# Technological paradigms and the power of convergence

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## Abstract

With the advent of Industry 4.0, technological interdependence is becoming increasingly important in the delineation of technological development dynamics. In the present paper, we propose an extension of the theory of technological paradigms conceptualizing the role of technological interdependence in the emergence of paradigms and the coevolution of the corresponding trajectories. We corroborate our conceptual extension by means of an in-depth historical account of the genesis and evolution of the additive manufacturing paradigm. Accordingly, we elucidate how different technological paradigms may give rise to an aggregate paradigm through a process of convergence, and how the aggregate paradigm may contribute to steering the direction of technological change alongside traditional science-push, demand-pull, institutional and socio-economic factors. Our work has two main implications: first, it shows that a technological paradigm may emerge from a process of incremental convergence, and not only from radical innovations and scientific breakthroughs. Second, it shows that dynamics of epistemological interdependence (i.e. interdependence between paradigms) matter significantly in the determination of technological development paths.

**JEL**: B52 – Historical, Institutional, Evolutionary, O33 – Technological Change: Choices and Consequences; Diffusion Processes

## 1. Introduction

Insightful and wide-reaching in its academic impact (Von Tunzelmann et al., 2008), the long-standing theory of technological paradigms frames socio-economic, industrial and institutional factors as a complex nexus of focusing devices, which operate in concert to select a technological development path among the whole of notionally possible ones. Once a paradigm is established, it delineates a trajectory of improvement of selected performance trade-offs between technological attributes (Dosi, 1982). Within this classic framework, the present paper explores the role of technological interdependence, proposing a conceptual extension that may benefit both theory and practice, especially as an interpretative lens for the latest technological advancements.

Innovations falling under the label of Industry 4.0, such as additive manufacturing (AM), artificial intelligence (AI) and cyber-physical systems, have the potential to revolutionize various aspects of economic systems (OECD, 2017), including labor markets (Frey and Osborne, 2017) and the international competitive landscape (Strange and Zucchella, 2017). However, unlike innovations in previous industrial revolutions, this potential does not lie only in the technologies themselves, but especially in their complementarity (EPO, 2017). This sheds new light on the necessity to consider technological interdependence as a possible route to the emergence of new technological paradigms and the characterization of their epistemological implications.

Technological interdependence is a well-acknowledged aspect of technological development (Rosenberg, 1979). Technologies do not stand alone. For this reason, they can often be framed as complex systems where the performance and development paths of single components affect the whole (Hughes, 1993). This is particularly evident in technologies linked by direct vertical relationships, as in the case of computers building upon integrated circuits, which in turn build on transistors. In such cases, the development paths of the upstream and the downstream technologies are clearly intertwined, with smaller transistors paving the way for more powerful computers. Technologies with numerous downstream applications, popularized as general purpose technologies

(GPTs), are widely regarded as one of the main engines of techno-economic progress (Bresnahan and Trajtenberg, 1995). However, downstream dependence is not the only possibility. Vertically unrelated technologies belonging to the same system are still likely to influence each other, as in the case of jet engines affecting aircraft body design (Nelson et al., 2018). Most interestingly, even technologies originally belonging to different systems may happen to converge over time, as in the case of digital photography being integrated into mobile phones (Hacklin et al., 2005).

In the present study, we argue that technological interdependence may entail epistemological interdependence, meaning that interdependence between technologies may translate into interdependence between technological paradigms. Technologies originally grounded on different paradigms and following separate improvement trajectories may eventually converge into a unique aggregate paradigm, thanks to functional complementarities revealed along their development path. This has a twofold implication. First, it pinpoints incremental convergence as one of the possible routes to the emergence of a new technological paradigm. Second, it highlights the epistemological intertwinement between the aggregate paradigm and the subparadigms on which it is grounded. Once the aggregate paradigm is in place, it will acquire its own epistemic locus, delineating a technological macrotrajectory. Like standard technological trajectories comprise a cluster of directions of technological change (Dosi, 1982), the macrotrajectory defined by an aggregate paradigm will comprise a cluster of trajectories. The clusterization of trajectories accounts for the influence of the aggregate paradigm over its foundational paradigms, steering the evolution of technological change alongside scientific, market and institutional factors.

Our theoretical extension is supported by an in-depth historical account of the evolutionary path of AM. AM denotes the nexus of technologies that enable production through layer-by-layer overlapping of material by a 3D printer, proceeding from a digital model. AM can be framed as a technological paradigm, being consistent with the epistemological notion of "*an outlook, a set of procedures, a definition of the relevant problems and of the specific knowledge related to their* *solution*" (Dosi, 1982, p.148). The outlook is clear-cut and revolutionary, creating a direct bridge between digital and physical objects. The set of procedures has been formalized in the ISO/ASTM 52900 standard:[1] binder jetting, directed energy deposition, material extrusion, material jetting, sheet lamination, powder bed fusion and vat photopolymerization are the seven additive process categories. These processes are complemented by supports for digitalization (computer-aided design software, commonly known as CAD) and automation (computer-aided manufacturing tools, commonly known as CAM). CAD and CAM are indeed regarded as pre-smart technologies (Martinelli et al., 2021), and their epistemological connections with the AM paradigm constitute a key part of our argument. Relevant technological problems such as the speed, accuracy, reliability and versatility of the 3D printers have been identified, analyzed, and linked to industrial applicability (Petrovic et al., 2011; Berman, 2012). The knowledge related to their solution lies in their relationship with the aforementioned processes, which is often unambiguous (e.g. the number of printing heads affecting speed). To the present day, AM has significantly affected several industries, including aerospace, jewelry, automotive, electronics, construction, fashion and biomedical applications (Hannibal and Knight, 2018).

A recent Delphi prospection predicts AM will fully manifest its revolutionary effects on business models, supply chains and relationships among economic actors by 2030 (Pérez-Pérez et al., 2018). However, modern AM techniques have been in place for more than three decades, and their conceptual antecedents, like photosculpture and topography, date back to the second half of the nineteenth century. This enables a fine-grained analysis of the evolutionary path of the paradigm, which we have conducted by gathering and triangulating scientific papers, grey literature on the topic and information from well-established specialized sources (e.g. Wohlers Report, 2019). To further highlight the patterns of epistemological interdependence, we have complemented this historical

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[1] ISO/ASTM 52900 is the most recent standard available. It is worth noting that these standards are typically reviewed every 5 years.

account with an empirical inquiry into the trends in scientific research and inventive efforts, by collecting and analyzing scientific publications and patents through ad hoc keyword searches on Scopus and Espacenet. All the analyses point in the same direction, supporting our proposed theory from multiple angles.

The remainder of the paper is organized as follows. Section 2 provides a critical literature review of the technological paradigm stream and its relationship with other relevant contributions on technology and innovation. Section 3 develops our theoretical extension. Section 4 analyzes the genesis and evolution of the AM paradigm, elucidating the application of the proposed extension. Section 5 concludes, suggesting avenues for future research.

## 2. Technological paradigms: evolutions and revolutions

### 2.1. The notion of technological paradigm

The theory of technological paradigms proceeds from a critical analysis of two opposing conjectures about technological progress. Demand-pull theories suggest innovation stems from the recognition of a need (Myers and Marquis, 1969; Von Hippel, 1976; Mowery and Rosenberg, 1979). This, with varying degrees of determinism, leads inventors and engineers to channel their efforts into the most needed products or product characteristics. Although market incentives are widely recognized as important forces shaping the rate and direction of technological progress (Christensen, 1997; Adner and Levinthal, 2001; Fontana and Guerzoni, 2008), this approach features a missing link between the recognition of needs and the development of corresponding technologies. In reality, the responsiveness of technological progress to customer and user needs is not always as immediate as pure demand-pull theories posit. Another significant drawback of the demand-pull stream lies in its inadequacy to account for technological revolutions: while the continuous effort to satisfy target customers and users is coherent with incremental improvements, it is often the case that sudden discontinuities can hardly be explained on the sole basis of radical shifts in preferences.

Instead, technology-push approaches (Freeman, 1974; Pavitt, 1979) tend to assume an automatic translation of scientific/technological breakthroughs and R&D effort into innovative output. While the impact of R&D on innovation is intuitively clear and empirically well documented at multiple levels of analysis (Godoe, 2000; Bilbao-Osorio and Rodrìguez-Pose, 2004; Baumann and Kritikos, 2016), its direction, dynamics and antecedents revolve around multifaceted techno-economic interdependences, which pure technology-push approaches tend to overlook.

The notion of technological paradigm reconciles these views, making up for their shortcomings. A technological paradigm is defined as a structured perspective involving a set of patterns, procedures, modes of problem identification and knowledge acquisition (Dosi, 1982). In analogy with the concept of scientific paradigm (Kuhn, 1962), it defines an epistemic locus where the quest to technological augmentation takes place, according to a set of norms. Such norms concern the selection of focal performance trade-offs among technological attributes, a shared understanding of the pattern of inquiry to improve them, and the use of decision heuristic for actualization. Hence, they shape both the objective and the route to achieving it, tracing an improvement trajectory along which *normal* technology augmenting activity takes place, in analogy with the *puzzle-solving* activity of science as defined by Kuhn (1962).

Comprising a cluster of directions of change, technological trajectories may be characterized by a varying extent of internal heterogeneity. Paradigms define outer boundaries, inside which a variety of directions may actualize, emphasizing different dynamics of trade-off improvements between attributes, often shaped by contingencies and competitive pressures. Indeed, even if not as strongly as in pure demand-pull approaches, the market still matters in the context of technological paradigms. The "*definition of the relevant problems*" (Dosi, 1982, p.148) is often sensitive to economic needs. Sometimes economic needs are pressing and relevant problems are clear and unambiguous, as shown by the wage-driven labor-saving bias of technological change in the British Industrial Revolution (Allen, 2009; Nuvolari et al., 2020), and the effort by 19th century British producers to develop technologies augmenting Indian cotton due to the supply shortage triggered by the U.S Civil War (Hanlon, 2015). Other times the relevance of problems is more subjective, possibly leading to competing directions of change within the same paradigm, with the market acting as an ex-post mechanism of reward and punishment.

However, the market is far from being the only player. Technological paradigms are bound to a nexus of social, economic, industrial and institutional factors, which act jointly as focusing devices, selecting a specific route among the complex of ideally possible ones. Once a given paradigm emerges, it acquires a momentum of its own, delineating a technological trajectory grounded on the cumulative features of theoretical and practical knowledge, until disruption occurs. The dynamic interplay between scientific, socio-economic, industrial and institutional factors in shaping the direction of techno-economic progress is indeed the crux of the construct, which constitutes one of the cornerstones of evolutionary economics (Dosi, 1988; Dosi and Orsenigo, 1988; Dosi and Nelson, 1994, 2010; Nelson, 2009; Nelson et al., 2018).

## 2.2. Technological paradigms and discontinuity

It is common practice to frame technological progress as a curve in the bidimensional space plotting technological performance as a function of R&D effort.[2] This curve is often assumed to be S-shaped (Foster, 1986; Asthana, 1995). The S-shape stems from the properties of knowledge accumulation: new knowledge formation is difficult when no previous knowledge exists, and when the circumscribed epistemic potential of a particular instance is exhausted; in the remainder of the spectrum it tends to be exponential, as subsequent knowledge-blocks build on one another.

This framework is useful in depicting the conceptual distinction between incremental and radical innovations. While incremental innovations correspond to the normal (often S-shaped) progress along the curve, radical innovations represent a rupture in the curve, which may be followed by a separate

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[2] Assuming constant R&D effort, it is also possible to plot technological progress as a function of time.

curve initiating a new pattern of knowledge accumulation. When a technology fully develops, being in the mature stage of the “S”, a point of discontinuity is required to reach new performance peaks, which is typically associated with a radical innovation.

The cyclical model of technological change proposed by Anderson and Tushman (1990) brings this conceptualization closer to the perspective of technological paradigms, positing technological discontinuity as a hiatus between a dominant design and an era of ferment: major technological breakthroughs dethrone the previous dominant design, initiating a period of fervent experimentations, after which a new dominant design emerges. With some exceptions, most notably in the pharmaceutical sector, the dominant design can often be conceived as the materialization of a technological paradigm into an artifact (Dosi and Nelson, 2010).

Following the Kuhnian tradition, technological paradigms incorporate discontinuity as a paradigm shift. In his seminal paper, Dosi (1982) argues that new paradigms emerge from radical innovations, and extraordinary innovative effort arises either due to scientific breakthroughs or to the impossibility of advancing along the extant technological trajectory. This assumption seems to have been kept in more recent works on the topic, where the authors assert that they “*reserve the name of radical innovations for those innovations linked with paradigm changes*” (Dosi and Nelson, 2010, p.17). The association is generally maintained in both academic and practitioner-oriented debates aligned to the technological paradigm stream, including its techno-economic extension (Perez, 2004, 2010; Drechsler et al., 2009). The “paradigm shift” expression is indeed ubiquitous as a lens to describe, analyze and predict disruption.

The theoretical distinction between incremental progress embodied in trajectories and discontinuities represented by paradigm shifts has guided many relevant empirical inquiries in this area. For example, plenty of studies have exploited main flows of knowledge within patent citation networks as the empirical embodiment of a technological trajectory (e.g. Mina et al., 2007; Fontana et al., 2009; Barberà-Tomàs et al., 2011). Network analysis on patent data has also been successfully employed to detect discontinuities in engineering heuristics as a way of identifying paradigm shifts (Martinelli, 2012). The dichotomy between “movements along a trajectory” (driven by incremental innovations) and “paradigm shifts” (driven by radical innovations) is informative and applicable to many empirical instances. However, we argue that interdependent movements along multiple trajectories may sometimes be the very reason underlying a paradigm shift. The acknowledgement of this possibility may lead to more fitting and enlightening explanations for dynamics of technological change, especially in domains characterized by strong convergence and interdependence.

## 2.3. The power of convergence

We propose a further analogy between scientific paradigms and technological paradigms: the one between *epistemic convergence* and *technological convergence*. Pure science tends to proceed vertically, expanding the boundaries of human knowledge through systematic inquiry. When a system turns out to be inadequate (i.e. a Kuhnian anomaly arises), it may be supplanted by a new system (i.e. a new scientific paradigm). Accordingly, the technological analogy suggests that the inadequacy to advance along a given trajectory may trigger a technological paradigm shift. However, science may also proceed horizontally, by bringing together the perspectives of different disciplines (e.g. mathematics, physics, psychology and medicine in the field of neuroscience). Such a tendency is even stronger with applied science, and reaches its peak with technology (Jeong et al., 2015). Technological artifacts enable the fulfillment of specific functions, and many of such functions are complementary, often yielding exponential benefits when put together. Hence, we put forward the idea that the integration of different functions under the same technological umbrella, following a process of incremental convergence, may carry considerable disruptive potential.

Epistemic and technological convergence are conceptually analogous, but structurally and procedurally different. The former stems from knowledge complementarities (often different facets of the same phenomenon), while the latter may also derive from functional complementarities. Although knowledge complementarities are often desirable, they rarely trigger the emergence of a new scientific paradigm. In science, the vertical dimension is predominant. The development of different disciplines, and paradigms within them, is what distinguishes modern science from the ancient practice of treating knowledge as a homogeneous bulk, and the difference in the rate of progress between the two approaches is self-explanatory. When working in neuroscience, mathematicians, physicists, psychologists and physicians bring to the table their different training, cognitive frames and decision heuristics, and that is precisely where the added value lies.

Conversely, we argue that functional complementarities may well underlie the emergence of new technological paradigms. Technology is not only knowledge embedded in artifacts, but also a nexus of functional nodes and arcs, forming systems of varying complexity. Components of such systems interact in various ways. Technological components lagging behind in development can hold back the growth of the entire system they belong to (Bijker et al., 1987). Furthermore, progress in one component of the system may influence, more or less directly, the allocation of innovative efforts on other components. An historical example is given by cutting machines in the 19th century U.S., whose increase in speed triggered the need to improve the resistance of materials, as well as the efficacy of cooling methods (Rosenberg, 1963).

Progress may be driven by incremental or radical enhancements, but also by recombinative efforts. As Nelson and Winter (1982, p.130) note: "*The creation of any sort of novelty in art, science, or practical life - consists to a substantial extent of a recombination of conceptual and physical materials that were previously in existence*." Pioneered by the seminal research on recombinant uncertainty in technology search (Fleming, 2001), the notion of combinatorial innovation is now well-established in both theory and practice, denoting the idea that innovation may arise even just from the creative recombination of extant technologies. Combinatorial innovation is increasingly frequent and relevant in the present digital context, where digital product modules can be easily adapted and recombined to form new products (Arthur, 2009; Yoo et al., 2012). A strictly related concept is the notion of architectural innovation, denoting the idea that innovation may stem from changes in the architecture of components rather than components themselves, with plenty of managerial, organizational and strategic implications (Henderson and Clark, 1990; Bozdogan et al., 1998; Galunic and Eisenhardt, 2001; Hofman et al., 2016; Park et al., 2018). Recombination starts, in either case, from the recognition of novel insights on component configurations or the release of previous constraints. Incremental improvements may trigger both. Improvement along a given trajectory may create a new arc or enable the actualization of one that has already been envisaged, prompting the emergence of new artifacts.

We maintain that the application of these insights to the epistemological domain is a valuable addition. Technological convergence, combinatorial innovation, architectural innovation and, more generally, any view of technology as a complex dynamic system are all grounded on the key notion of technological interdependence. While they differ in the unit of analysis, these views all reflect the functional dependence of each component on every other component. In the case of technological convergence, components depend on each other due to their prospective integration. In the case of combinatorial innovation, components depend on each other to form the spectrum of possible recombinations. In the case of architectural innovation, components depend on each other as parts of an architecture that may be revolutionized. However, despite their technical, organizational and strategic insights, these views are largely silent on the epistemological implications of technological interdependence. How may technological interdependence affect the rate and direction of progress within the boundaries of technological paradigms? Within this question lies indeed the object of our theorizing.

Technological paradigms are conceived as being governed by a concert of science-push, demand-pull and institutional factors. Furthermore, they are generally assumed to emerge and supplant each other based on scientific breakthroughs or radical innovations. While this is a large part of the story, it captures mainly the vertical dimension of technological progress, the one which most closely resembles pure science. However, in the technological domain, we argue that the horizontal dimension, made of convergence, integration and recombination, plays a fundamental role, which is growing in relevance. Steady incremental advances in different technological trajectories may lead to a proliferation of recombinative insights and a reduction of functional constraints, leading to the emergence of a new aggregate paradigm with its distinctive set of outlooks, procedures and heuristics. The aggregate paradigm may be revolutionary enough to substitute for previously existing paradigms in certain domains of application, as in the case of AM displacing subtractive manufacturing in prototyping, spare parts production and even final product manufacturing in many industries (e.g. hearing aids). Furthermore, by steering the trajectories of its subparadigms, it may contribute to determining the direction of technological change alongside scientific, market and institutional factors.

## 3. A proposed conceptual extension

### 3.1. The role of technological interdependence

In the present conceptualization, we abide by the traditional notion of technological paradigm as defined in the previous Section. We also abide by the notion of technological trajectory as the progressive actualization of the potential of the paradigm, through the accumulation of knowledge and practical expertise aimed at improving the trade-offs between selected technical and economic attributes. Referring to the decision-making level of the relevant economic actors,[3] selection is kept on track by positive and negative heuristics determining the directions of technological progress to pursue and exclude, respectively. Such heuristics may vary in strength and persistence, reflecting on the binding power[4] and stability of the paradigm over time.

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[3] A practical example is the creative effort of engineers directly involved in the focal technology.

[4] The binding power of a technological paradigm can be defined as the power exerted by its (positive and negative) heuristics in shaping the direction of technological progress. A paradigm with a strong binding power admits little variability in the improvement of the selected performance trade-offs. In other words, it traces a well-defined and narrow technological trajectory in the multidimensional space of attributes. This may be due to a variety of reasons, ranging from scientifically grounded technical priorities to clear market incentives and powerful institutional pressures.

In this regard, we advance the possibility of *an epistemological interdependence between trajectories of different paradigms*. Although related to the widely acknowledged interdependence among technologies, this is a slightly subtler concept. In the following paragraphs, we will provide an overview of the role of technological interdependence in the context of technological paradigms, for the twofold purpose of clarifying its boundaries and paving the way for the main argument. As the word suggests, interdependence may imply the mutual influence among technologies. However, for the sake of simplicity, we will refer only to the impact of a second technology (hereafter denoted as the *influencing technology*) over a focal technological trajectory. In case of mutual dependence, the reasoning is symmetric in its logic.

One might conceive a technological trajectory as a mathematical locus traced by a point moving in the *n-dimensional* space defined by *n* relevant technological attributes, where movement implies the improvement of such attributes according to the underlying paradigm's criteria. The binding power of the paradigm determines the width of the trajectory, namely the degree of regularity in the direction of progress of the point tracing it.[5] In this setting, technological interdependence may determine a change in the speed of the point and/or a perturbation in the regularity of its direction of progress, at any given time.[6] Here, two elucidations are in order.

First, the extent to which the focal trajectory is perturbed depends not only on the characteristics of the interdependent technological developments, but also on the binding power of its underlying

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[5] More precisely, the interaction between the technological paradigm and other factors also contributes to determining the speed of the moving point, as well as variations in speed over time. For instance, a strong scientific understanding increases the speed of technological progress (Nelson, 2008).

[6] For example, the integration of digital photography into smartphones made memory more valuable, due to the necessity to store pictures and videos. This steered the direction of progress of smartphones' attributes in favor of storage capacity. Conversely, the advent of the cloud meant photos and videos could be stored in online repositories, making storage capacity comparatively less important. Both these effects have plausibly contributed to perturbing the regularities induced by the smartphone paradigm in the trajectory's dynamics. It is outside of the scope of this paper to attempt any measurement of the true impact of these interdependences, which may well sum up to be negligible given that they point to opposite directions. By virtue of their straightforwardness, they should be taken as a pure exemplification of the underlying logic.

paradigm. In this regard, the continuum ranges from a serendipitous discovery[7] to the fruit of systematic research and experience taking place in a highly structured epistemic locus.[8] Ceteris paribus, the more structured the epistemic locus, the clearer and more prescriptive the notion of technological progress embedded in the selection of the performance trade-offs to improve. Thus, the stronger the binding power of the focal paradigm, the weaker the impact of other technologies on the focal trajectory. In the extreme case where a technological paradigm is fully binding, extraneous technologies bear no relevance by definition.[9]

Secondly, the influencing technology's evolutionary dynamics matter considerably. In this regard, the continuum ranges from a component, procedure or piece of know-how that becomes readily available soon after its discovery/invention, to a slowly developing technology that reveals its relevance to the focal instance only after some time. In cases closer to the latter extreme, the impact of the influencing technology may manifest gradually according to many possible patterns. A case that is already well-acknowledged is a paradigm shift triggered immediately by the emergence of a new complementary technology. As a matter of fact, this instance falls into the typical scenario of a new technological paradigm born out of a technological breakthrough. Indeed, one of the various ways whereby a technological breakthrough may lead to the emergence of a new paradigm is through a full or partial embedment into a game-changing complementary artifact (e.g. the combination of innovative virtual reality headsets with classic video game consoles). However, this is just one of the extremes of the spectrum delineated above.

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[7] An example is given by aspartame, which was discovered accidentally while experimenting with L-phenylalanine and L-aspartic acid in an effort to develop an anti-ulcer drug.

[8] A strongly binding technological paradigm can be found in the domain of microelectronics, where the selected trajectory of improvement was so clearly defined that it gave rise to Moore's law, the famous empirical projection about the number of transistors per integrated circuit doubling every two years (Moore, 1965).

[9] A fully binding technological paradigm is an extreme theoretical case, analogous to perfect competition in neoclassical microeconomics. A hypothetical actualization of this case may consist in a dystopian dictatorship forcing technological progress along extremely rigid preconceived tracks.

### 3.2. A proposed model of epistemological integration

Technologies grounded on well-defined paradigms give rise to well-defined technological trajectories. We shall denote two arbitrary technologies with such features as A and B (see Figure 1). Representing different universes of trade-off improvements between attributes, they move in distinct multidimensional spaces. We shall denote such spaces as $S_a$ and $S_b$. Assuming technological interdependence, improvement in a subset of attributes in $S_a$ and/or $S_b$ beyond given *performance thresholds* (the dotted lines in the figure) may break functional and/or economic barriers toward technological integration.[10] We shall denote as $R_a$ and $R_b$ the resulting *integration regions* (the shaded areas in the figure). Graphically, the *integration region* is the subset of points in $S_a$ and/or $S_b$ beyond all *performance thresholds*. Conceptually, it is the locus of points in $S_a$ and/or $S_b$ leading to technological integration.[11] It may be the case that only technology A or B has to overcome one or more *performance thresholds* for effective integration. In such cases, the *integration region* of the other technology ($R_b$ or $R_a$, respectively) would comprise the entirety of its multidimensional space (i.e. the corresponding figure would be all shaded). Clearly, it can never be the case that both $R_a$ and $R_b$ comprise the entirety of their multidimensional space, otherwise the technologies would be integrated a priori by definition.

Once the techno-economic optimality of integration becomes visible (i.e., the outer boundaries of *a* and/or *b* appear on the epistemological horizon), it will act as a gravitational force, attracting the corresponding trajectory with an intensity proportional to its closeness to the integration region. The closer it is, the more evident the integration possibility, and the stronger the incentives to pursue it.[12]

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[10] This may hold for one or more of the technologies involved. An example of the former is given by a component that becomes small enough to be integrated in a given architecture. An example of the latter is given by a new type of engine and a new aerodynamic structure becoming compatible after a series of improvements on both sides.

[11] For simplicity, we are assuming that the integration region denotes the locus of points where integration happens, being both feasible and optimal. In principle, these two properties could be distinguished: there might be a sub-region where integration is only feasible but not optimal (e.g. being too costly). However, such a distinction would increase complexity without significantly affecting our line of reasoning.

[12] To have a more vivid picture of the rationale for this abstract process, one may imagine designers, engineers and the other actors involved in the innovative process being increasingly pressured for pursuing certain directions of

It is worth noting that the closeness of the other trajectory to its integration region matters just as much in determining the intensity of attraction.[13] Furthermore, the techno-economic benefit of integration is likely to moderate the intensity of attraction at all stages of the process.[14] In the context of our extension, the notion of techno-economic benefit of integration embodies Dosi's harmonization of the demand-pull and technology-push aspects of technological progress, both semiotically and conceptually. The drive toward integration may stem from the identification of market incentives, the acknowledgement of technical opportunities or, more likely, a combination of both.

Once both technological trajectories enter the integration region, the two multidimensional spaces merge[15] and give rise to a new aggregate paradigm, delineating a macrotrajectory of improvement grounded on a new epistemic locus (see Figure 2).[16] The new paradigm may be revolutionary enough to supplant previously existing paradigms in certain fields of application, but it does not necessarily supplant the subparadigms on which it is grounded. The trajectories associated to those subparadigms may keep on existing as a part of the macrotrajectory delineated by the aggregate paradigm. The macrotrajectory represents a cluster of trajectories, in the same way a trajectory represents a cluster of directions of trade-off improvements between performance attributes. As such, it will influence

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improvement, by virtue of the integration possibility. Such pressures may be explicit (e.g. top-down directives, formal incentives) and/or implicit (e.g. hype, bandwagon effect and other social mechanisms).

[13] This is because integration happens only when both trajectories enter the integration region. The distance of one of the two trajectories from its integration region may severely weaken the gravitational force of the integration region of the other technology. The importance of *conjoint distance* of the trajectories from their respective integration regions is an interesting point, which may be modelled in different ways (e.g. considering the maximum between the two). However, while relevant for a computational model aiming to measure and/or predict these dynamics, such considerations are outside the scope of this paper.

[14] It is reasonable to assume that the stronger the techno-economic benefit of integration, the stronger the dynamics described in footnote no. 12. Both explicit pressures (due to economic incentives) and implicit pressures (due to increased hype and circulation of information) are likely to increase in cases where technological integration is highly anticipated and welcomed.

[15] The merged multidimensional space will be the union of the attribute sets of the two underlying spaces. However, this does not necessarily (and typically) imply that the merging technologies have all the attributes in common: trajectories of technologies not possessing one or more of the attributes of the merged multidimensional space will simply not move in those directions.

[16] The vast majority of technologies have more than three relevant performance attributes. Hence, the hereby presented tridimensional representation is likely to constitute only a partial snapshot (i.e. slice) of the true multidimensional space where the technologies reside. Still, the representation proves useful for visualization purposes. Conceptually, the generalization to *n* dimensions is immediate.

the way in which the embedded trajectories steer the directions of technological change. Like traditional paradigms, aggregate paradigms may have varying degrees of binding power, depending on the prescriptiveness of their notion of progress and the pervasiveness of their heuristics. In this respect, the functional scope of the underlying technologies matters as well. We expect subparadigms embedding technologies with few alternative applications to be comparatively more susceptible to the influence of an aggregate paradigm. Conversely, subparadigms related to more versatile technologies are likelier to retain their epistemological independence. The reason is that, even when integrated, the underlying technologies have multiple alternative uses subject to many technical and economic forces, weakening the epistemic predominance of the aggregate paradigm.

[Insert Figure 1 around here]

[Insert Figure 2 around here]

### 3.3. Main implications

Our conceptual extension has two main implications. The first is that a technological paradigm shift may be triggered not only by a scientific breakthrough, a serendipitous discovery or a radical innovation, but also by a process of incremental convergence of existing paradigms. This is the case of AM, which emerged from the convergence of paradigms in the domains of automation, digitalization and fabrication, and overthrew traditional manufacturing in many fields of application (more details in the next Section). In the first stage, convergence relies on accidental evolutionary matching, emphasizing the well-known relevance of path dependence. In other terms, the integration region must be brought within reach by the natural pathway of the trajectories involved. More specifically, the perceived feasibility and optimality of integration must be sufficiently strong as to engender a modulation of the positive and negative heuristics steering the directions of technical change. Once trajectories get close enough to their integration region, convergence is likely to acquire a momentum of its own, eventually triggering the emergence of an aggregate paradigm.[17] How close they must be to engender the self-actualization of convergence depends on contextual factors like the binding power of the paradigms underlying the involved trajectories, as well as the benefits of techno-economic integration.

The second implication pertains to the relationship between the aggregate paradigm and its subparadigms. The former will exert a steering force of varying power over the trajectories delineated by the latter, ultimately affecting the directions of technological change they embed. This steering force is well exemplified by the CAD/CAM aggregate paradigm, which has considerably shaped the direction of progress of CAD software along a pathway defined by its functionality for manufacturing (more details in the next Section). It is worth noting that the subparadigms still exist on their own, as long as they have alternative applications. However, the aggregate paradigm will impose, with a varying extent of forcefulness, its set of positive and negative heuristics, which may be in conflict with the extant heuristics. Such potential conflicts determine a perturbation in the regularity of the original trajectories, exerting a varying extent of influence over the directions of technological change.

## 4. Genesis and evolution of AM

### 4.1. Overview

From a practical viewpoint, the functioning of AM is rather simple: a digital model of the object to be printed is inserted into a 3D-printing machine. Then, the model is decomposed into a series of 2D layers, which one or more printing heads physically reproduce and juxtapose, recreating the whole. Materialization of layers follows the binding of liquid, powder or solid inputs. Depending on the input, different fabrication processes exist. For instance, stereolithography consists in the

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[17] The resulting aggregate paradigm is not necessarily revolutionary, nor does it necessarily determine a paradigm shift in one or more fields of application. Still, it might do so. Thus, it represents a possible vehicle of revolution that ought to be recognized.

solidification of a photosensitive polymer emulsion with a laser, while binder jetting takes advantage of a liquid agent to bind powder particles together.

AM can be conceptualized as an aggregate paradigm resting on subparadigms belonging to the domains of digitalization, automation and fabrication. Digitalization refers to the creation/acquisition, manipulation, storage and transmission of the three-dimensional model of the object to be printed. Automation concerns the class of technologies, mechanical and electronical supports underlying the ability of the printer to perform the required set of movements fast, accurately and independently. Lastly, fabrication encompasses the set of additive processes categorized by the ISO/ASTM 52900 standard, as well as the set of processable materials. Throughout this Section, we show how the dominating technological paradigms within these domains have come to converge over time, in accordance with the conceptual extension illustrated in the previous Section.

A technological paradigm implies an underlying perspective in the first place. In other words, principles precede technical actualization. In the case of AM, the fundamental principle is fairly simple: a whole can be composed through a layer-by-layer overlapping of parts. This principle was known as early as the second half of the nineteenth century, when François Willème used to create three-dimensional portraits by aggregating photographic profiles from multiple angles. The process was grounded on the equivalence between a volumetric whole and the sum of all its profiles (Sobieszek, 1980). However, the nineteenth century conception of AM was rather constrained in its applications, and could not possibly give rise to a well-founded paradigm.

Actualization of the AM paradigm requires multiple supporting technologies. Fabrication processes are needed to aggregate solid, powder or liquid inputs into an output. However, the fabricator needs guidance. First, it needs a clear definition of output. Second, it needs to perform a predetermined series of steps toward accomplishment. Without digitalization, the process would be blind. Without automation, it would be crippled. The industrial declinations of these domains came to be governed by technological paradigms following well-defined improvement trajectories: CAD, CAM and the aforementioned cluster of additive processes.[18] A first impulse of convergence brought together the CAD and CAM paradigms into the well-known CAD/CAM aggregate paradigm. Then, the systematization and development of additive processes, and their integration into the CAD/CAM architecture, brought into existence AM as we know it.

## 4.2. Seminal developments: automation and digitalization

Historically, the first steps toward technical actualization of the AM paradigm took place in the domain of automation. The beginning of modern automation may be identified in the mechanization of the data registration process in the 1890 U.S. census, by means of a punch card. Punch cards contained instructions in the form of distinguishable combinations of holes. These instructions could be used to store data or to instruct machines to perform simple operations. Machines instructed in this way are defined "numerically controlled". Accounts of the first numerically controlled machine, demonstrated by MIT engineers, date back to 1953 (Schurr et al., 1990). Numerical control received incremental improvements in the following years, such as the introduction of a magnetic tape, but it was still plagued with inefficiency and inaccuracy. An abundance of innovations in the 1960s and early 1970s, like the transistor and the integrated circuit, eventually led to the emergence of computer numerical control (CNC), debuting in 1976 at the Chicago Trade Show (Haggen, 1988). CNC was a real revolution in the domain of automation: the possibility to codify machine instructions in electrical signals, instead of holes, implied enormous efficiency gains, revolutionizing manufacturing. Instructed through a numerical programming language - the most common being G-code - a variety of machines like mills, lathes and drills could perform predetermined operations accurately and independently. CNC machines laid the foundations for CAM,[19] which has undergone tremendous

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[18] A technological paradigm may indeed concern also a cluster of technologies, as in the case of semiconductor technologies and organic chemistry technologies (Dosi, 1982). Given the presence of seven categories of additive processes, this is one of the cases where a technological paradigm does not imply a dominant design (Dosi and Nelson, 2010).

[19] By CAM, we mean the ensemble of automation software, interfaces and CNC machines needed to carry out computer-aided manufacturing. This is in contrast with narrower notions of CAM including only the software part.

improvements until the present time. Machines' speed, precision and freedom of movement increased exponentially thanks to a series of incremental innovations, like the introduction of lasers and plasma torches as cutting devices, and the rise of multi-axis machining.

Seminal developments in the digitalization domain happened largely in parallel. CAD denotes the set of software and graphical user interfaces aimed at visualizing and modifying three-dimensional models. Its conceptual foundations are rooted in the cumulative contributions of applied mathematicians on polynomial curves. The development of Sketchpad, the pioneering CAD platform, set an important milestone in 1963 (Weisberg, 2008). At that time, CAD was used mainly by large automotive, aircraft and electronics companies, due to the prohibitive costs of computing. In the 1970s, after several meetings hosted by leading EU countries resulting in a report to the European Council of Ministers, strong institutional pressures were placed on the CAD paradigm, leading to interactive graphics and visual display software tools (Llewelyn, 1989). In the 1980s, the invention of solid modeling and the development of AutoCAD constituted relevant advancements. In the 1990s, costs were reduced and graphical user interfaces optimized, contributing to the diffusion of CAD software into many other industries. At the dawn of the 21st century, the technology had already matured considerably: it allowed for the manipulation of 3D models with satisfactory resolution and few constraints, at a price that was low enough to justify adoption in most industries.

## 4.3. The CAD/CAM aggregate paradigm

CAD and CAM originated as separate paradigms grounded on different technical principles and heuristics. CAM stemmed from the need to be efficient in performing repeated activities, and benefitted from innovations in codification and elaboration mechanisms, which culminated in electrical signals interacting with machines of increasing sophistication. Instead, CAD emerged as a way to harness the potential of digital technology as a creativity support tool (Shneiderman, 2002, 2007). Indeed, the pioneering platform Sketchpad was born as a versatile system with many possible uses (Sutherland, 1964), reflecting a relatively low *binding power* of the corresponding paradigm (i.e.

no preconceived directions of improvement). However, the development of procedures and protocols to connect design offices with manufacturing, especially in automotive and aircraft industries (Llewelyn, 1989), put an increasing pressure on the convergence of CAD and CAM. For effective integration, CNC machines needed to import data from digital images reliably and effectively. Furthermore, CAD needed to achieve satisfactory levels of interoperability[20] and functionality for manufacturing.[21] According to our conceptual extension, these can be regarded as the *performance thresholds* underlying the *integration regions* (see Figure 3).

[Insert Figure 3 around here]

Initially, information from product design to manufacturing was transmitted only through the traditional blueprint (Wang, 2012). However, CAM software soon became able to extract and postprocess machine toolpaths directly from a CAD file, generating axis machine instructions (Nassehi et al., 2008). Likewise, CAD was drawn toward its integration region thanks to the development of data exchange formats such as IGES in 1979 and STEP in 1984 (Chao and Wang, 2001), and the birth of AutoCAD in 1982. Being still nowadays the paradigmatic software for technical drawing, AutoCAD arose as the emblem of the selected direction of technical change, favoring manufacturing-oriented modeling instead of other forms of drawing (e.g. artistic sketching). These interdependent developments were driven by strong *techno-economic benefits of integration*, rooted in the remarkable economic advantages brought by the conjoint application of CAD and CAM for manufacturing purposes. The immediacy and quality of the information flow from design to manufacturing translates indeed into evident gains in both efficiency and efficacy in production. As a result, CAD/CAM integrated models were rapidly adopted. In the second half of the 1980s, the

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[20] By definition, CAD/CAM interoperability is essential for effective CAD/CAM integration. However, interoperability between different CAD systems is also important, as the interaction among suppliers of different parts mandate the sharing of design information (Kim and Han, 2007).

[21] In the case of CAD, functionality for manufacturing lies mainly in the emphasis on technical drawing.

trend toward system integration by substitution of separate CAD and CAM with CAD/CAM was already strong and empirically documented (Cainarca et al., 1989).

The birth and consolidation of this aggregate paradigm exerted considerable influence on the direction of technical progress of CAD and CAM. Although CAD remains a multi-purpose subparadigm, with applications in the field of arts (e.g. sculptures; see Séquin, 2007), the direction of collective development efforts on its performance attributes has been deeply altered by its functionality for industrial manufacturing. This is testified by the proliferation of CAD software optimized not only for generic manufacturing, but also for specific industries, like Advance Steel, ProfiCAD and AutoCAD mechanical. In a similar fashion, the CAD/CAM aggregate paradigm stimulated improvements in translation software, shared interfaces and control languages optimized for CAD/CAM integration such as STEP-NC, which supported bidirectional information flows along the chain from design to manufacturing (Xu and He, 2004). The assertion "*without CAM, there is no CAD*" on the official website of Autodesk, the leading software service corporation, is particularly emblematic of the binding power of this aggregate paradigm (Deans, 2018) (see Figure 4).

[Insert Figure 4 around here]

To further appreciate the effects of the CAD/CAM aggregate paradigm on the trajectory of improvement of CAD, we have conducted a comparative analysis based on two ad hoc keyword searches on the Scopus database. As a multidisciplinary database of international scientific articles, Scopus is indeed appropriate to study epistemological trends from an historical perspective.

In order to capture the intersection between CAD and the world of manufacturing, we searched for publications containing [("computer-aided design"[22]) AND (manufactur*)[23]] in their title, abstract

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[22] We did not use CAD as a keyword because it would encompass all English words including CAD, confounding the analysis. "Computer-aided design" alone still leads to a wide and representative historical sample. For the same reason, in subsequent searches, we did not include CAM alongside "computer-aided manufacturing".

[23] Here and in subsequent searches, the asterisk allowed us to cover derived words. In this case, "manufactur*" includes "manufacture", "manufacturing" and other possible derived terms.

or keywords. We opted to use “manufactur*” instead of “computer-aided manufacturing” because the latter would erroneously restrict the sample, due to the way in which words are chosen in titles, abstracts and keywords. As a matter of fact, even when a CAD publication revolves around its functionality for manufacturing, it is relatively unlikely that the authors include the entirety of the “computer-aided manufacturing” expression in the title, abstract or keywords. We used the results of this keyword search from 1963[24] to 2020 to measure the strength of the epistemological trajectory favoring the application of CAD to the world of manufacturing.

To illustrate the influence of the CAD/CAM aggregate paradigm by comparison, we also measured the strength of alternative epistemological trajectories favoring the application of CAD for artistic purposes, in the same timeframe. To this end, we searched for scientific publications containing both “computer-aided design” and a set of keywords related to artistic applications in their title, abstract or keywords (see Table I in the Appendix for a detailed description of the query). Notably, we could not include “draw*” among the keywords due to its high confounding potential, given its wide usage also in engineering and manufacturing applications (e.g. the “engineering drawing” expression). Still, the selected keywords allowed us to cover a variety fields, ranging from sculpture to painting, sketching, craftsmanship and more generic artistry.

Figure 5 shows the two trends in comparison from 1963 to 2020.

[Insert Figure 5 around here]

The two trends were largely overlapping from 1963 to the mid-1970s, reflecting the original nature of CAD as a versatile system (Sutherland, 1964) and thereby the low binding power of the corresponding paradigm. They started to diverge minimally from the late 1970s to the very beginning of the 1980s, but the divergence increased suddenly and enormously throughout the early 1980s. According to our historical analysis, the 1980s can be regarded as the time when the CAD/CAM

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[24] 1963 has been chosen as a starting point as it is the year when Sketchpad was born.

aggregate paradigm was definitely consolidated, thanks to the development of AutoCAD in 1982 and new data exchange formats like STEP-NC in 1984. The evidence from Scopus resonates well with this analysis, as the trends start to diverge dramatically precisely in that timeframe. Afterward, the number of CAD publications with a manufacturing orientation appears to fluctuate around an increasing trend, while the number of CAD publications with an artistic orientation is more stationary, apart from two minimal spikes in the 1990s and 2000s. At any point in time after the early 1980s, the latter are always a small fraction of the former. This corroborates the idea of a strong binding power of the CAD/CAM aggregate paradigm, which has steered the trajectory of CAD toward its functionality for manufacturing for almost four decades.

## 4.4. Additive fabrication processes and the rise of AM

While automation and digitalization underlie any computerized manufacturing process, additive fabrication processes are specific to AM. Seminal developments in this direction took place in the second half of the twentieth century, with the emergence of precursors of modern particle aggregation processes. Examples are Munz's method for layer-wise exposure of liquid polymer (1956) and Ciraud's directed energy deposition process (1972). Founded in the 1980s, the companies Stratasys and Helysis went on to develop the first material extrusion and sheet lamination technologies, respectively. Then, the trend reached the most significant milestones with the rise of stereolithography, fused deposition modeling and selective laser sintering between the end of the 1980s and the beginning of the 1990s (Bourell, 2016). Considering concurrent developments in automation and digitalization,[25] the AM paradigm was technically feasible at the beginning of the 1990s, albeit with limitations.

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[25] CNC machines were born with the aim of processing inputs by selectively cutting away pieces of material. Thus, they are traditionally associated with subtractive manufacturing, and considered antithetical to 3D printers. However, this widespread dichotomy can be misleading. Subtractiveness is inherent in the presence of cutting devices, just like additiveness resides in particle aggregators. Still, CAD/CAM represents a foundational paradigm for both types of manufacturing. 3D printers operate under the instructions of a programming language based on a CAD model, just like CNC lathes and mills. Subtractive and additive processes can even be integrated into the same apparatus, as the proliferation of hybrid machines by leading manufacturer Mazak demonstrates.

After their emergence, the integration of additive processes into the CAD/CAM paradigm was fast, but the resulting machines were relatively expensive and slow. At the end of the 20th century, AM was known as rapid prototyping, being mostly used to produce prototypes. However, from the early 2000s onwards, there was a steady trend toward technical efficiency in 3D printers, with cost reductions and gains in speed and reliability. The resulting consolidation of AM as an aggregate paradigm prompted a powerful stimulus to the search for new additive processes and materials.[26] Since the mid-2000s, a variety of new materials were introduced, with properties ranging from flame-resistance and water-resistance, to high-elongation and biocompatibility. These materials were coupled with additive processes enabling their optimal treatment, and ensuring their application to industries as diverse as aerospace, jewelry, medicine and dentistry. The functionality of AM for small-batches production, efficient customization and complex shape creation triggered a paradigm shift in many industrial practices throughout the 2010s, going well beyond prototyping (Berman, 2012; Attaran, 2017). On the digital side, in the last decade, it is worth reporting the advent of web-based services of design and printing; the development of software to extract digital models from pictures, like Viztu Technologies' Hypr3D and Autodesk's 123D Catch; the emergence of the first bioprinting software from the collaboration between Orgonovo Holdings and Autodesk; the announcement by Siemens of a software supporting the entire AM pipeline from design to fabrication; and finally, the development of generative design software[27] like Autodesk's Dreamcatcher and Desktop Metal's Live Parts (Wohlers et al., 2019).

Differently from CAD/CAM, whose name itself evokes the merger of CAD and CAM, the nature of AM as an aggregate paradigm is slightly subtler. To substantiate it better, we have conducted a

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[26] This is a subtle point: the mere invention of additive processes was not sufficient for additive manufacturing to emerge as a paradigm. Multiple improvements were needed first, both on the side of printers and on the side of additive technologies. Then, the consolidation of the paradigm prompted further improvements in those directions.

[27] Generative design software automatically provides multiple design solutions given a set of specification. By relaxing design constraints, additive manufacturing enables the creation of shapes that used to be unconceivable. Hence, generative design is particularly suitable for AM, as it helps designers to overcome the constraining heuristics embedded in traditional manufacturing.

twofold empirical exploration on both patents and scientific publications, leveraging the Espacenet and Scopus databases, respectively. Both analyses follow the same logic and adopt the same keyword searches. The objective is to investigate the extent to which inventive efforts and scientific research in CAD/CAM have been influenced by the AM aggregate paradigm over the years. To this end, we measured the intersection between AM and CAD/CAM over the CAD/CAM broader set in both patents and scientific publications, from 1990[28] to 2020. First, the relative size of the intersection is a proxy for the importance of AM in the scientific and inventive efforts in CAD/CAM, thus giving a sense of the level of embeddedness of the CAD/CAM paradigm into the AM paradigm. Second, the change in the relative size of the intersection over time gives an indication on where the frontier is moving, and thereby the extent to which the AM macrotrajectory is steering the embedded CAD/CAM trajectory.

Both in Espacenet and Scopus, we proxied the relevance of the intersection between AM and CAD/CAM by calculating the ratio between two separate keyword searches, the first capturing the intersection (AM and CAD/CAM) and the second capturing the whole set (CAD/CAM) (see Table I in the Appendix for a detailed description of the queries). Hence, the ratio of the first over the second corresponds to the relative size of the intersection. While the operationalization, the logic and the timeframe are the same for both databases, in Espacenet we searched within the entire text of the patents, while in Scopus we searched only within title, abstract and keywords. Furthermore, given the less stringent requirements for novelty and relevance and the larger scope, in Scopus we further restricted the search to the top 100 most highly cited publications per year. This allowed us to obtain a sample of publications that is more representative of the true state-of-the-art for each year.

Results of the analysis on patents and publications are shown in Figure 6.

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[28] 1990 has been chosen as the starting point as it is the year when AM was technically feasible according to our historical analysis.

[Insert Figure 6 around here]

As the trends illustrate, results are largely coincident and coherent with our historical analysis. The relative size of the intersection between AM and CAD/CAM starts very low and grows slowly until 2010, when it gets around 10% both for highly cited scientific research and inventive efforts. These are the years when the paradigm emerged and started to exert a low-to-moderate influence. Most abstracts from the 1990s to the 2000s indeed mention only the "rapid prototyping" expression. From the early 2010s, a drastic change of pace in both patents and publications can be observed. This is the timeframe when a wealth of new materials were discovered and additive processes refined. Concurrently, the "3d printing" and "additive manufacturing" expressions gained popularity, and the AM aggregate paradigm was definitely established. From 2010 to 2020, the proportion of AM patents and scientific publications within the field of CAD/CAM skyrocketed, reaching percentages as high as 40% for patents and 35% for publications

## 4.5. Key insights

Both the historical overview and the empirical analyses corroborate the key insights of our conceptual extension. AM triggered paradigm shifts in many industries. However, it was not brought forward by serendipitous discoveries, extraordinary R&D efforts or scientific breakthroughs. It is rather the actualization of a centuries-old outlook, thanks to the integration of additive fabrication processes into the CAD/CAM architecture, which in turn stemmed from the convergence of CAD and CAM, the foundational paradigms in the domains of industrial digitalization and automation. While the consolidation of CAD/CAM steered the trajectories of CAD and CAM toward the optimization of integrated design and production, the birth of AM stimulated the search for innovative materials and fabrication processes, and the development of new digital design solutions. In particular, 3D scanning, bioprinting and generative design software are the embodiment of the new directions of technical change dictated by the AM paradigm in the CAD/CAM universe. For example, the second most cited CAD/CAM publication among those published in 2016 proposes "*a novel framework, namely 3D*

*Generative Adversarial Network (3D-GAN), which generates 3D objects from a probabilistic space by leveraging recent advances in volumetric convo-lutional networks and generative adversarial nets"* (Wu et al., 2016), and the fifth most cited CAD/CAM publication issued in 2018 is emblematically titled "*additive manufacturing of biomaterials*" (Bose et al., 2018).

Having other applications, the CAD/CAM paradigm retains a certain extent of epistemological independence. As a matter of fact, the percentage of AM patents and highly cited scientific publications within CAD/CAM has reached a maximum of 40% so far. Still, this is a highly influential proportion that testifies how innovators in the field now have an eye for digital tools, platforms and graphical interfaces aimed at optimizing layer-upon-layer addition, alongside subtraction (Thompson et al., 2016; Wiberg et al., 2019). This tendency, condensed in new heuristics, has arguably shaped the latest trade-off improvements in the CAD/CAM universe, and will probably do so to an even larger extent in the future.

## 5. Conclusion

Technological change is neither random nor completely deterministic. Scientific discoveries and market incentives play a fundamental role in shaping its directions. However, a fine-grained epistemological framing is needed to unveil the importance of institutional factors and path-dependent dynamics. The theory of technological paradigms (Dosi, 1982; Von Tunzelmann et al., 2008; Dosi and Nelson, 2010; Nelson et al., 2018) has answered to this need. In order to refine its explanatory power in the present context, increasingly characterized by technological complementarity, convergence and recombination, we have endeavored to explore the role of technological interdependence in the epistemological framework delineated by Dosi's seminal contributions. In this process, we have challenged the common assumption that relates paradigm shifts to a form of scientific or technological discontinuity (Anderson and Tushman, 1990), often condensed in knowledge-based breakthroughs or radical innovations.

Drawing a distinction between *epistemic* and *technological* convergence, we have recognized the potential of the latter to trigger a paradigm shift, and explored its evolutionary implications. Our conceptualization pinpoints the possibility of an epistemological interdependence in technological trajectories, whenever they are sufficiently well-defined and susceptible to integration. Furthermore, we have identified factors like the binding power of the original paradigm, the techno-economic benefits of integration and the distance of the trajectories from the *integration regions* in their multidimensional spaces as relevant determinants of convergence.

Should convergence happen, a new aggregate paradigm arises, with its own epistemic locus made of relevant know-how, procedures and heuristics. The aggregate paradigm traces a macrotrajectory representing a cluster of trajectories, in the same way a trajectory represents a cluster of directions of technological change. Thus, it ultimately influences the extent and direction of technological change alongside scientific, market and institutional factors.

In order to clarify and empirically ground our conceptualization, we have analyzed the genesis and evolution of the additive manufacturing paradigm. Additive manufacturing can be regarded as an aggregate paradigm founded on CAD/CAM and additive fabrication subparadigms. In turn, CAD/CAM is itself an aggregate paradigm consisting of CAD and CAM, the foundational paradigms in industrial digitalization and automation. Our historical overview achieves a twofold objective. First, it shows the emergence of a deeply revolutionary technological paradigm from a process of convergence. Secondly, it illustrates the dynamics of that convergence, as well as their ex-post implications on the directions of development of the technologies involved.

The main purpose of our research effort is to renew the interest in the epistemological architecture of technological change, by extending its boundaries. The conception of technology as a complex system, made of interacting sub-systems and interdependent components is indeed well-acknowledged (Rosenberg, 1979; Bijker et al., 1987; Henderson and Clark, 1990; Hughes, 1993; Fleming, 2001; Yoo et al., 2012). However, the epistemological reverberations of this view deserve more emphasis, especially in the context of the upcoming Fourth Industrial Revolution (EPO, 2017; OECD, 2017). Our core conclusion is that technological paradigms should not be intended as self-standing boxes. On the contrary, they may interact with each other, even to the point of being nested one within the other. When this nesting manifests, aggregate paradigms modulate the binding power of their subparadigms over the pace and direction of technological change. CAD/CAM shaping the technical nature of CAD provides a good example in this sense, as does AM with its recovery of creative aspects through its emphasis on generative design.

As a conceptual extension to the theory of technological paradigms, the present work contributes theoretically to the streams of technology and innovation management, economics of technology and evolutionary economics, and its underlying constructs are versatile enough to be applied to different perspectives. For instance, it would be interesting to verify whether the proposed dynamics of epistemological interdependence shed new light on the emergence and characterization of platforms and ecosystems (Iansiti and Levien, 2004; Gawer and Cusumano, 2014). Furthermore, they may prove relevant to strategic management topics, in particular the dynamic capabilities framework (Teece et al., 1997; Teece, 2007). This is because convergence can be perceived and predicted more easily than extraordinary events like scientific breakthroughs, with potential implications for dynamics of firm adaptation and resource reconfiguration.

The present work may also provide a useful interpretative lens for the growing recombination and convergence of advanced technologies. For example, companies like AMFG and Printsyst are already employing artificial intelligence in combination with additive manufacturing for optimization purposes (Valdivieso, 2020). Even three-way combinations, such as Internet of Things-enabled cloud-based additive manufacturing platforms (Wang et al., 2019), seem to be on the horizon. While these initiatives are still far from maturing, the trend toward convergence of advanced technologies looks promising, as also indicated by patent data (EPO, 2017), calling for new interpretative tools. More generally, the conceptualization of aggregate paradigms and epistemological interdependence might prove useful in every instance where dynamics and determinants of technological change must be assessed.

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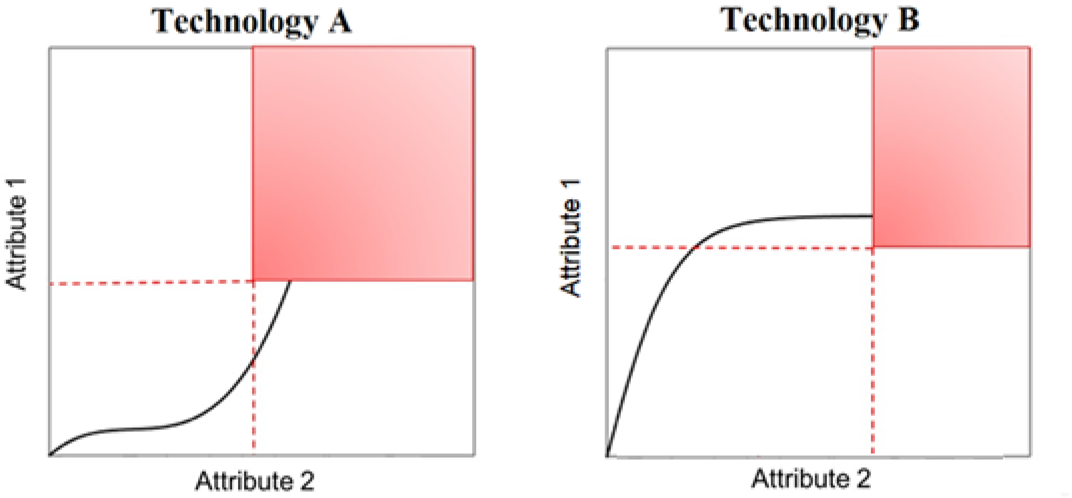
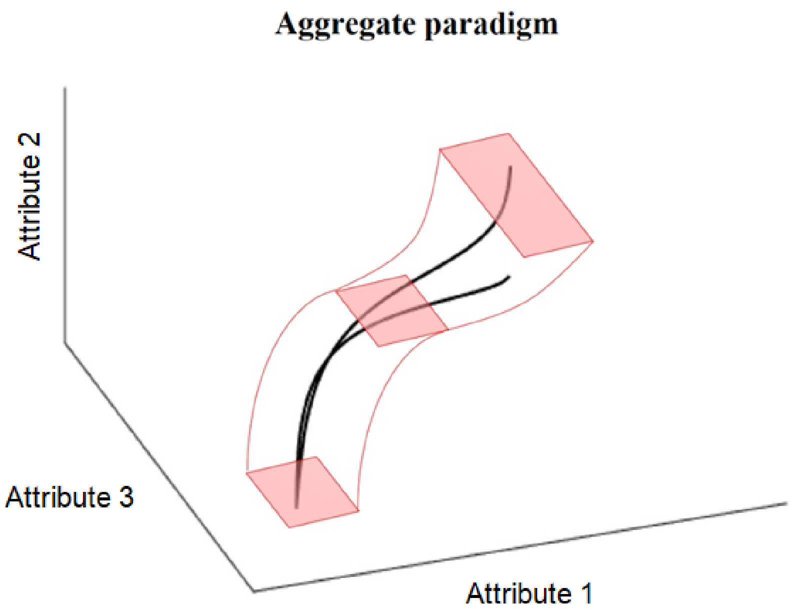
**Figure 1. Multidimensional space of attributes and integration region.**



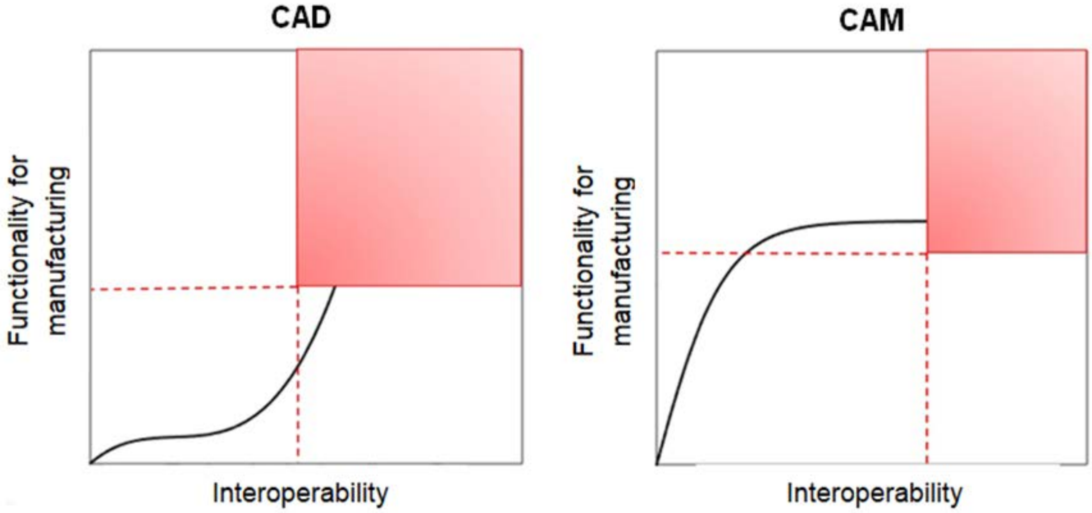
*These are two examples of distinct technological trajectories moving in a multidimensional space of attributes. For visualization constraints, we hereby present only a partial (bidimensional) snapshot of their true multidimensional space, depicting the trade-offs between two attributes. For each attribute, the dotted lines represent the minimum performance thresholds for integration. Accordingly, the shaded area constitutes the integration region. The figure provides an intuition of how the integration region may act as a gravitational force. The trajectory of technology A initially favors the improvement of attribute 2 over attribute 1, but this trend reverts as the trajectory approaches the integration region. The same logic holds for the trajectory of technology B, initially favoring attribute 1 and eventually being drawn toward attribute 2 as it gets closer to the integration region.*

**Figure 2. The new aggregate paradigm.**



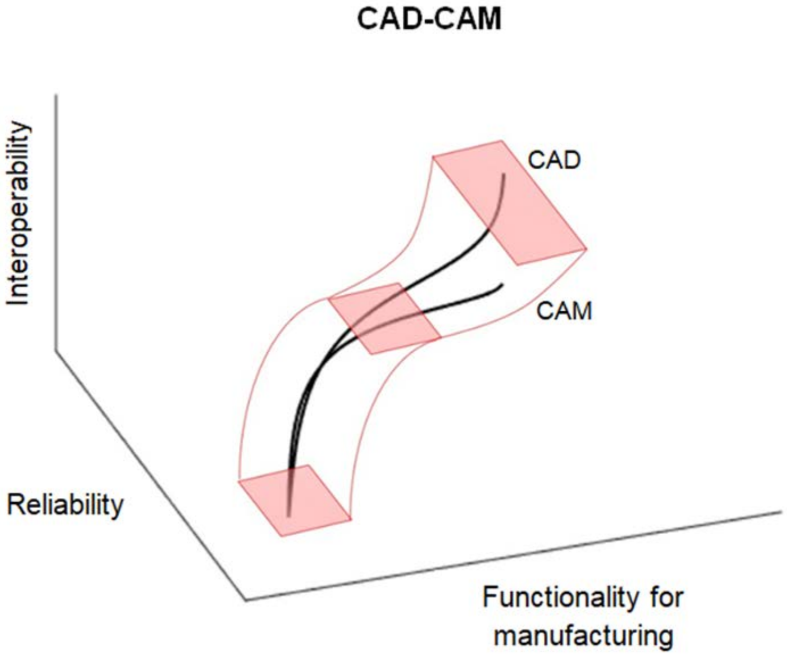
*This is a possible representation of the effects of the aggregate paradigm resulting from the integration of the paradigms guiding the development of technology A and B. The aggregate paradigm generates a macrotrajectory shaped as a tubular solid moving in the multidimensional space of attributes. The macrotrajectory embeds the trajectories of technologies A and B. While such trajectories retain a certain freedom of movement, their progression is constrained and guided by the macrotrajectory embedding them. In this respect, one may regard the volume of the tubular solid as inversely proportional to the binding power of the aggregate paradigm in question. Indeed, smaller macro-trajectories exert a greater constraining power over the trajectories they embed. Also in this case, a space of three attributes should be regarded as a partial snapshot of the true multidimensional space where the trajectories reside. In this example, it is also worth noting that technologies A and B have (at least) three attributes in common, as they both move in all of the three visualized dimensions (see footnote no. 15).*

**Figure 3. Multidimensional space of attributes and integration region: CAD and CAM**



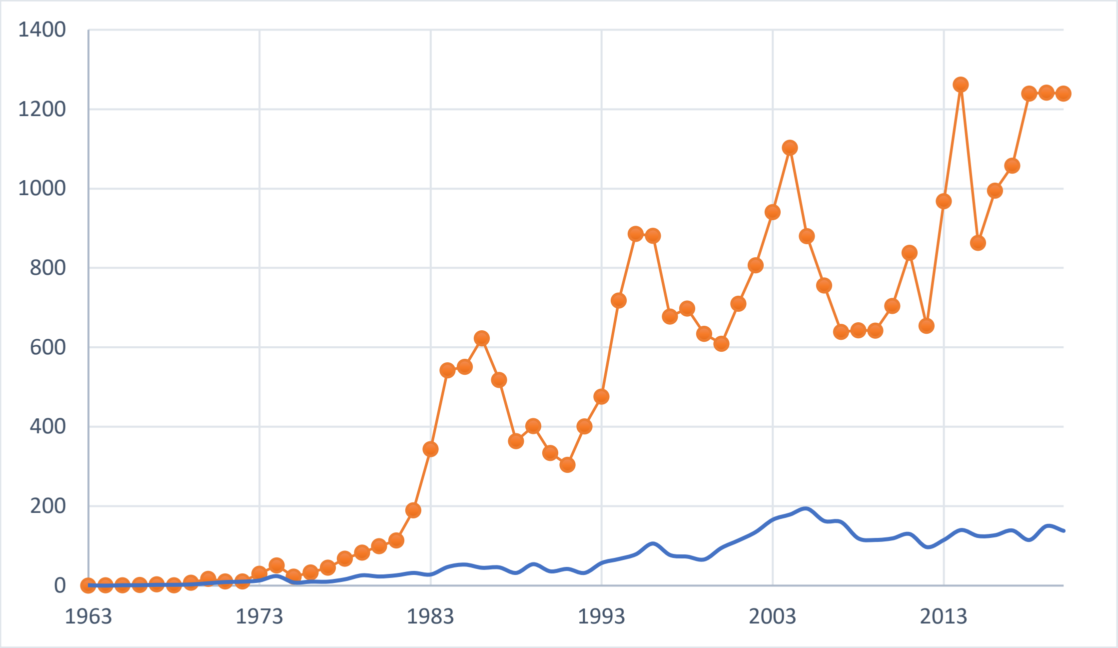
*This is a possible application of the abstract framework presented in Figure 1 to the case of CAD and CAM. In order to be integrated into a new manufacturing paradigm, both CAD and CAM needed to achieve sufficient levels of interoperability and functionality for manufacturing. By definition, functionality for manufacturing can be regarded as a natural trajectory for CAM. The same does not hold for CAD, which emerged as a versatile system, and was progressively drawn toward the optimization of technical drawing precisely due to its functionality for manufacturing.*

**Figure 4. The new aggregate paradigm: CAD/CAM**



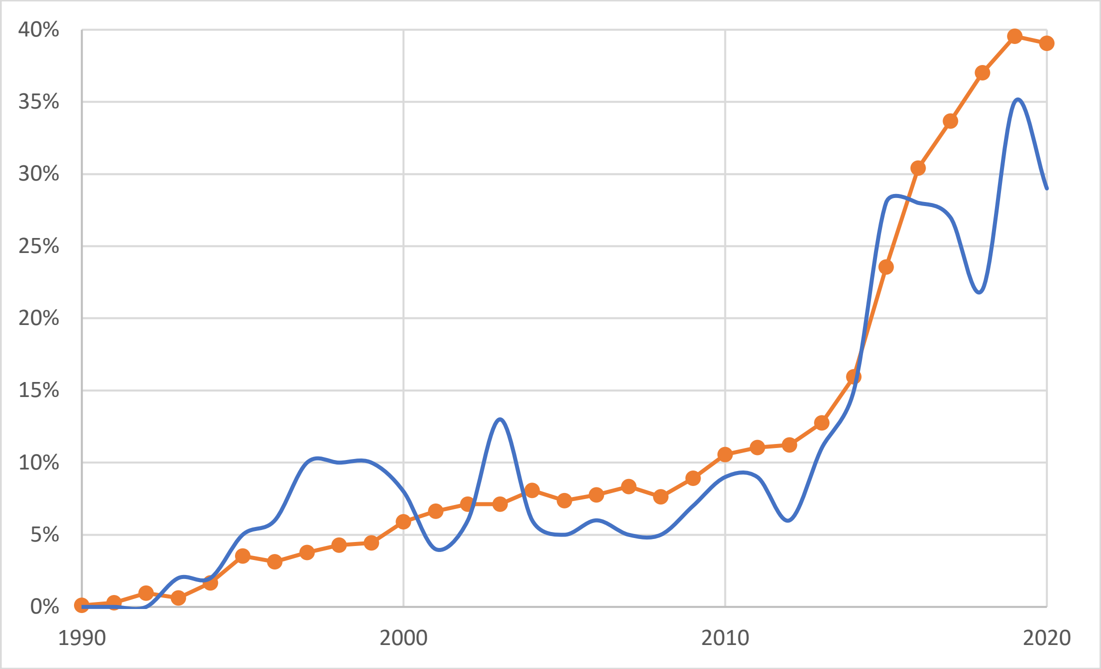
*This is a possible application of the abstract framework presented in Figure 2 to the case of CAD/CAM. After its emergence as an aggregate paradigm, CAD/CAM stimulated the improvement of both interoperability and functionality for manufacturing in both CAD and CAM architectures. Despite being part of the same paradigm, CAD and CAM follow distinct trajectories of trade-off improvements, as they still have a separate ontological status (e.g. CAM is natively designed for manufacturing). The third attribute, software reliability, exemplifies a random dimension on which the aggregate paradigm does not have particularly strong prescriptions.*

# Figure 5. The effects of CAD/CAM on the trajectory of CAD



*This graph compares the strength of the epistemological trajectory favoring CAD applications to manufacturing (the line with dots), and the cumulative strength of alternative epistemological trajectories favoring artistic applications (the line without dots). The horizontal axis indicates the year, while the vertical axis indicates the number of Scopus-indexed publications per year.*

## Figure 6. The epistemological implications of AM on CAD/CAM



*For each year, the line with dots indicates the percentage of AM patents among CAD/CAM patents on Espacenet. Instead, the line without dots indicates the percentage of AM publications among the top 100 most highly cited Scopus-indexed CAD/CAM publications (in each given year).*

# Appendix

## *Table I – Keyword searches*

| Query | Database | Scope | Timeframe | Purpose |
|---|---|---|---|---|
| *[("computer-aided design") AND (manufactur*)]* | Scopus | Title, abstract and keywords | 1963-2020 | Proxy for the strength of the CAD-manufacturing trajectory |
| *[("computer-aided design") AND (sculpt* OR paint* OR craft* OR sketch* OR depict* OR artwork* OR picture OR artis*)]* | Scopus | Title, abstract and keywords | 1963-2020 | Proxy for the strength of the alternative CAD trajectories |
| *[("computer-aided design" OR "computer-aided manufacturing" OR "CAD/CAM" OR "CAM/CAD" OR "CAD-CAM" OR "CAM-CAD") AND ("additive manufactur*" OR "3d print*" OR "3d-print*" OR "rapid prototyp*")]* | Scopus and Espacenet | Title, abstract and keywords of the top 100 most highly cited publications per year (Scopus); entire text of patents (Espacenet). | 1990-2020 | Numerator of the ratio estimating the relative size of the intersection between AM and CAD/CAM |
| *[("computer-aided design" OR "computer-aided manufacturing" OR "CAD/CAM" OR "CAM/CAD" OR "CAD-CAM" OR "CAM-CAD")].* | Scopus and Espacenet | Title, abstract and keywords of the top 100 most highly cited publications per year (Scopus); entire text of patents (Espacenet). | 1990-2020 | Denominator of the ratio estimating the relative size of the intersection between AM and CAD/CAM |