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Toward qualitative growth: Exaptations, graphene and Industry 4.0

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ABSTRACT

This contribution aims to address the intriguing issue of whether Industry 4.0, as a techno-economic paradigm shifter, may have a greater potential for exaptation (i.e., using it not for pursuing of quantitative but that of qualitative development) and, if so, what technologies may accelerate this process. Existing research indicates that graphene technology has the potential to lead the way in this area. The paper addresses not only why and how a graphene-aided Industry 4.0 can be conducive to this function (i.e., making exaptations easier on a larger scale), it examines the wider context for exaptations by questioning whether the current setup of the real economy, the financial universe, and the public sector offers a supportive environment for exaptations.

KEYWORDS

exaptation, Industry 4.0, graphene, zombies, complexity

JEL CLASSIFICATION INDICES

G1, 031, 033, 025

1. INTRODUCTION

Against widespread professional expectations, the much-awaited productivity-boosting character of Industry 4.0 (Fragapane et al. (2022) or Elnadi – Abdallah (2023)) is still yet to come

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in most developed economies. Naturally, given the protracted period of uncertainty-inducing polycrisis (Bloom et al. (2022) (e.g., the war between Russia and Ukraine, inflation, energy crises, health crises, demographic issues, trade wars, and techno-nationalism), high expectations are reasonable. The general public's expectations of governments to reduce uncertainty are stoked by this permanent crisis-mode.[1]

As such, there is an urgent need for genuine socioeconomic development. Industry 4.0 (I4.0) can have a significant impact on it, but it's also important to look at social learning from a wider angle. Here, mechanisms other than innovation, like exaptations (i.e., repurposing), can play a part.

In essence, social learning is an outcome of the open, dynamic, adaptive, and out-of-equilibrium socio-economic innovation ecosystem, in line with the principles of complexity economics (Kovacs 2022a). Surprisingly a small number of studies have been done on the contextual factors that influence social learning, and even fewer – if any – have addressed the problem of technological exaptations. Furthermore, this has not been approached from the perspective of shifting techno-economic paradigms (TEP), and the literature to date has not even attempted to address the question of whether I4.0, with its much-anticipated productivity boom, has the potential to be transformative, where such a power might originate, and whether systemic inhibitory processes might exist.

In order to explain how crucial social learning is in initiating sociogenesis, our paper advocates for a systems view. It examines development via the prism of TEPs, offering a more complex understanding of how social learning occurs than approaches that primarily focused on how production and income changed quantitatively over time. Furthermore, the research closes a gap in the state-of-the-art literature by attempting to decipher elementary exaptations over such paradigms. The possibility for sociogenesis through the exaptationary power of I4.0 is then examined by considering the potential role of graphene technology, taking into account systemic disincentive forces such as the zombification of enterprises. In this approach, a whole new understanding of how zombie enterprises contribute to sociogenesis is revealed. This is the first study to date that connects graphene technology to I4.0, addressing the intricate relationship between three systemic processes that fall under the sociogenesis domain: zombification, exaptations, and I4.0.

2. MATERIALS AND METHODS

The paper examines the potential for a sociogenesis towards qualitative development by forming a verbal model based on both quantitative and qualitative data (OECD, World Bank, Eurostat, etc.) and shining light on the intricate relationship between exaptations, graphene technology, I4.0, and zombification. It defines exaptations as the functional repurposing of an innovation, technology that is already in use, and even processes and approaches (including policy). On the other hand, it defines zombie firms as companies that are at least ten years old and are kept afloat by the government or the financial sector despite the fact that they are unable to generate enough revenue before taxes to pay for their interest costs (interest coverage ratio<1 over three

[1]German GDP estimates are weakening and recessions are possible (−0.3% real GDP growth for 2023) and for the UK (−0.4%), alike (OECD 2022).

consecutive years). Furthermore, we refer to a broad class of two-dimensional materials as graphene.

3. PARADIGMATIC SHIFTS AND SOCIAL LEARNING

3.1. The manifestation of development in complex systems: social learning

Humanity may have believed for a very long time that we live in the best possible world.[2] Violent conflicts have been on the decline for a long time, life expectancy has been growing, the proportion of people living in extreme poverty has dropped to a historic low, as is child mortality. The average GDP per capita increased twelve times in two centuries, whereas the global GDP expanded hundredfold. Vaccinations, medications, and the availability of clean drinking water have helped to contain diseases that formerly killed millions of people and bring epidemics down to a manageable level.[3]

Diverse opinions are prevalent in the most recent research on the universal mechanism of socioeconomic growth. The majority of influential thinkers strive to be as integrative as possible in exploring the contingent and accidental nature of much technological progress, even though the profession still has a tendency to use development economics as a way of investigating catching up opportunities to be learned by emerging or developing countries (de Janvry – Sadoulet 2014).

To put it briefly, socio-economic development originated in the temperate zone and could only begin there, according to famous anthropologist Jared Diamond. This geographic area made it feasible to domesticate certain livestock in large numbers, which could also be used for daily work (using their skin, fur, bones, and meat, thus the various professions could emerge). It also made it possible to grow large quantities of grain (basing demographic boom) in a more resilient basis. All of this resulted in rivalry, which is necessary for ongoing social learning and, consequently, for growth (Diamond 1999, 2004, 2013).

Development can only begin, continue, or even be increased in an environment that is inclined to it, just as disease occurs in an individual who is predisposed to it. Well-functioning markets McCloskey (2011) and inclusive formal and informal institutions are all essential, but far from sufficient, in such an environment Mumford (1934, 1971, 1973, 1974). The work of American polymath Lewis Mumford aims to comprehend development as a multifaceted phenomenon that is heavily influenced by the prevailing (cultural) environment, where the dynamic relationship with nature is crucial. According to Mumford, the idea that time and space are measurable and divisible into equal units led directly to more explicit exploration, machines, the rationalisation of labour, capitalism, and ultimately science and modern industry. It also became a part of the coevolved cultural-institutional configuration, e.g., the invention of measuring time, optical lenses, etc. changed people's way of looking at nature and directed towards better organising the daily lives (Tabellini 2008; Bisin – Verdier 2017; Roland 2020; Almudi – Fatas-Villafranca 2021). The Mumfordian perspective aligns with the legacy of renowned sociologist William F. Ogburn (1922, 1949) who demonstrated that social learning is culture-dependent and that major

[2]It lasted roughly until February 2022, when the conflict between Russia and Ukraine broke out.

[3]The COVID-19 vaccine was developed in less than a year, which was an unprecedentedly quick innovation.

scientific advancements have always been influenced by prevailing social philosophy and attitudes. Ogburn also showed that technological changes are patterned by these social philosophy and attitudes. Furthermore, because new technologies are perceived as weird intrusions, Ogburn stressed that there is a cultural lag between a culture's technological and non-technical aspects. As such, social learning and adjustment are dynamic processes, of which Mumford also included comprehension (i.e., shifting perspectives on nature).

The economic historian Joel Mokyr (2002, 2016) emphasised a more nuanced and dynamic view of cultural change, despite the long-standing belief that culture is a static category, in his explanation of the rise of Western economies and the causes and mechanisms of the first, second, and third Industrial Revolutions. He asserts that people's beliefs are what propel economic development. A key component of it is the adaptable cultural belief, the attitude towards the natural world, and the readiness and capacity to add to a vital body of scientific information that enables people to understand the rationale behind the many methods and instruments that are employed and shared. According to Mokyr, this kind of cultural transformation in a politically divided continent, along with a shared culture and intellectual heritage that supported individuality and experimentation, was what gave life to Europe.[4] Although Mokyr does not address exaptations, such a design was advantageous for more productive and successful idea production leading to social learning via instigating innovations.[5]

Thus, development is a complicated, multifaceted, and never monocausal configuration of dynamic processes. Nevertheless, there's a propensity to overemphasise a few key elements while ignoring the fact that every link in the chain contributes equally to the overall process of social learning.[6] How a society uses creativity for innovation, exaptation, and diffusion of technologies serving economic and environmental development and sustainability, as well as how it produces and applies knowledge to ensure, organise, and/or rearrange its aggregate attitude (and/or resources) in case of endogenous crises, are all influenced by and defined by social learning capacity. Not coincidentally, the esteemed economic historian Deirdre N. McCloskey emphasised that ideas, public opinion, and discourse shape development in a liberal manner. She argued that equability is the foundation for the market economy's innovativeness and rapidly increasing productivity, which have resulted in the so-called Great Enrichment over the past 200 years. Mokyr's story of when science began to matter much to the economy is very different from McCloskey's.[7]

Furthermore, our logic falls halfway between the arguments made by Mazzucato (2013) and Phelps (2013) about the true origin of development. According to Phelps, the driving force behind the widespread prosperity that occurred in Europe between 1850 and 1950 was neither stagnation or complacency, but rather vitalism that originated entirely from the bottom up and did not significantly involve the state, namely private sector entrepreneurs. Take note that

[4]As Weede (1990) contended, heterogeneity was essential. See Dauerlauf – Ioannides (2010) for information on the impact of social contacts on development; Bisin –Verdier (2010) and Alesina – Giuliano (2015) for information on the relationship between cultural transition and developmental phases.

[5]In the 2002 book, he made only one reference to exaptation (p. 98). See McCloskey (2006, 2016) for additional information on shifts in culture and ideology as the cornerstones of contemporary development.

[6]Social learning is hence the Bergsonian *élan vital* to development.

[7]See: McCloskey (2021), Chapter 16.

Phelps' formula removed all mention of science. Mazzucato (2013), on the other hand, believed that great innovations were made possible by the state and science. We contend that, as Mokyr (2002) has stated, the innovation ecosystem fosters development through enabling interactions between the public, commercial, and scientific domains to unlock exaptation and innovation-driven social learning patterns.

To put it briefly, all of the different perspectives view *development as a means of explaining how ever-more technologically efficient output has been sustained across time*. We wonder if this objective could shift: if I4.0's use of graphene and other 2D materials has the ability to promote a cultural exaptation.[8] Given that promoting sustainability is currently one of the hottest topics,[9] such a sociogenesis would be equivalent to viewing development as a content and the socio-economic innovation ecosystem[10] as a qualitative issue.

Specifically, social learning takes the form of (i) anticipating, absorbing, recovering from, and adapting to a wide range of systemic threats; and (ii) allowing creativity to unfold in order to grasp entirely different contextual backing through the repurposing of already existing and already available tools and means in a way that amounts to system-reprogramming in order to foster the irreversible emergence of a qualitatively new developmental phase (i.e., to augment phase transition via innovation or even through exaptation). In this spirit, considering the economy as a complex, open and adaptive far-from-equilibrium system is a *de rigueur* requirement (Kovacs 2022a) of understanding that elementary-level irregularities allow the system to behave irreversibly (i.e., giving rise to symmetry breakings and heterogeneity from which new can emerge). Innovations and exaptations introduce inclinations towards chaotic disorder into the economy, particularly in the case of general-purpose technologies (GPTs). This process results in a phase transition into a newly emergent TEP, which permanently modifies the system's programming. This provides a more nuanced understanding of the process of social learning than would be possible with techniques that only focused on how quantitative increases in output and revenue (i.e., GDP) were measurable over time.

3.2. Exaptation-aided sociogenesis

Social learning occurs in complex systems in two ways: first, through the creation of resilient structures and processes through innovation and exaptation; second, through paradigmatic shifts[11] that result in qualitative changes (where more significant innovations and exaptations

[8]Cultural exaptation, as demonstrated by d'Errico and Colagè (2018), has existed throughout human history when, for example, a utilitarian cultural element may be appropriated for nonutilitarian, aesthetic, or symbolic purposes.

[9]See: Alston (2020).

[10]A socio-economic innovation ecosystem is a complex network of organisations and people in the public and private sectors whose interactions and activities have the potential to nonlinearly create, import, alter, and disseminate new technologies and knowledge. For additional details on its attributes, see to Kovacs (2022a).

[11]According to Perez (2009), the opening of the Cromford Mill in 1771 started the first industrial revolution, the rocket steam engine in 1829 started the age of steam and railways, the steel plant in 1875 started the age of steel, electricity, and heavy machinery production, the first Ford Model-T in 1908 started the age of oil, cars, and mass production, and the Intel microprocessor in 1971 started the information revolution (including today's Industry 4.0, AI and ML phenomena). Since the Industrial Revolution in England at the end of the 18th century, the world economy has seen technical revolutions every 40–60 years. Each uses new or somewhat new technology with clever combinations and exaptations.

are crucial). From evolutionary biology, the term "exaptation" refers to traits that initially evolved for one function but were subsequently co-opted for another.[12] This shift is mostly the result of environmental changes. To put it another way, exaptation can be broadly defined as the process by which something that once originated for one purpose eventually finds utility for another. Keep in mind that exaptation is a part of complex systems where the dynamic state that is far-from-equilibrium ensures that evolution retools structures for new uses without intentional design.[13] For instance, the cecum, a pouch at the beginning of the large intestine that aids in the digestion of plant food, is assumed to be an exaptation of the human appendix. The cecum shrank in size as our diet become less plant-based and more meat-based over time. It did not vanish; instead, it evolved into the appendix, which is now regarded as a vestigial organ. It may, however, be hiding other crucial roles, such as defending the gut's beneficial bacteria.[14]

When an organism exaptates, it can expand its functions by adjusting to novel surroundings and obstacles.[15] Accordingly, exaptations enable firms and industries to expand their roles by adjusting to new technologies and new difficulties in the dynamic socio-economic innovation ecosystems.[16] As was previously mentioned, the industrial revolution was a time of immense change; in other words, as a result of its effects on the economy, exaptations were growing.[17] Let us just shortly decipher some major exaptations appeared during TEPs.

- 1st TEP: the age of new manufacturing processes
  - *The Spinning Jenny:* was a significant invention during the first industrial revolution (Gragnolati et al. 2013). It was originally created to assist weavers spin thread faster, but it was quickly used to spin cotton and other materials. The spinning jenny helped build the textile industry and is still used today.
  - *The Cotton Gin*: Eli Whitney created the cotton gin in 1793 with the aim at simplifying cotton seed removal. The cotton gin unintentionally made cotton textile production cheaper and easier by boosting cotton production. Cotton gin raised demand for cotton and slave labour because it made seed-fibre separation simpler.[18] Cotton gins were game-changing because they hastened the use of slave labour and allowed mass manufacturing in the American economy owing to their interchangeable and patented parts.
- 2nd TEP: the age of steam and railways
  - *The Steam Engine*: Although Thomas Newcomen invented the steam engine in 1712 to pump water from coal mines, it was swiftly adapted for various uses, including powering

[12]See: Gould – Vrba (1982). Let us note that Charles Darwin's theory of evolution had already recognised that not all organisms' characteristics or attributes are the consequence of natural selection. Darwin agreed that certain features may have started for one reason but later served another. Exaptation means that some traits or qualities can be co-opted or reused for fitness-enhancing tasks. Exaptation now includes molecular genetic levels like gene and genome evolution through neutralised repetitive DNA. Understanding how nonadaptive characteristics might contribute to evolution requires distinguishing adaptations from exaptations. See more: Frenkel-Pinter et al. (2022).

[13]That contrasts sharply with Behe (2019).

[14]See: Laurin et al. (2011).

[15]See: La Porta et al. (2020).

[16]See: Buss et al. (1998) p. 541.

[17]See: Dew et al. (2004).

[18]See: Finkelman (2001).

trains and ships. The steam engine spurred social learning and design advancements, which led to the remarkable movement of industrial operations into bigger urban centres, boosting agglomeration and population expansion.[19] Steam engines are still employed in some industrial applications (e.g., steam injection into internal combustion engines to reduce emissions[20]), although petrol and electric engines have increasingly replaced them.

- 3rd TEP: the age of steel, electricity, heavy machinery production
  - *Air Conditioner*: Air conditioning was invented to keep printer ink moist at Sackett & Wilhelms Lithographing and Publishing Company in Brooklyn.[21] The unpredictable humidity levels worried the enterprise while printing in colour. Literally, an exaptation was needed. Air conditioning was soon discovered to cool houses and businesses in hot weather. To keep dealers cool in summer, the New York Stock Exchange introduced air conditioning in 1902. Trading volume increased dramatically as more individuals worked in hot weather. AC became ubiquitous in all business buildings and one of the most prevalent equipment in households, transforming the economic landscape (Dubai or Singapore would not have existed without such comfort-making technology).

- 4th TEP: the age of oil, cars and mass production
  - *Microwave ovens*: Radar magnetrons (microwave vacuum tubes) inspired microwave ovens. While developing radar technology in 1945, American inventor Percy Spencer found his pocket chocolate bar had melted. After discovering microwaves induced melting, he experimented with cooking. The first microwave oven was developed in 1947 and became a kitchen mainstay. They used less energy than other cookware and contributed to cultural change towards environmental awareness by reheating leftovers.[22] Microwaves are also being used to inactivate biohazardous compounds.[23]
  - *The compact disk*: The compact disc was invented in the late 1960s in the US to solve a specific problem, the issue of poor sound quality and wear and tear experienced by vinyl records. In order to capture and replay sounds without physical contact, James T. Russell invented the device using light as a medium. CD-ROM was patented in 1970 as a digital-to-optical recording and playback technology. However, lab researchers with lots of experimental data used CD-ROM technology for computer data storage.
  - *Zerodur:* when the mirror of astronomical glass binoculars could no longer be made larger because weight causes distortion and heat softens the glass, engineers developed zerodur, a low thermal expansion glass-ceramic material. Space telescopes have used zerodur for decades, especially for primary mirrors (Behar-Lafenetre et al. 2014). This was repurposed for energy-efficient induction cookers.

[19]See: Rosenberg – Trajtenberg (2009).

[20]See: Gonca et al. (2014).

[21]The newspaper was printed on paper that swelled due to humidity in Brooklyn, and the colours didn't match. Ink drying on pages caused major deadline concerns.

[22]See: Li et al. (2022).

[23]See: Zimmermann (2017).

- 5th TEP: information revolution and hyper-globalisation
  - *The Internet*: It was created by the US Department of Defense to maintain communication during a nuclear assault. The context was too urgent because the Cold War between the US and the USSR was at its peak. Civilians adopted this new technology for personal use. Companies soon saw the internet's commercial potential and invested extensively in its development. In 1989, the *world wide web* – a network of remote servers – was created. Mosaic, the first graphical web browser, made this new wealth of knowledge available to anybody with a computer and internet connection in 1993. The internet has become part of billions of people's daily lives, and I4.0 relies very much on the Internet-of-Things as well.
  - *Firefighter plane engine*: One of the world's most efficient firefighting vehicles uses 1,319 gallons of kerosene per hour and was created by Hungarians. When the UN liberated Kuwait occupied by Iraq after the Gulf War in 1991, Saddam Hussein's oil rigs were burning, spewing black smoke. The four-person Hungarian drilling firm crew utilised an ancient T34 Russian tank tool to extinguish the fire while the Americans employed explosives. The assistance troops going to Kuwait christened the harsh vehicle "Big Wind" because two MiG-21 fighter aircraft were installed on top of the 42-ton fire engine to extinguish the burning oil and gas wells. The superstructure was relocated to a VT55A combat towing vehicle that replaced the T34 tank. That Big Wind helped the Hungarian quintet destroy nine oil wells in 42 days, including one in 34 s.
  - *Metal foam*: Its similarity to bone made it useful for developing prosthetic limbs, resulting in exaptation. Later, metal foam was repurposed in the automotive, aerospace, architecture and art industries to achieve their goals. A clever combination of metal and foam creates a lightweight, strong, spongy material by barding modern aircraft and spacecraft with stronger shock absorption. It has also been used to insulate and soundproof buildings. On the other hand, metal foam can be used to make fireproof and bulletproof materials. In addition, metal composite foam is now saving lives by embedding air-filled metal bubbles in a metal matrix such as steel, aluminium or other metal alloys to mitigate heat, fire, radiation, blast and ballistics.
  - *Turnaround of the European Central Bank*: Immaterialized exaptation can occur in public policy. On the brink of the Eurozone crisis, Mario Draghi, president of the European Central Bank, thought outside the box and freed the ECB from its shackles by stressing that "*do whatever it takes*" to safeguard financial stability and the Eurozone by launching the unlimited purchase of debt instruments from troubled states from July 2013. This robust institutional signal improved market confidence by decreasing uncertainty (i.e., an institutional and policy exaptation because ECB obtained new functions).[24]
  - *Cryptocurrency*: For instance, Bitcoin was created to be a global cryptocurrency that would be safer than traditional payment methods and money. With bitcoin's ever-volatile price,[25] high cost of creation and lack of fundamental value[26] (except insofar as people continue to think it is valuable by increasing the number of users), the cryptocurrency has been

[24]Of course, this step also created some sort of ambiguity since the proclamation was unlawful.

[25]See: Baur – Dimpfl (2021).

[26]See: https://www.coindesk.com/markets/2022/11/21/more-than-50-of-bitcoin-addresses-are-now-in-loss/.

repurposed as a huge liquidity absorber[27] of speculative assets and financial hype (folly with pump-and-dump strategies) for many. Several reasons have shown that its exchange rate is resilient and immune to radical shocks in the cryptocurrency world (for a long time, hacking events did not affect Bitcoin or Etherium prices).[28] In the autumn of 2022, further successful bitcoin thefts occurred, raising questions about the durability of the concept. This suggests that tectonic systemic changes in the socio-economic innovation ecosystem can lead to exaptation by breaking symmetry in subsystems such as the financial universe, the real economy and the public sector. In the pre-crisis period of 2008, the liberalised and under-regulated financial universe expanded at the expense of the real economy, dampening productivity/innovation dynamics and making it less attractive to investors (Kovacs 2022b). Crisis management has overburdened the public sector, and the underregulated crypto-world has attracted investors large and small. The Bitcoin industry relies on a systemic configuration with a weak real economy being coupled with pressures to stream and place liquidity.

- *Remdesivir*: It became increasingly important for those exposed to the coronavirus (and its variants) to avoid hospitals and ventilators during the COVID-19 epidemic. As the virus surged, countries ran out of newly approved COVID-19 pills and several antibody drugs failed, Veklury (containing remdesivir) prevented SARS-CoV-2 from multiplying in cells, helping high-risk patients avoid more serious (and potentially fatal) infections.[29] The combination of remdesivir, an antiviral drug, with hydroxychloroquine, a malaria treatment used for decades, has saved many lives.[30] Liu et al. (2021) also noted that the pandemic led to the redesign and remanufacturing of hand sanitiser and personal protective equipment.

During industrial revolutions exaptations did contribute (beyond innovations and smart adaptations/imitations) to making the social-economical pendulum swing to change in another direction by allowing the emergence of newer and newer TEPs. Our historical overview proves that sociogenesis happens via contextual social learning in which exaptations play a role next to pure innovations[31] (especially when the context is pressing, what is more, exaptation might emerge intentionally, by contrast to the original idea talking about *byproduct of selection* (Gould 2002), by virtue of creativity a the firefighter plane engine exemplified).[32] As shown, exaptations are not coming from an ecosystem which is suppressed by regulation or which is inexorably tried to be optimized via intense state interventionism. The formation and preservation of high concentrations negatively affect exaptations, which are the result of a system with growing complexity (heterogeneity, competition, fragmentation) based on liberal and decentralised cultural backing in sparking ideas, narratives, and explorative forces. La Porta et al. (2020) stressed the necessity of open-minded, unprejudiced researchers in public and private settings.

[27]See: Conlon et al. (2021).

[28]See: Ramos et al. (2021).

[29]See: Gottlieb et al. (2021).

[30]See: Ardito et al. (2021).

[31]See: Andriani – Kaminska (2021).

[32]As stress can sometimes heal, times of pressure can therefore trigger exaptations, as Winters (2019) suggested.

A complex ecosystem with constant interactions, exploration, exploitation, specialisation, and de-specialization might inspire exaptations.[33]

The global ICT-based techno-economic paradigm, which emerged in the early 1990s, transformed the production process and adapted it to a more service-oriented economy, grounding technologies and processes that are now unleashing I4.0. Still, the function and potential of exaptations in I4.0 have not been explored.

4. EXAPTATION POTENTIAL OF INDUSTRY 4.0: GRAPHENE AS PATHFINDER TOWARDS SOCIOGENESIS?

I4.0 can be defined as a new production philosophy and mode of operation based on the concept of the Internet of Things and Services (IoT), when smart factories are created by integrating resources, machines, and even logistics into an online hyper-connected cyber-physical system being featured with independent and self-optimizing local production processes (Kovacs 2018). This definition takes into account the original German concept (Acatech 2013, 2015) as well as the narratives of international organisations (OECD 2016) and the European Union (European Parliament 2016).

Although the ultimate promise of I4.0 is the dynamization of productivity growth, which is of paramount importance[34] in increasing redistribution, in making public finance sustainable and thereby in improving people's development opportunities (i.e., to cultivate social learning, sociogenesis); a series of processes has been acting against it.[35]

Research on I4.0 suggests that the manufacturing revolution has not fully lived up to productivity expectations (Bhagwan – Evans 2023). Studies also show that I4.0 prioritises economic sustainability, such as growth and productivity, over qualitative sustainability or qualitative growth (Beier et al. 2021; Calabrese – Falavigna 2022). It is by no means certain that the rapid deployment of I4.0 will not exacerbate further already significant inequalities (Kuzmenko – Roienko 2017; Cserhati – Pirisi 2020). Therefore, economic policy should make the transformation human scale.[36]

At this point, the question arises whether I4.0 has the potential to foster a sociogenesis towards qualitative growth (i.e., less emphasis on productivity and more emphasis on quality of life). I4.0, with its separable technologies, is an example of how modular systems stimulate exaptations.[37] To this end, we investigate (*i*) whether graphene technology, often considered a breakthrough material, to be used in I4.0, can unleash sociogenesis for qualitative growth by stimulating exaptations, and (*ii*) whether it has systemic problems to be addressed.

[33]See: Llerena and Oltra (2000).

[34]Especially after secular stagnation (Baldwin – Teulings 2014).

[35]See: Kovacs (2018).

[36]E.g., policy supports automation/robotization if human-machine cooperation is preferred (Kovacs 2022c).

[37]See: Andriani – Carignani (2014); Beltagui et al. (2020).

4.1. I4.0 sociogenesis: graphene-powered exaptations?

While every I4.0-related technology has the potential for exaptation, we have not yet seen such efforts in a thorough manner (e.g., big data can be repurposed to solve new challenges in a different context; recycling and repurposing of plastic waste for advanced 3D printing applications are possible;[38] augmented reality glasses can be repurposed to assist vision[39] etc.). Exaptations alone do not change I4.0's goal from productivity growth to sociogenesis (i.e., qualitative development).[40] Many anticipate this from graphene.

The information revolution spurred graphite and graphene research.[41] The dominant belief is that graphene's widespread application in I4.0 technologies may empower a new force.[42] Its superior application in electronics as the cornerstone for I4.0 may encourage such change. We briefly explain graphene and why it may be essential to sociogenesis via I4.0.

Much has happened since Wallace (1947) demonstrated the flexibility of graphite and the discovery of a single layer in 2004, which led to the 2010 Nobel Prize in Physics. As a two-dimensional material, graphene is a hexagonal lattice of carbon atoms that is lightweight, incredibly conductive, flexible and super-strong, making it transformative. The mainstream thinks of graphene as a material for electrical devices, but its properties make it a great choice for flexible electronics, water filtration, and the exaptation of I4.0.

I4.0 can benefit from graphene's ability to make structures and components in aerospace, automotive, civil, and defence more versatile. Sensing, energy storage, EMI shielding, and property improvement are possible (Muhammad et al. 2023). Energy harvesting, strain sensor technologies, and the steel industry use graphene's excellent mechanical, electrical, and thermal capabilities (Nassef et al. 2020). In composites production, graphene-based smart embedded sensors can evaluate structural health in real time, connecting physical and cyber domains (Muhammad et al. 2021). Graphene metrology was also developed for industrial quality control, measuring layer thickness, edge structure, flaws, and thermal conductivity (Kyle et al. 2012). Commercialising graphene-based technology requires cooperation between academia, industry, and government. All in all, I4.0 uses of graphene are currently being investigated. Accepting the polyphonic nature of exaptations, we juxtapose three pathways through which graphene could lead I4.0 to pursue qualitative rather than mere productivity gains.

- *Graphene batteries* will last 20 years and charge 10 times faster than lithium-ion batteries. The expensive cost of these batteries has prevented their commercialization, although that trend is improving.[43] Additionally, 2D materials with atomic properties similar to graphene are being

[38]For instance, creating building bricks from plastic bottles (PET).

[39]See: Sutton (2022).

[40]Manufacturing companies struggle to repurpose production (Pansare – Yadav 2022). Gregolinska et al. (2022) found that I4.0 has only been implemented to boost productivity. A survey of 1,452 European firms in March 2022 found that 82% of CEOs expected I4.0 to spark the efficiency of manufacturing production. See: TeamViewer (2022).

[41]See: Schönenberger (2000), Mondal – Bhowmick (2022).

[42]See: Nelson (2018), Liu et al. (2022).

[43]A Swiss start-up produced a graphene-based battery whereby halving the recharging time of an electric car's battery to 80% (only within 72 s) has become possible. See: https://www.electrichybridvehicletechnology.com/news/swiss-based-morand-etechnology-introduces-72-second-charging.html Accessed on: 19.02.2024.

studied for energy applications, such as by combining 2D molybdenum disulphide crystals with platinum nanoclusters to create new catalysts that break down water more efficiently and produce green hydrogen in an economically and environmentally friendly manner.[44]

- *Solar cells* are another use for graphene and other 2D materials. When combined with other materials, graphene can boost solar cell efficiency by collecting more light across more wavelengths. Graphene solar cells are lightweight and flexible, making them easier to carry and install.[45]
- *Water filtration* is also possible through graphene. Graphene filters heavy metals and microorganisms from water while letting it pass. Graphene-oxide's one-atomic-layer scales can bind poisonous or radioactive compounds from natural or human sources into the water faster than bentonite or granulated activated carbon.
- *Graphene sensors* are being developed for use in environmental monitoring and healthcare, among other sectors. These sensors are essential for identifying things like early indications of sickness or environmental pollution since they are sensitive enough to pick up on even the smallest changes in their surroundings.
- *Composite materials* can have more strength, conductivity, and flexibility via graphene added. For example, incorporating thick graphene nanoplatelets into silicon nitride enhances the tribological properties of these ceramic composites.[46] These composite materials offer a wide range of possible uses in industries like electronics and construction.

It is hard to avoid the conclusion that graphene is one of the prospective General-Purpose Technologies aimed at accelerating the shift from a productivity-boosting to a qualitative development-focused I4.0 (which would be equivalent to a sociogenesis).[47] Nevertheless, it is puzzling why the beneficial effects of (graphene-driven) I4.0 are still taking so long to materialise. Something about the way the subsystems in the innovation ecosystem are configured has led to the weak exaptation power of I4.0.

4.2. Subsystemic deterrent to exaptationary I4.0

Actually, the financial system has held up quite well in spite of the problems the world economy facing, which are having ever worse socioeconomic effects.[48] Theoretically, nothing would therefore stand in the way of an effective financial intermediation that relentlessly supports the real economy's dynamism (i.e., accelerating the growth of I4.0 towards sociogenesis driven by graphene). Despite this, during the past twenty years or more, economic growth has remained moderated, has not become more inclusive, or even noticeably greener, either.

[44]See: Er, D. (2018): 2D Materials for Energy Applications. Publicly Accessible Penn Dissertations. 2875.

[45]See: https://www.european-mrs.com/2d-materials-energy-applications-emrs.

[46]See: Tapasztó et al. (2017).

[47]See: Beloin-Saint-Pierre and Hischier (2021). Additionally, industries (electronics) can substitute very rare or precious minerals thanks to graphene (Kinaret – Johansson 2022).

[48]Between early 2019 and 10 December 2021, S&P 500 was on an unstoppable upswing, posting a 71%-win rate after weekly losses of 2%. COVID-19 and Russian aggression against Ukraine since February 2022 affected sentiment, but it has remained resilient.

More fundamentally, there is an issue that has not yet been explored, namely that since the state took its soothing hands off the financial system in the 1970s, the financial universe began to expand[49] in the belief that the real economy was no longer needed to generate high short-term returns (Kovacs 2023). It raised market concentrations in the real economy[50] and the financial sector[51] and reduced real investments, which weakened productivity and innovative dynamism. Due to the abundance of credit provided by the expanding financial universe, the markets for corporate and sovereign debts have grown exponentially. This growth has not been shared, but rather has become increasingly unequal and unsecured, with complex side effects like *zombification* that are incomprehensible with traditional economic theories.

Zombie enterprises can stay on the market without improving profitability, productivity, or employment growth (i.e., they struggled to pay their debt service for three years).[52] Given the COVID-19 crisis-management, most zombie company literature believes zombies are not a systemic problem.[53] Some believe zombies might boost economic development by keeping workers employed and salaries from plummeting. Still, if zombie numbers keep rising, they might hurt the European economy.[54]

Zombification appears to have been systemic, because zombie firm dynamics have not changed significantly between crises and non-crises (De Martiis et al. 2020).[55] So, zombification is closely connected to excessive systemic financialization of the socio-economic innovation ecosystem.[56] Recent years have seen a substantial rise in zombie enterprises for several reasons.[57] For years, interest rates were at historic lows until mid-2022. This makes it simpler for struggling enterprises to borrow. Additionally, several European countries have rules that make it tougher for banks to foreclose on non-performing enterprises. So, zombies can remain "living" after they should have perished.

[49]The expanding financial universe spawned new systemic patterns: (i) the rising percentage of capital in national income since the 1970s (see Milanovic 2019); and (ii) intensifying share buy-backs to artificially bolster the stock market. Financial sector tends to avoid riskier, productivity-boosting real economy investments (40% of S&P 500 firms bought back shares in 1990, 60% in 1997–2003, and 85% presently).

[50]See: Vollrath (2020), OECD (2021). These money-power conglomerations worsen inequality and threaten democracy (Glick et al. 2022).

[51]See: Calice – Leonida (2018).

[52]See: McGowan et al. (2017).

[53]See: Bowman (2022), Cella (2020), Favara et al. (2021), or Schivardi et al. (2020).

[54]As more enterprises get bank finance, zombies increase. Europe is a case in point Frick (2022).

[55]One in seven listed real estate businesses worldwide are at risk of being classed as zombie firms, eerily resembling the pre-2008/2009 financial catastrophe. https://www.prnewswire.com/news-releases/the-walking-debt-zombie-companies-unable-to-meet-borrowing-costs-rise-10-in-2022-finds-new-kearney-report-301659156.html.

[56]Copley (2021) noted that the UK economy was pushed by the desire to mitigate globalization's negative consequences by using excessive financialization as an escape route since the 1970s. The UK has a high proportion of zombie enterprises by worldwide standards. For more on their sectoral shares. https://www.hqtrust.de/en/articles/wo-es-die-meisten-zombies-gibt 4.

[57]See: Acharya et al. (2020), Banerjee and Hofmann (2020), Andrews – Petroulakis (2019), Storz et al. (2017).

Contrary to the Panglossian view that zombies have little effect, we argue that zombies have become a systemic feature that could slow growth (i.e., make the system noisier)[58] or *condition the system* (i.e., curb excessive concentrations) to give birth to exaptations once symmetry breaking between the real economy and the ever-expanding financial universe occurs. This contradicts current literature that has called for the elimination of all zombies.[59]

First, because zombification exhibits self-sustaining and self-reinforcing characteristics, it has become an essential component of the system. For example, a higher proportion of zombies discourages productivity, which lowers interest rates and encourages more credit consumption by maintaining and even increasing zombie activities. Zombie companies invest less in R&D, new technology, and staff training and are less productive.[60] Due to this, they are less innovative and are offering lower wages than healthier competitors. Zombie enterprises can also affect markets by driving away rivals. Finally, zombie enterprises that default can threaten financial stability too. When a zombie business collapses, its creditors may incur unexpected losses. This reduces future loans and economic activity.

Second, given the disharmony between the financial universe and the real economy, which continues to cement market concentrations (dominance of large companies resulting in huge inequalities across firms), zombification may prevent *competitive release phenomena*:[61] Eliminating all zombies would make it easier for the bigger ones to reach even greater concentrations, limiting innovations and exaptations by worsening the financial sector-real economy relationship, income and wealth inequality, and inclusive growth. This would damage entrepreneurship and social learning. A glance at market concentrations in advanced nations shows that industry concentrations have been expanding on a gradual moderating track, accompanied with a growing percentage of zombie businesses across the board.[62]

Since the 2008 financial and economic crisis, Germany, Greece, Italy, and Spain have taken steps to reduce zombie firms, but large concentrations rose,[63] which could fossilise innovation dynamism and increase inequalities.[64] After a long period of fiscal and monetary stimulus (low interest rates, intensive fiscal transfers, and Quantitative Easing in Europe) in response to the 2008 financial and economic crisis and the COVID-19 pandemic, the number of zombies in all zombie firms that are more likely to be a latecomer via innovation and exaptation has increased.

[58]Noisier in the sense that with zombification it is more difficult to make decisions without errors (e.g., misinformation leading to wrong decisions when choosing suppliers that are, in turn, zombies etc.).

[59]See: Hallak et al. (2018), Qi et al. (2022), Blažková – Chmelíková (2022).

[60]See: Belullo et al. (2015).

[61]Competitive release happens in living systems. In cancer research, when treatment-sensitive cells die *en masse* owing to aggressive chemotherapy, the previously controlled resistant subpopulations erupt fast, making the outcome worse than without treatment (Seton – Rogers 2016).

[62]See: Autor et al. (2020) or Ciapanna et al. (2022). From 1999 to 2020, Euromonitor International's Passport Industrial database shows a small decrease in markups and concentrations (Koltay – Lorincz 2021).

[63]Since 2011, the EU27 has seen more major firms (250+ employees). Since 2010, Greek, Italian, and Spanish insolvency laws have been amended to reduce the number of zombies, and the findings suggest that medium and even bigger enterprises might dominate more. It is instructive that the number of medium-sized firms has been declining (from 102,000 in 2011 to 100,000 in 2019 in the EU27) (Eurostat SBS_SC_SCA_R2).

[64]See: Nieto-Carrillo et al. (2022).

Thus, zombie businesses may include latecomers, optimistic martyrs, and even those that are eventually succeeding in expanding their ideas through exaptations.[65]

5. DISCUSSION

In this paper, we constructed *a verbal model* considering the following linchpins: (*i*) there is a need for a sociogenesis via social learning (relying on innovation as well as *exaptations*) manifesting in the move from quantitative growth to qualitative growth; (*ii*) the systemic configuration (i.e., interplay between the financial universe and the real economy) affects the feasibility of such sociogenesis; (*iii*) I4.0 can serve as a potential mechanism of such shift if and only it is repurposed toward qualitative growth; (*iv*) the application of graphene (and other 2D materials) technologies can aid I4.0 to tailor the system toward qualitative growth.

We addressed the puzzling but so far unresearched issues whether graphene technology, often considered as a revolutionary material, can serve as a pathfinder for I4.0 to reach out higher exaptation potential to be pervaded by new attitudes towards the natural order of socio-economic innovation ecosystem by unleashing a sociogenesis to qualitative growth, and whether it is also beset with systemic difficulties?

Leaving behind pursuing quantitative growth by moving toward qualitative growth calls for repurposing. In the context of the ongoing industrial revolution (I4.0), we can achieve this if such revolution integrates general-purpose technologies, especially graphene and other 2D materials, that streamline production and increase energy efficiency in a more conspicuous way. We also tried to point out that the growing financial cosmos, long ignored, was a systemic obstacle to this sociogenesis. We identified zombification as a negative effect of such a systemic configuration, implying at the same time that these companies also have positive macro effects in such a systemic setting. Further research is needed on how to use graphene more purposefully and precisely with I4.0 technologies, on how to select which zombies should stay and which should die, and on what types of sociogenesis regulation seem appropriate in different socio-economic contexts. Nevertheless, at least six policy-oriented insights can be summarised as follows.

Firstly, heterogeneity and the fragmented nature of the socio-economic system being pervaded by equability can be considered as the basis of social learning and thus that of sociogenesis via innovation and exaptation dynamism.

Secondly, studying the context is essential when addressing how interdisciplinarian interfaces are given by leading to repurposing opportunities (exaptations) in coping with context-dependent challenges.

Thirdly, on the one hand, we challenged the myth that the current form of I4.0 will inevitably boost productivity in a spectacular way; on the other hand, some channels are really out there through which graphene may drive I4.0 to be repurposed to pursuing qualitative growth (a sociogenesis) rather than productivity growth.

Fourthly, during earlier techno-economic paradigms (when the goal of the financial system was exclusively to serve the real economy as an efficient intermediary) without symmetry breaking between subsystems (real economy, financial universe), dampening the share of zombie

[65]See: Codini et al. (2022).

firms might have stimulated competition and liberated financial constraints by grounding social learning. Similar to living systems, where exaptation is best driven by extreme environmental/contextual conditions, as noted earlier, zombies may be the most pressured entrepreneurs to drive exaptations (to lead social change as social entrepreneurs).

Fifthly, in the current configuration of the socio-economic innovation ecosystem having a symmetry breaking, a policy that does not differentiate among zombie firms might be a wrong inference especially in a time when Industry 4.0 could contribute to the sociogenesis via promising GPTs like graphene. If economic policy leaves the disharmonic configuration between the financial sector and the real economy, coupled with the overburdening nation state, intact, there is no place even for graphene, having an exaptationary power, to reprogram I4.0 toward a qualitatively different socio-economic innovation ecosystem.

And sixthly, systemic zombification may be *per se* a sign of a sort of sociogenesis that is already well underway (i.e., preventing the big ones from becoming even bigger, the development of business organization practices along other types of social goals such as fostering more inclusive development). The goal is not to completely disable the zombies, but to gradually starve them since they have cross-firm heterogeneity (i.e., via interest rate hikes, revised and tightened fiscal supports). In this way, some zombies are forced to innovate or think about exaptations.

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