the invasive behaviour of technology focuses on a scientific field dominated by a single dominant invader technology (transformers). However, studies of multiple technology invaders are mostly lacking. Such studies are, however, important to understand shifts in dominance of invading technologies, possibly leading to interactions among multiple invaders. In the context of invaded ecosystems, an emerging challenge is also to understand the role of gradual changes of technologies and environmental factors in determining invasion trajectories over time and space between fields in science and society. (e.g., Smith et al., 2009). Hence, it is interesting to compare the invasive behaviour of the same technologies across multiple industries and research fields, to assess if 'invasiveness' and effects on the environment of technologies may be highly variable at different sites. Such differences in invasion dynamics of technologies between industries might stem from (1) the variability of the architecture of a technology between industries– through product and process differentiation; (2) technologies and environment interactions. In analogy with biology, the impacts of invasive technologies are strongly co-shaped by the relation of (technologies) ⊚ environment interactions (Hulme et al., 2012; Pysek et al., 2012) which can only be understood through comparative studies across industries (cf., Kueffer et al., 2013). More studies that compare the behaviour of technology in native research fields and invaded ranges are needed (van Kleunen et al., 2010), because such insights form the baseline necessary for drawing conclusions about the characteristics of specific technologies in invasions (Parker et al., 2013).

These studies are needed in future because the investigation of only one technology is highly likely to arrive at spurious conclusions. In general, synthetic analyses in invasion behaviour for technologies must be constrained to appropriate subsets of invasions, rather than seeking universal explanations (Pyšek & Richardson, 2007; Jeschke et al., 2012; Kueffer, 2012). For instance, characteristics that are most frequent among invasive technologies in markets might not be relevant for predicting invasive technologies within a specific industry or field.

In fact, a future idea is to verify if technological superiority or flexibility applies to all invasions (e.g., Daehler, 2003; Blumenthal et al., 2009; Cavaleri & Sack, 2010; Chun et al., 2010; Jeschke et al., 2012a; Moles et al., 2012; Uçkaç et. al., 2023; Kargı, et. al., 2023; Kargı, et al., 2024).

Other limitations are that: scientific outputs and research topics can only detect certain aspects of the ongoing dynamics of invasive technologies and next study should apply complementary analysis; confounding factors (e.g., level of public and private R&D investments, international collaboration, etc.) affect the evolution of new technologies and these aspects have to be considered in future studies to improve technological analyses.

In short, there is need for much more detailed research into the investigation of the role of invasive technologies to clarify evolutionary patterns of technologies in society. Despite these limitations, the results here clearly illustrate that invasive technologies can clarify basic characteristics of technological, economic, and social change. These findings here can encourage further theoretical exploration in the terra incognita of invasive technologies within and between scientific and technological domain that have rapid change in the new digital era. These aspects are basic for improving the prediction of evolutionary pathways in emerging and disruptive technologies and supporting R&D investments towards new technologies and innovations having a high potential of growth and of impact on the socioeconomic system. However, a comprehensive explanation of sources and diffusion of invasive technologies to explain technological change is a difficult topic for manifold complex and inter-related factors in the presence of changing and turbulent environment, such that Wright (1997, p. 1562) properly claims that: "In the world of technological change, bounded rationality is the rule."

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Author statements
Acknowledgements: Not applicable.
Author contributions: The contribution of the authors is equal.
Funding: No funding was received for this study.
Availability of data and materials: Not applicable.
Ethics declarations
Ethics approval and consent to participate: Not applicable.
Consent for publication: Not applicable.
Consent to participate: Not applicable.
Competing interests: The authors declare that they have no competing interests.
Informed consent: Not applicable.
Consent for publication: All authors agreed with the content and gave explicit consent to submit the manuscript to *Journal of Innovation, Technology and Knowledge Economy*
Data Availability Statement: Not applicable.