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Monitoring innovation metrics in construction and civil engineering: Trends, drivers and laggards

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A R T I C L E I N F O

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A B S T R A C T

The study presents and analyzes innovation metrics in construction and civil engineering, domains which are found to lag behind other fields of science and technology in terms of innovation output. A specific line of focus is put on research and development (R&D) both in academia and industry. Scientific production is analyzed by treating eighteen of the oldest peer-reviewed journals in the field with over a hundred thousand articles published over the past fifty years. The aim is to capture and interpret trends with respect to four field verticals: (i) new materials and systems (hardware), (ii) digitalization, (iii) environmental impact and (iv) novelty/efficiency. The analysis reveals distinctive rates of innovation for each vertical, with some slowing down, as innovation becomes standardized and mainstream, and others peaking up, stemming from developments in other fields of science. Results are treated with respect to the S-curve technology maturity framework which accounts for effort and time towards development and the widely adopted scale of technology readiness levels. Further, corporate innovation is analyzed through patent search covering twelve key inventors and various technology focuses. While no straightforward approach exists to present innovation metrics without considering the broader socio-political and economic context, the present work seeks to provide a comprehensive monitoring of the progress in the field which reflects capital, time and effort put together, towards advancing propositions for future research.

1. Introduction

Both in times of crisis and prosperity, striving for innovation reflects efforts towards achieving competitive advantages and increasing the overall techno-economic and environmental efficiency of products and systems. To understand the motivation behind the present work it is important to provide first critical background on the breakdown of innovation per sector, territory as well as to distinguish between academic research and corporate innovation.

According to Sargent (2019), total global research and development (R&D) expenditures have nearly tripled, from $676 billion to $2.0 trillion, between 2000 and 2017. From the $2.0 trillion invested in 2017, only $0.145 trillion was spent by governments on university R&D (World Economic Forum, 2019, Information Technology and Innovation Foundation (ITIF), 2019), with nearly 60% of it, invested in five countries (US, Germany, China, France, Australia). Therefore, corporates are responsible for the lion's share in total R&D spending.

Further, innovation creation and adoption does not run at the same speed across various technological sectors. The above preliminary gap identified between publicly funded and corporate R&D becomes even more pronounced when considering available data on innovation output per field. According to data from OECD (2017) for the period 2014 to 2016, 60% of the world's patents (in the US Patent and Trademark Office, the European Patent Office, the Japan Patent Office, the Korean Intellectual Property Office and the National Intellectual Property Administration in China) was filed by the top two thousand R&D spenders. Contrary, the same inventors were responsible for just 3% of all scientific articles published during the same period. This reveals a preliminary important gap between the two metrics, i.e. patent and scientific output.

A comprehensive industrial R&D investment scoreboard (Hernández et al., 2020) shows that among the world's 2500 biggest R&D investors only 61, i.e. 2.44%, are construction & materials companies, while among Europe's top thousand R&D investors, the relevant share is similar, at 3.5%. It should be noted herein, that chemicals, industrial metals and mining or real estate investment and services are separate categories in the same scoreboard. Additionally, when considering the taxonomy of sectors by quartile of digital intensity (OECD 2017), construction places in the 2nd quartile in terms of software investment, in the 3rd quartile with respect to ICT tangible investment and intermediate

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ICT goods while at the bottom quartile with respect to intermediate ICT services, robot use, online sales revenue and ICT specialists. The above further validate that construction lags far behind in terms of R&D and innovation with the opportunity for closing the sector's productivity gap amounting to about \$1.6 trillion (McKinsey 2017). Despite the field's sluggish performance in terms of creating and adopting innovations, one should consider that construction-related spending accounts for 13% of the world's GDP (OECD 2019) while greenhouse gas emissions due to the building and construction sectors account for a 39% share of the total global emissions (World Green Building Council, 2019).

Considering the above landscape, the work presented herein aims to establish a comprehensive monitoring of innovation output in the global field of construction with a specific focus on four verticals which are representing primary pillars to inspire, drive and grow innovations. These verticals are: (i) new materials and systems (hardware), (ii) digitalization, (iii) environmental impact and (iv) overall novelty/efficiency.

2. Current state of the art & background

Efforts to understand and measure innovation have been reported previously in literature focusing on specific technologies or the process of innovation itself. More precisely, projects of increased complexity have been found to trigger novel ideas, mainly during project preparation, result often of collaborative efforts of likeminded key stakeholders, including project owners, contractors and suppliers (Nam et al., 1991; Noktehdan et al., 2019). For example, complex projects such as nuclear plants (Tatum, 1984) and high-strength concrete for high-rise buildings (Nam et al., 1991) have been used as case studies to understand the process of generating innovative concepts and engineering real solutions out of them. Historically, innovation is found to move slowly in the field due to the high investment required, the competition landscape, the seasonal cyclicity in projects or the fragmented landscape in supply and execution of infrastructure projects (Tatum 1986) as well as the size of the company and other cultural factors (Lijauco et al., 2020, Jang et al., 2020).

Another critical element that becomes clear when addressing the evolution of innovation over the span of decades is that it is not possible to analyze innovation output without considering the broader socio-political and economic context within which new technological developments are triggered and advanced. Interesting insights are revealed when comparing data on industrial activity slowdowns with the growth of the construction sector. The global annual CO_2 emissions (World Carbon Project, 2018) are used as an indicator of the former and cement's Producer Price Index (PPI) serves as indicator for the latter (Federal reserve bank of St. louis (FRED), 2019). It is observed that major turmoils, such as the two oil crises in the 70s and 80s or the fall of the USSR and the most recent 2008 global financial crisis, have drastic and immediate impacts on cement's PPI, which last longer than the temporary halt in CO_2 emissions (WCP 2018, The Economist, 2020). The associated economic crises reflect also on the total innovation output (Fig. 1b) with the total number of patents filed in the US (U.S. Patent and Trademark Office (USPTO, 2019) demonstrating fluctuations which correspond to industrial activity slowdowns. These slowdowns appear to impact both the scientific and patent outputs which are analyzed in this work. Patent output is especially impacted for the period between 2000–2012 where industry downfalls echo slowdowns in patent output while scientific output seems to undergo similar fluctuations with the economic landscape for the period 1984–2012, precisely.

How this finding, though, impacts the effort to identify innovation metrics and especially ones that represent the least innovative sectors, such as construction? First, it should be understood that within the process of monitoring innovation, patents serve as one indicator, but not as the sole or governing one. Many patents do not always result into tangible products, systems or services which would foster further developments, generate hype and therefore reflect on the rest of scientific production until standardization and broader adoption. The reality is that innovation is a rather complex ensemble of metrics difficult to measure. Despite attempts to study specific examples of innovation in construction (Abd El Halim and Haas 2004; Lindblad and Guerrero 2020; Khanzadi et al., 2020; Pan and Pan, 2020), and certain metrics introduced through surveys (Ercan 2019) to capture the level of activity, collaborations and technological capacity, no specific data exist on quantifying and understanding the reported evolution of the innovation

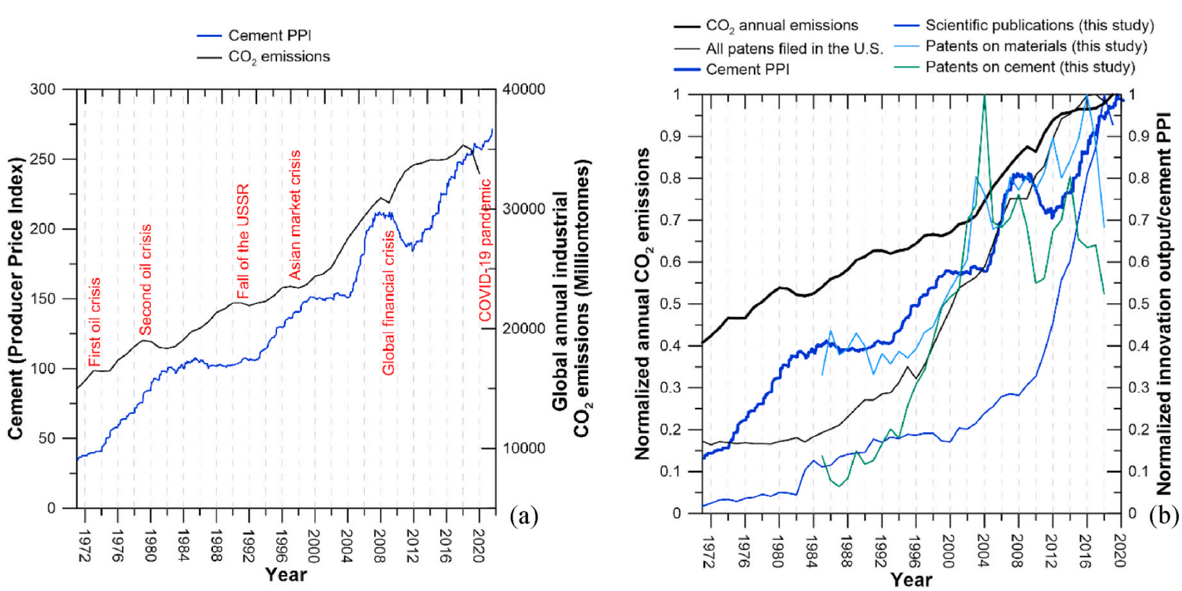

Fig. 1. (a) Comparison of global industrial CO_2 emissions with respect to major socio-political and economic crises and in relation to cement's PPI; for PP Index 1982=100 (source: Federal Reserve Economic Data, FRED); PPI measures the average changes in prices received by cement producers for their output; (b) cement's PPI evolution with respect to the scientific and patent output considered in this study, the total number of patents filed (all fields) in the US, global industrial CO_2 emissions; all data are normalized over the maximum corresponding value, i.e. 35,331.43 Million tons (2018), 606,956 (2017), 8226 (2018), 261.3 (2018), 561 (2004) and 1743 (2016) respectively for CO_2 emissions, total number of filed patents in the US, number of peer-reviewed publications, cement's PPI, patents on cement and patents on other materials (both analyzed in the results section).

landscape in the field. To this purpose, two key metrics are introduced in the present work by accounting for: (i) scientific publications in the domain since 1948 and (ii) patents filed by construction & materials companies included in 2019's scoreboard with the world's top 2500 R&D investors (Dernis et al., 2019). A preliminary analysis of these two chosen metrics reveals fluctuations in the analyzed innovation output (Fig. 1b) which correspond to the general economic and industry trends (Fig. 1a). This output will be further analyzed and understood in detail below.

3. Methods and sources

Scientific literature is used herein to capture and study the evolution of innovation trends for construction and civil engineering. Eighteen of the oldest peer-reviewed journals are selected as databases based on their age, impact and specific focus. Conference papers are not considered in this work due to the periodicity of their proceedings, which largely affects the appearance of certain trends and their evolution over time, and due to the absence of a consistent and continuous reviewing process among various publications. The list of journals considered is shown in Table 1 with respect to those of general interest and to four specialized areas, namely (i) structural/materials, (ii) numerical, (iii) geotechnics and (iv) transportation.

The chosen journals have an average impact factor of 3.48 (2018) and a SJR (Scimago) ranking of 1.91 while the mean foundation year is 1977. For eight among those, the publisher is located in the US, for five in the UK, for four in the Netherlands and one is based in Canada. Fig. 2 presents the geographic distribution of origin of the analyzed articles. A quasi-equal representation of the production from three continents is shown, with about thirty thousand papers published, in total, per territory, by 2020, despite early discrepancies in output volume. These three territories make up for 90% of all the articles published in the analyzed journals. For Europe, the top ten contributing countries are considered in this graph, i.e. UK, Italy, France, Spain, Germany, Turkey, Portugal, Switzerland, Netherlands and Greece, while for Asia the top contributors included in Fig. 2 are China, India, South Korea, Japan, Hong Kong and Taiwan. It should be noted that the primary scope of this work relies on monitoring innovation over the span of the last 50 years. Hence, other journals based in, otherwise, large contributing countries, such as in China or India, are not considered in this work due to their younger age. For comparison, the China Civil Engineering Journal (Tumu Gongcheng Xuebao) was first published in 2006 and has 3930 documents indexed in Scopus while the Journal of the Institution of Engineers: Civil Engineering Division (India) has 1278 documents indexed in Scopus with an average of 40 papers published per year.

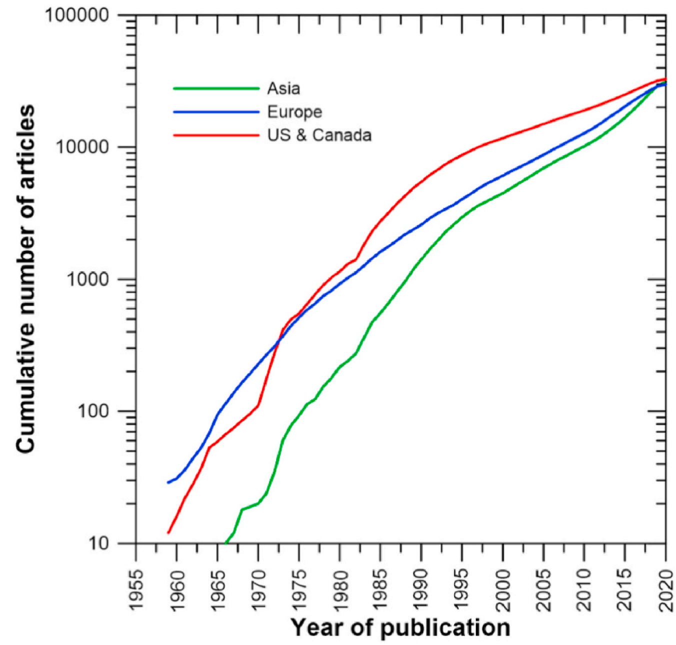

Fig. 2. Origin of the peer-reviewed articles published from in the field in the journals of Table 1.

Table 1
List of peer-reviewed journals considered for this study with their 2018 impact factor, SJR score and Year of foundation.

Focus	Journal Title	Impact Factor	SJR score	Year
General	Canadian Journal of Civil Engineering	0,87	0,32	1974
	ASCE Construction Engineering & Management	2,73	1,04	1956
	Energy and Buildings	4,50	1,93	1977
Structural/ Materials	Cement and Concrete Research	5,62	3,79	1971
	Composite Structures	4,83	1,97	1983
	ASCE Composites for Construction	2,61	1,75	1997
	Construction and Building Materials	4,05	1,52	1987
	Constructional Steel Research	2,65	1,72	1980
	ASCE Materials in Civil Engineering	1,98	1,06	1989
	Structural Control and Health Monitoring	3,74	1,50	1994
	ASCE Structural Engineering	2,53	1,91	1956
Numerical	Computers And Structures	3,35	1,54	1975
	ASCE Computing in Civil Engineering	2,55	0,85	1987
Geotechnics	Géotechnique	3,56	2,57	1948
	Earthquake Engineering and Structural Dynamics	3,42	2,78	1972
Transportation	Transportation Science	3,31	2,54	1967
	Transportation Research Part B: Methodological	4,57	2,92	1979
	Transportation Research Part C: Emerging Technologies	5,78	2,61	1993

The above journals are all analyzed to identify articles which include in their title, abstract or keywords the specific keywords of Table 2. Once the choice of sources was completed, the next step in the adopted approach was to determine the vertical axes which will be subsequently investigated for specific innovation output. Four axes were chosen, which are believed to group together innovation output driven by: (i) new materials and systems (hardware innovation), (ii) digitalization and (iii) environmental impact of man-made structures. These three verticals were subsequently treated for identifying specific keywords and their rate of appearance across decades. For the verticals of materials and that of digitalization, the approach is more evident and covers known, physical, products or digital/numerical tools respectively, such as "fiber reinforcement/reinforced" (reinforc*), "nano" (nanomaterials for example), "Structural Health Monitoring" (SHM) or "Building Information Modelling" (BIM) and "Computer-Aided Design" (CAD). However, the exercise of the approach is not as straightforward when it comes to understanding and measuring the evolution of the field's focus on issues of environmental impact. For this latter case, the present study browses through the ensemble of literature to seek keywords such as "life cycle" or "recycled/recycling" (denoted as recycl*), and "pollution/polluting" (pollut*) as examples of specific focus on environmental impact. Finally, a fourth vertical was considered as an interesting source of emerging innovation. This category deals with scientific output that focuses on novelty, efficiency or questions of optimization, costs and case study showcasing. These keywords are believed to serve as indicators of the broader sense of innovation and R&D in the field and are hence treated globally through a fourth vertical.

Aside the approach to monitor innovation output in scientific

Table 2
Keywords used for analyzing trends in scientific output from articles in the journals of Table 1 and inventors identified in (Dernis et al., 2019) and further analyzed based on patent production; Komatsu and Soletanche Freyssinet, do not feature in the above R&D scoreboard but have been found to yield important patent filing and are used to extend the present study to equipment innovators. Keywords accompanies by asterisk (*) denote any derivative word which includes the prefix.

	Category	Keywords/(category) inventor
Peer-reviewed scientific articles	Materials & Systems (Hardware)	Fiber reinforc*, Fiber sens*, Grout, Nano, Precast*, SHM, Ultra
	Digitalization	AI, BIM, CAD, FEM, GIS, Internet, Machine Learn, Neural
	Environment	Carbon/CO_2 emission, Life cycle, Polutt*, Recycl*
	Innovation & Efficiency	Case stud*, Cost, Efficien*, Innovation, Novel, Optimis/z*, Progress
Patents	Corporate Inventors	**Contractor:** China State Construction Engineering (China CSE), **Equipment:** Komatsu, Soletanche Freyssinet, Hilti **Cement/minerals:** LafargeHolcim, HeidelbergCement, Cemex, James Hardie, Rockwool International **Other materials:** KCC corporation, PPG Industries, Saint-Gobain, Tarkett
	Corporate Innovation from patents filed in the US under CPC "E"	Grout, Machine Learn, Precast, Recycl*, SHM

literature and provide with a breakdown based on verticals and keywords, Table 2 summarizes the search of innovation metrics by means of patent search. More precisely, according to Dernis et al. (2019), almost $17 Bn was spent in 2019 on corporate R&D in construction and materials from 61 actors among 2019's top 2500 R&D investors. These actors are therefore chosen to be further analyzed in the present work. Ten of them are classified as cement, general materials or equipment producers (Table 2). Their patents are used in this study for evaluating the innovation output in the field between 1985 and 2018. Comparison of this cluster of innovators is done with the total number of patents filed in the US under Cooperative Patent Classification (CPC) category "E", which represents "Fixed Constructions" including, among others, subcategories such as: "Construction of roads, railways or bridges" (E01), "Hydraulic engineering, Foundations, Soil shifting" (E02) and "Earth drilling and mining" (E21). Patents that fall under classification "E" are analyzed to search for keywords in their title, abstract or claims, which represent innovative hardware/systems, similar to those used to search through scientific literature (Table 1). Through this comparison, the output of the chosen innovators is compared to the global patent output trend in the field to avoid potential bias due to the small pool of high-performing innovators identified in Dernis et al. (2019).

To summarize, all industrial property (IP) records are extracted from the European Patent Organization's (EPO) Worldwide Patent Statistical Database while records on the scientific articles are extracted using Elsevier's Scopus database. For scientific articles the title, abstract and keywords are analyzed to filter those that include the keywords of interest while for patents that fall under CPC category "E", the title is filtered to provide additional insights into trends behind each of the keywords.

To benchmark findings with existing approaches which aim to capture and interpret innovation and technology readiness, the present work uses the framework of S-curve technology maturity which was described by Sahal (1980, 1985) and Foster (1986). The technology S-curve approach is seen as a way of assessing the emergence of new technologies and their potential towards improvements in the performance of products or systems. S-curves express the evolution of engineering effort or capital over a given period of time to ultimately identify when technologies become mature. A schematic approach of the S-curve framework is presented in Fig. 3. The present work integrates the widely used technology readiness levels (Table 3), which were first introduced by NASA (Mankins, 1995) and since then became widely adopted as a centerpiece tool for assessing research proposals and allocating research funding (Bruno et al., 2020), into the S-curve framework to facilitate the discussion of the obtained results.

4. Results

Results are presented with respect to the four following field verticals: (i) new materials and systems, (ii) digitalization, (iii) environmental impact and (iv) novelty/efficiency. Scientific output is treated with respect to the evolution of the total number of articles which put the focus on the chosen keywords, to identify trends and interpret qualitatively their growth rate in literature. All results are compared with the total number and evolution of publications in the field to remove any uncertainty related to potentially growing presence of specific terms due to simply an increasing output in the field.

Fig. 4a presents trends on the appearance and evolution of terms that relate with new materials and systems. This category of hardware innovation refers to physical products and systems which require a certain level of capital and time expenditure on their conception, production and characterization. Overall, hardware innovations are known to be the ones that entail the biggest risks in R&D investment and to require longer processes when compared to, for example, digital innovation. This latter requires a different level of infrastructure to develop, standardize and distribute.

The studied systems of hardware innovation appear to emerge between 1970 and 2000. Among the oldest innovations are those that use fibers for reinforcement or those around precast materials, mainly referring to concrete and walls. The first demonstrate a higher degree of penetration in the literature reaching ten thousand publications in less than fifty years (Fig. 4b). This could be attributed to the fact that various materials are known for their usage in fiber reinforced elements, such as steel, glass or synthetic fibers, and therefore engage the interest of various scientists or specialists and could therefore reflect

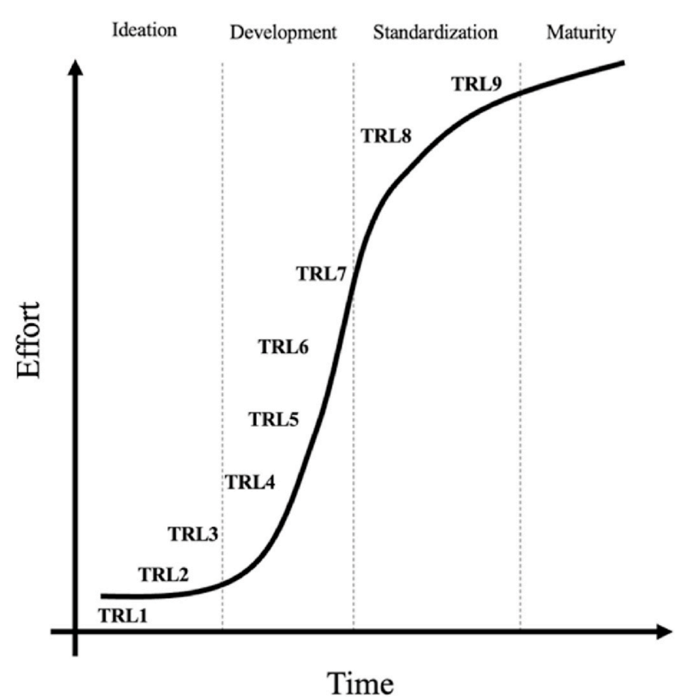

Fig. 3. The S-curve framework of technology maturity.

Table 3
Technology readiness Levels (Bruno et al., 2020).

Maturity level	Description
TRL1	Basic principles observed
TRL2	Technology concept formulated
TRL3	Experimental proof of concept
TRL4	Technology validated in lab
TRL5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL7	System prototype demonstration in operational environment
TRL8	System complete and qualified
TRL9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

interdisciplinary collaborations. Despite their earlier appearance in literature, the terms "precast" and "grout" do not achieve the same level of evolution with fiber reinforcement. However, such materials and systems have been proven to be successful and widely used in practical applications. One would also expect that terms that appear earlier in the literature would gain momentum faster and grow their presence with respect to more recent ones. However, this is not observed in Fig. 4b where all keywords are compared with respect to their first appearance in literature. For the terms "grout" and "precast" there appears to be a slowdown after the first 20 years since appearance in literature which serves as an indicator of increased maturity according to the S-curve and TRL frameworks discussed previously. The terms "nano" and "ultra" appear to have the fastest growth rates in produced articles. The former is the newest of the analyzed terms and the latter is found to undergo a shift towards increasing growth rate, after almost twenty years in literature. This shift, which distinguishes from the rest of the presented trends, can also be seen as a double S-curve which is believed to indicate growing interest for a second phase of developments. Such double S-curves are known to be signs of breakthrough developments which initiate new innovation cycles (Christensen, 1992). Another significant trend is that of SHM which is found to grow at a similar pace with the most successful innovation, that of fiber-reinforcement.

Literature data covering digital and numerical tools in the fields of construction and civil engineer are summarized in Fig. 5 and suggest different evolution with respect to the analyzed trends representing hardware innovation. More precisely, two predominant trends appear to establish, relatively early. These are FEM and CAD. The important developments in computer science and the current, considerably higher, capacity for operating complex analysis of large computational costs do not seem to reflect on the fate of CAD-related topics treated in literature with the term found to reach a plateau before 2000, reaching maturity. However, this is not the case for FEM-related articles, which continue a somewhat growing presence in literature. A notable distinctive trend is that of Machine Learning (ML) which is found to gain ground faster after

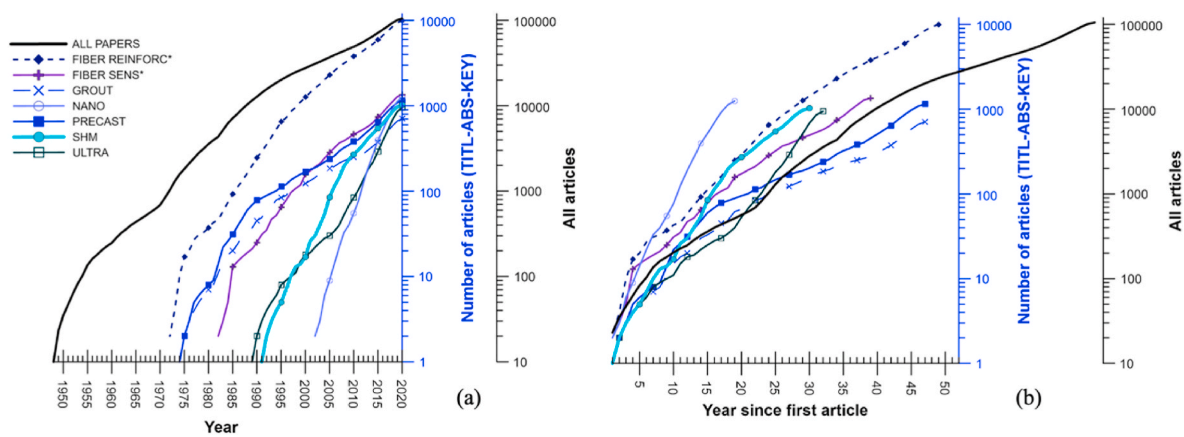

Fig. 4. Hardware innovation in construction with respect to seven key systems that have appeared in literature (blue axes); all papers in the field published in the journals of Table 1 (black axis) with respect to publication year (a) and number of years since first appearance (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

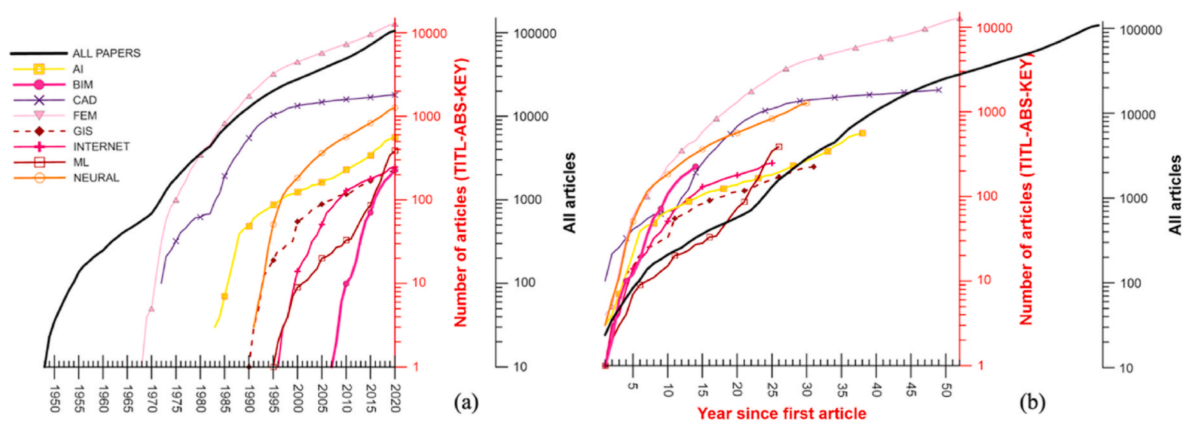

Fig. 5. Analysis of terms representing digital and numerical innovation in construction, with respect to eight keywords (red axes); all papers in the field published in the journals of Table 1 (black axis) with respect to publication year (a) and number of years since first appearance (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2010, with respect to its rate during the first 15 years in literature, representing yet another example of double S-curve. Similar trend was observed for nano- and ultra-related articles in Fig. 4 around 2005. Similar, but not as pronounced, shift is observed for articles on Artificial intelligence, which appeared in literature much earlier (Rooney and Caldwell, 1982) but grew in output faster after 2010. Neural networks appear first in the studied journals in 1991 (Rosyid and Caldwell 1991; Moselhi et al., 1991) and have grown since then to the third most populated term among the studied ones, with relevant articles expected to grow higher than CAD.

Data on the evolution of terms related to the environmental impact in the field, are shown in Fig. 6. Agreement is generally captured for the analyzed trends, which are relatively younger compared to the rest of keywords treated in this work (Figs. 4 and 5). More precisely, articles related to CO_2/carbon emissions grow faster their presence after 2010. Articles that treat recycling also seem to undergo a double S-curve and gain territory for various applications, ranging from recycled waste in construction, recycled concrete and aggregates or tire rubber (Khatib and Bayomy 1999). Recycling appears as the fastest growing term which can be explained by the relevant progress in recycling technologies (Longana et al., 2016) and recent shifts in the understanding of reusing resources and adopting circular models in construction. It is pertinent to consider herein that just for the UK and 2019, the total construction, demolition and excavation waste reached 120 Mt which is in par with 59% of the country's total waste and 30% of construction firms' pre-tax profit (UK Green Building Council 2019). Overall, environment-related articles in the field appear to have become more popular within a shorter time, than most of the terms in the previous categories, and have crossed the thousand publication milestone by 2015. This can be explained by the fact that such topics touch the ensemble of the field, irrespectively of specific focus or material and system category and also reflect the important role or regulatory aspects which change in recent years, impacting the conception and implementation of building projects.

Questions of efficiency/optimization and costs seem to be particularly popular in the field. Fig. 7 presents relevant terms and a total yield which varies from seven hundred to above ten thousand related articles in the past fifty years. This finding implies that researchers have been active in reporting on the improvement of processes or delivering, for example, case studies, which represent an established way to introduce and test new and innovative concepts. Most of the terms appear around 1965 with the exception of innovation and novelty (novel*) which appear later but grow equally dynamic presence in literature. Fiber reinforcement and FEM are the only two trends from Figs. 4 and 5, respectively, which are found to match the total yield of those of Fig. 7.

Another innovation metric adopted in the present work relates to patent output. This is analyzed in two levels. First, by treating the output of twelve innovators, with ten of them listed in the work by Dernis et al. (2019) among the world's top 2500 R&D investors. Two additional ones are found to demonstrate important production in terms of equipment innovation (Komatsu and Freyssinet) and are included in Fig. 8c. Results are presented with respect to three categories: (i) cement/minerals providers (Fig. 8a); (ii) other materials providers, including glass, resins and coatings (Fig. 8b) and equipment manufacturers (Fig. 8c). Comparison is finally provided between the total annual output, illustrated in 8a and 8 b, with the patent production of China State Construction Engineering company (China SCE), which is identified (Dernis et al., 2019) as the top R&D spender in the construction and materials category. It should be noted that patents filed after 2018 are not yet fully publicly disclosed in patent offices and therefore are omitted from the analysis.

Results reveal distinctive trends for patents on cement/minerals and other materials. An inflation in output is observed until a peak is identified in 2004 for both categories. This is followed by a decrease in output for cement/minerals and a gradual increase in the number of patents on the rest of materials. These results are interpreted with respect to the broader socio-economic context presented in Fig. 1a, which reveals a long-lasting impact of the 2008 global financial crisis on cement's PPI which serves as indicator of the demand for construction and therefore of the growth of the sector. Results reveal a larger number of patents filed for other materials compared to cement/minerals and at some extend validate the hypothesis that patent filing, result of R&D spending, depends highly on the strategy adopted by each entity around developing and securing innovations and the competition landscape. This is further illustrated in Fig. 8c, with one of the three equipment providers (Komatsu) found to yield over four times the patent production of the other two. When combined, the annual output in cement and in other materials, trails that of the China SCE after 2012 which provides yet another example of the different approach on patent filing, adopted by individual stakeholders.

Given the dependency of patent output on individual strategies and corporate cultures, a second level of analysis on patent output is presented in Fig. 9, where all patents filed in the US Patent office under Cooperative Patent Classification (CPC) category "E" since 1999 are filtered, irrespectively of the inventor. This allows capturing the trends in patenting around four keywords related to hardware innovation ("grout", "precast", "recycl*" and "SHM") and to machine learning (ML). One should consider that patents are valid for twenty years, therefore the goal of this comparison is to reveal output which was potentially active until 2019 or is still active today. Results are compared with the

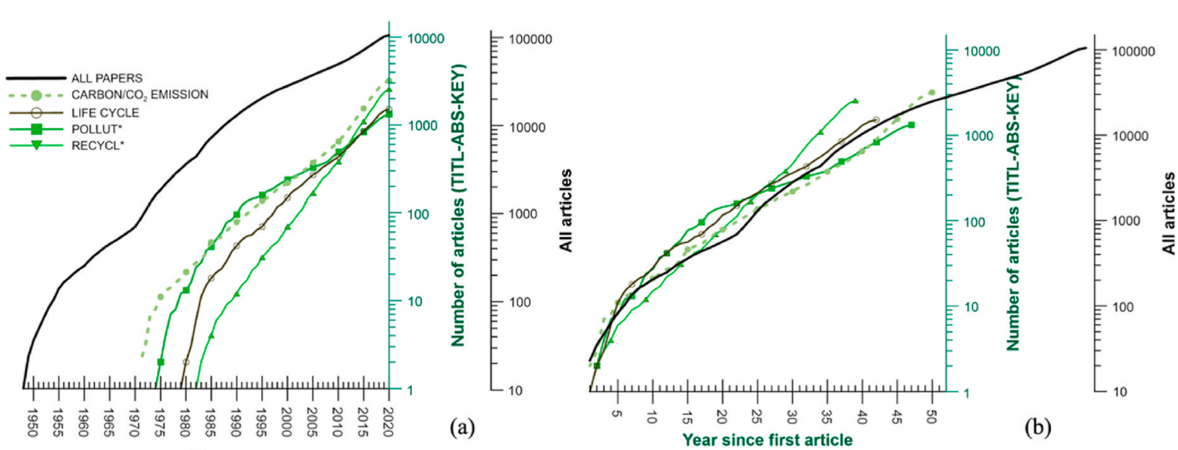

Fig. 6. Analysis of terms representing environmental-related research in construction, with respect to eight keywords (green axes); all papers in the field published in the journals of Table 1 (black axis) with respect to publication year (a) and number of years since first appearance (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

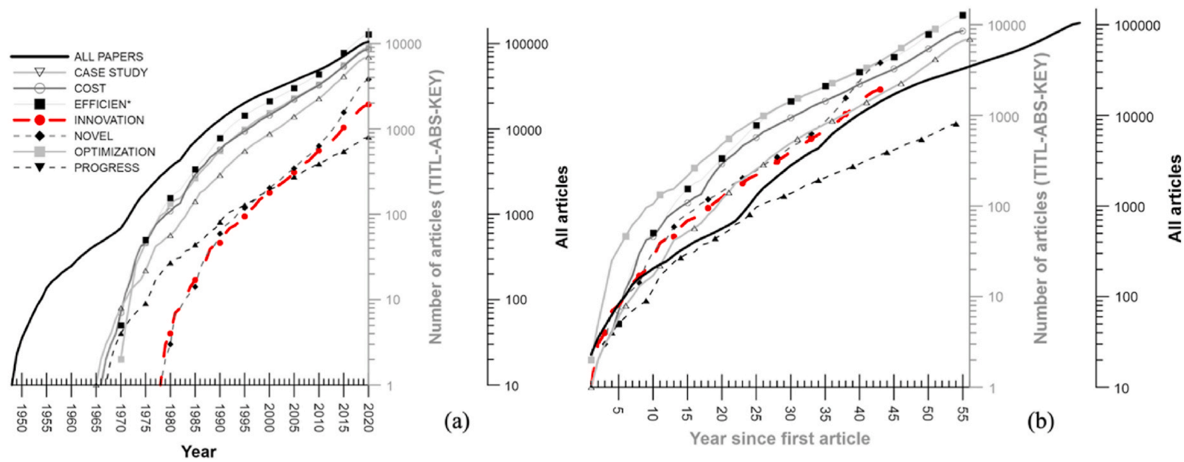

Fig. 7. Analysis of terms standing for efficiency, novelty and the innovation process, with respect to eight keywords (grey axes); all papers in the field published in the journals of Table 1 (black axis) with respect to publication year (a) and number of years since first appearance (b).

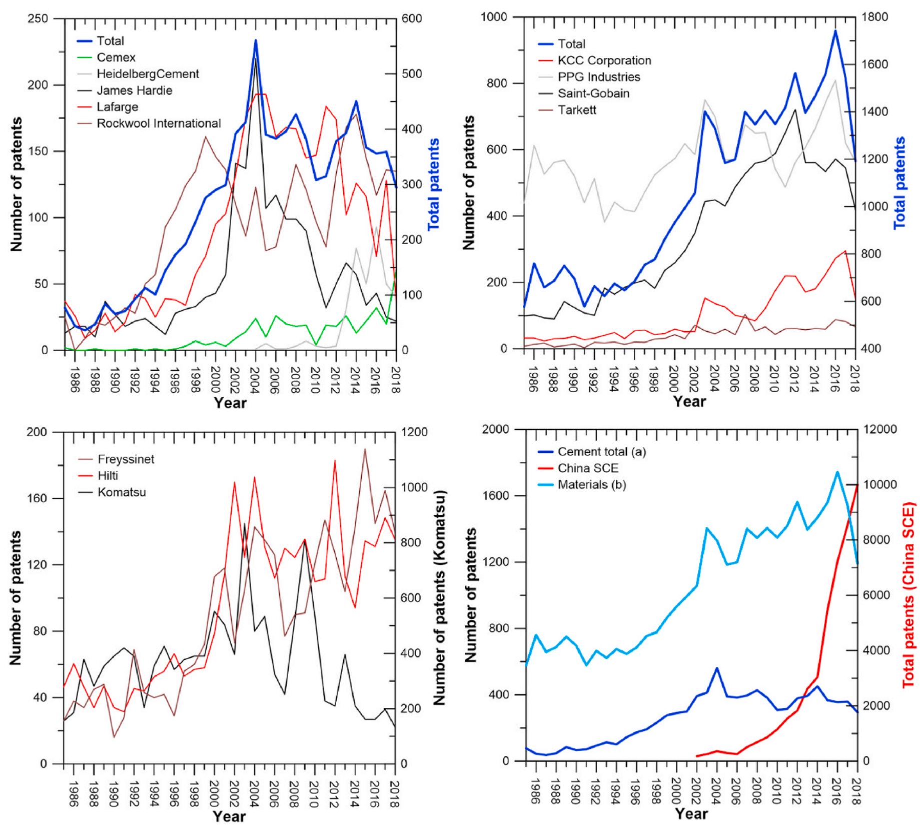

Fig. 8. Patent output from twelve innovators in the fields of cement/minerals (a), other construction materials such as resins, glass, coating and polymers (b), construction equipment (c) and comparison from total annual output in cement/minerals and other materials with the total annual output of the China State Construction Engineering company (d).

evolution of the same terms in scientific literature. Fig. 9 shows that within the last twenty years, patents in the US and relevant scientific publications follow similar trends in their growth, despite journal articles appearing earlier and growing their presence. More precisely, Machine Learning shows the biggest discrepancy between patents filed and scientific articles published, with both, however, yielding similar shift in their output rate after 2012 as noticed earlier in Fig. 5. More patents are also filed for grouting compared to the total scientific articles on the same topic. For the rest three terms, patents filed in the last twenty years in the US fall behind in terms of absolute numbers, when compared to published articles to-date. All patents appear to reach a maximum number of 700–800 patents filed since 1999, with the exception of SHM which reaches just above 200 documents. Fig. 9 further analyzes the patents that fall under CPCP category "E", with respect to the most popular keywords in their titles. Interestingly, certain machine learning-related patents appear to cover drilling operations/systems, while SHM applications cover at a certain extend oil and gas applications (featuring "oil" or "well" in their title). Grouting-related patents cover walls, anchors and piles while for recycling applications the most predominant term relates to walls.

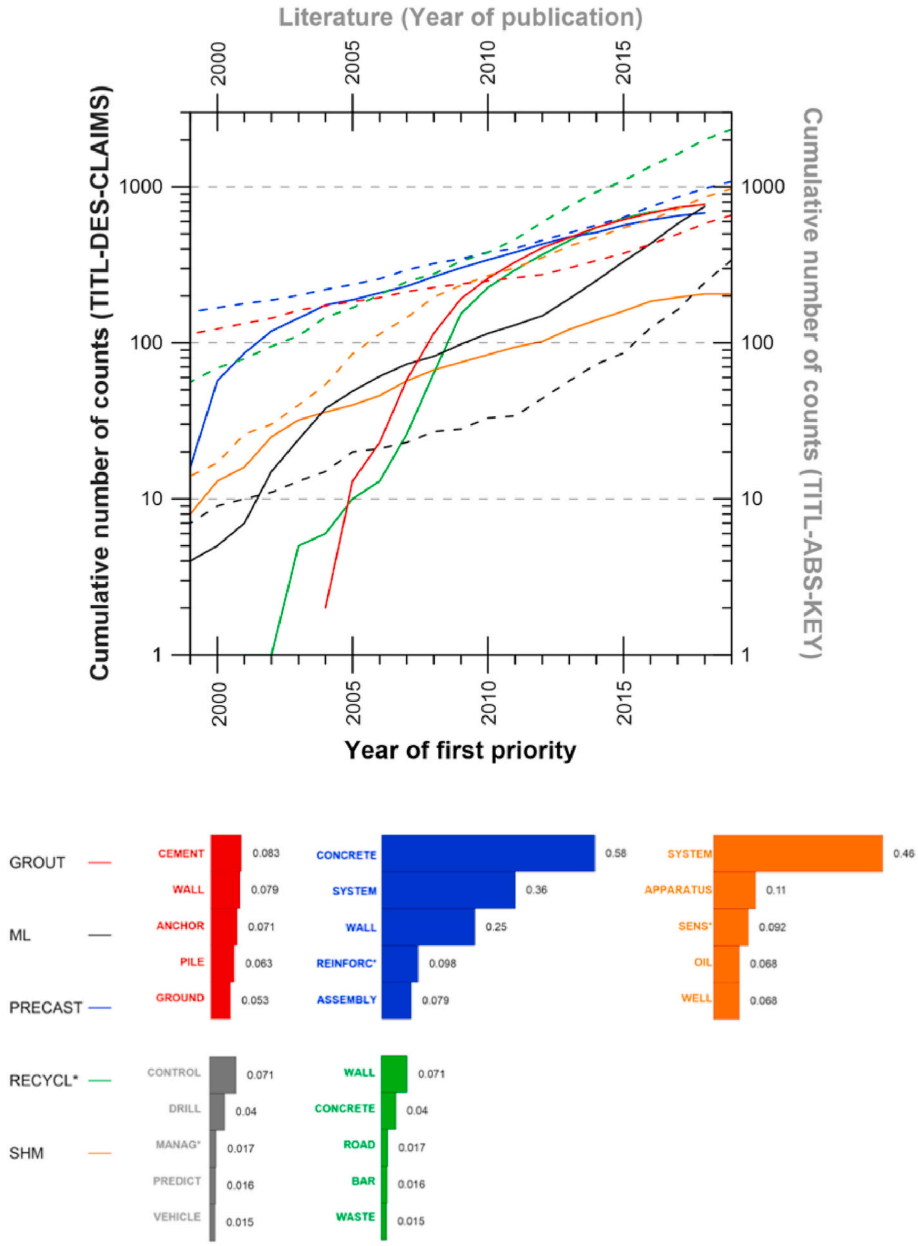

Fig. 9. Patent output in US with respect to CPCP category "E" (solid lines/black axes) including five keywords; comparison with the same keywords found in scientific literature (dashed lines/grey axes); each patent featuring a keyword is further analyzed to identify the five most commonly appearing terms in their titles and the corresponding ratio.

5. Conclusions

The present study monitors trends in scientific literature from the fields of construction and civil engineering, which indicate the momentum, maturity and respective penetration that innovative concepts and procedures achieve over the course of the past fifty years. Insight is offered into distinguishing between corporate innovation and academic research by analyzing and comparing patent output and scientific articles with respect to four key categories that inspire, drive and grow innovation. Based on the findings of this work:

- Two predominant indicators to measure innovation in the field are suggested, i.e. patent output, result of corporate R&D, and scientific literature, result of academic research.
- The S-curve framework on technological maturity is adopted as a metric concept for evaluating the fate of the certain studied verticals. Plateauing, which stands for increased technology maturity, varies for the various verticals, but starts overall between 15 and 20 years since first appearance in literature. Plateauing is clearer for digitalization tools compared to physical systems/materials (hardware). Certain terms appear to yield a double S-curve which reflects growing interest for new developments once a first innovation cycle has been defined. Such double-S curves were obtained for the terms: (i) "ultra"; (ii) "machine learning" and (iii) "recycle*" respectively in the verticals of: (i) materials; (ii) digitalization and (iii) environment.
- Some terms gain ground faster, compared to the overall growth in literature output (all papers), which serves as yet another sign of growing traction and consolidation of interest.
- Hardware innovation shows slower growth rates when compared to digital innovation, which validates a longer readiness and adoption cycle for physical products/systems. Hardware innovation mostly underperforms compared to the overall growth in literature output

(all papers) while digitalization terms overperform the average literature output growth rate.
- Nanomaterials-related research is the best performing of the analyzed themes in the hardware vertical, crossing the bar of 1000 publications in just 20 years. The same milestone took 45 years to meet for studies focusing on pre-cast materials and systems.
- Environment-related focus is identified as the youngest trend, compared to the studied hardware and digital innovation, but grows at a constant rate in recent years without signs of plateauing.
- The field is found to treat questions of efficiency/optimization and novelty at about 10% of the total publications analyzed, i.e. over 10,000 articles per term.
- Construction is not a patent-intensive industry despite its predominant role in economic and societal growth and several indicators are presented which suggest it lags behind other fields in terms of innovation adoption and R&D spending.
- Corporate innovation and patent output appear to depend heavily on individual patent strategies among the analyzed stakeholders. However, distinctive trends are captured when comparing the output of cement/minerals companies and that of other materials specialists. These trends are found to reflect the broader sector's growth which is interpreted with respect to the general socio-economic landscape.
- Patent output and scientific publications seem to reflect certain similar trends around specific topics, such as machine learning which peaks up in both indicators around 2012 implying that recent developments in other domains of science reflect into growing interest in the field, resulting in a double S-curve of maturity.

The above findings shed light into the evolution of the innovation potential through published data which cover a period of over fifty years. Innovations that filled past research gaps are analyzed for their traction in the field. Trends vary throughout the years and their analysis suggests that opportunities for future research to fill current and future gaps in knowledge are likely to follow the growing patterns captured for older and now well-established technologies to eventually tackle the closure of a productivity gap which is found to reach $1.6 trillion.

Data availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The author declares no conflicts of interest.

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