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Benefits of international collaboration in computer science: a case study of China, the European Union, and the United States

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Abstract
Co-authored publications can bring positive results for those who participate, such as gaining additional expertise, accessing more funding or increasing the publication impact. China, the European Union, and the United States have been collaborating between each other throughout the years in the field of Computer Science. These collaborations varied over time, as well as they impacted the regions in different ways. In this paper, we collected the publications from these territories across 31 years on the topic of Computer Science and studied them focusing on how the regions have approached co-authorship. In particular, we have analyzed the number of collaborations during that period, the impact of those papers measured as the number of citations, and the topics that have been researched. We conclude that China's focus on Computer Science fields has led it to be the most productive region in recent years; plus, it has benefited from the American and European reputation, by increasing its citation rates when collaborating with them. On the other hand, the EU and the US have benefited from Chinese interest in computer science, increasing the number of publications together.

Keywords Computer science · Co-authorship · Collaboration · Citation

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Introduction

The proportion of internationally co-authored scientific papers has significantly increased since the turn of the century, representing a growing share of all scientific cooperation, while the rate of the in-home collaboration has been proportionally falling (Adams, 2013; Wagner et al., 2015).

This growth is mainly attributed to emerging nations, most notably China, that have amplified their engagement in global scientific endeavors, partly by doubling their investment in research and development. As a result, they are progressively more inclined to collaborate as partners in internationally authored scientific publications (Wagner et al., 2015). International collaboration can in general bring positive results to the countries that participate. For example, papers co-authored by individuals from multiple nations receive higher citation rates compared to those authored by individuals from a single nation (Glänzel & Schubert, 2001; Kwiek, 2021; Levitt & Thelwall, 2010). Other positive trends observed are that co-authored publications or higher development index of the research and innovation system of the collaborating countries receive higher citation rates compared to single-authored papers (Ronda-Pupo, 2022; Shen et al., 2021; Vieira, 2023). Apart from general benefits, international coauthoring can also bring specific advantages for a country depending on the other countries it is collaborating with, such as access to more funding opportunities, more R &D activity, and local knowledge (Lee & Haupt, 2020; Harhoff et al., 2014). The top 3 most prolific countries[1] in terms of the number of scientific publications published in Computer Science fields are China, the European Union (EU), and the United States (US); also they are the regions that collaborate between each other quite intensively, as well as are the ones that received most citations on average (Burke et al., 2022; Wang et al., 2017; Zhang et al., 2018). Although the scientific collaborations between China and the US have been increasing in the recent past, the latest studies suggest that this tendency has stopped (Cai et al., 2021; Lacey, 2021; Schüller & Schüler-Zhou, 2020; Zhao & Yin, 2019). This rivalry leaves the EU somewhat in the middle of a crossfire, in which it is not clear yet if it will take the anti-China approach proposed by the US or will follow another path keeping the positive collaboration tendency (Schüller & Schüler-Zhou, 2020; Ullah et al., 2020). It is in this context that we want to contribute to the current literature by providing a long-term analysis of these territories.

Our objective is to explore the collaborative patterns between China, the US, and the EU in the field of computer science over a span of 31 years. We make significant contributions to the current literature in three ways. Firstly, we conduct an analysis of collaboration trends within and between these regions over time, shedding light on the dynamics of their partnerships. Additionally, because of the market-oriented possibilities of the different fields of computer science, we offer novel insights by investigating whether the institutions that participated in the article's creation were public or private institutions. Secondly, we analyze the impact of these collaborations on the outcomes of academic and privately conducted research papers, by measuring the number of citations obtained. By evaluating the relevance and visibility of the resulting articles, we provide valuable insights into the significance of these partnerships. Lastly, we look into the prioritization of computer science

[1] Although we are aware of the differences in collaboration between the European countries, we regard UE27 as a single "country" to simplify the discussions and comparisons, which is also more comparable to the USA and China in terms of economic size, population number, and the overall scientific activity than any individual country in EU.

subfields by the analyzed regions over time and the patterns of their shared interests. This examination allows US to uncover how the participating nations allocate their resources and focus within the realm of computer science.

In this paper, we address to answer the following research questions:

- How much have China, the European Union, and the United States been collaborating in computer science over the years?
- How do the collaborations between the regions affect the number of articles' citations?
- In which particular topics do the regions have focused on when working together?

Our research findings could be useful in assisting policymakers, lawmakers, and public agencies in making informed decisions when creating restrictions or enhancements for scientific collaboration between the analyzed regions, either in the public or private sector. These insights could inform about the historical context associated with different types of collaborations and assist in formulating effective policies that strike a balance between openness and protection of national interests. Furthermore, our findings may offer guidance to public agencies from all countries, including those analyzed in this study, for better research prioritization in the field of computer science. By analyzing the collaborative trends among the three regions, we provide valuable information about the areas of computer science that are receiving significant attention and resources, enabling the alignment of research priorities with them for potential collaborative opportunities.

The remainder of this paper is organized as follows: In "Related Work" section we discuss the related work on scientific collaborations, as well as survey current literature about the relations between China, the EU, and the US in scientific co-authorship. In "Analysis" section, we provide the details of the journal article dataset and explain the process we followed to collect and analyze it. This section then shows the results we obtained when investigating the data. Finally, we discuss the results in "Discussion" section, we draw conclusions based on the findings we got and we outline potential future research directions in "Conclusion" and "Limitations" sections , respectively.

Related work

Scientific co-authoring

Publication co-authorship has been thoroughly examined within the field of bibliometrics, which is a quantitative branch of information and library science that studies the publication of research accomplishments (Broadus, 1987). Research collaboration offers various advantages across different academic disciplines. In the fields of science, physics, and medicine, collaboration is heavily exploited, resulting in benefits such as the division of tasks and the sharing of competencies and abilities. Additionally, it plays a crucial role in improving the level of knowledge and skills of domestic scholars, fostering an environment for continued growth and development in these fields (Franceschet & Costantini, 2010; Shen et al., 2021). In addition to this, collaborations between individuals from different affiliations can enhance impact and quality, providing researchers with the opportunity to draw on a diverse range of knowledge sources and the resulting works often lead to increased impact and higher valuation by peer experts (Franceschet & Costantini, 2010; Shen et al., 2021). The increased impact of the publications is particularly prominent for

developing countries, that benefit significantly from research collaboration, leading to higher citation rates (Shen et al., 2021). Working with senior colleagues is highly desirable for junior academics, and this practice fosters efficient collaborations, particularly in the context of the ever-changing landscape of academic research (Besancenot et al., 2017; Franceschet & Costantini, 2010; Biscaro & Giupponi, 2014). Focusing on collaboration within the different areas of science, previous literature suggests that international collaborations have been increasing in recent years, as measured by the number of co-authored papers, with global collaboration continuing to grow as a share of all scientific cooperation (Larivière et al., 2013). This behavior has been studied in computer science in particular, suggesting that the number of authors per paper has been increasing (Fernandes & Monteiro, 2017). Different studies have examined the citation impact of international and domestic co-publishing in different scientific disciplines, and they have found that international collaboration has a higher citation impact than domestic collaboration in sciences (Lancho-Barrantes et al., 2010; Newman, 2004; Puuska et al., 2014). Finally, in the field of computer science, it has been also found that its research networks are widely connected, allowing new collaborations to be created between scientists from different institutes, countries, or sub-disciplines (Franceschet, 2011).

However, research collaboration also presents certain disadvantages. In some scientific disciplines, such as physics, papers with an extraordinary number of co-authors may receive fewer citations due to quick citational obsolescence (Franceschet & Costantini, 2010). It has also been studied that in the different fields of computer science, the collaboration between researchers has produced a decrease in the number of complete papers written by each of the investigators (Cavero et al., 2014). Furthermore, partnering with nations that possess less-developed research and innovation systems often results in lower scientific impact and while open-access publications are linked to increased scientific impact, they can also introduce disparities in terms of resource accessibility (Vieira, 2023). There are also barriers to collaboration between the private and public sectors, such as funding allocation, with private organizations generally investing less compared to public institutions, communication gaps, varying timeframes, and the difficulty of identifying suitable research partners (Dan, 2013).

Despite the possible disadvantages, cooperation in research continues to grow in most academic disciplines (Chinchilla-Rodríguez et al., 2019; Wagner et al., 2015, 2017). Nevertheless, this tendency, as well as the collaboration outcomes, might vary across disciplines and whether the collaboration has been national or international (Franceschet & Costantini, 2010; Puuska et al., 2014).

Chinese–American collaborations

The United States and China have been the two leading countries in global research and development (R &D) performance during the last decades (Burke et al., 2022). Although the number of collaborations between these countries, measured as the number of scientific papers co-published, has constantly increased, their positioning is as global adversaries instead of allies (Lee & Haupt, 2020; Wagner et al., 2015; Zhao et al., 2022; Lewis, 2021). This can be seen in recent findings suggesting that the collaboration between these countries has been slightly decreasing, even when the relationship between the two countries can bring advantages to both (Cai et al., 2021; Wagner & Cai, 2022, 2022). Previous studies suggest that the collaborations between the US and China brings more citations than only those authored by Chinese researchers (Tang & Shapira, 2011). On the other hand,

the US benefit from collaborating with China by obtaining funds for research, as well as increasing their scholarly output (Lee & Haupt, 2020).

European–American collaborations

Although the global concentration of R &D performance continues shifting from the United States and Europe to countries in East-Southeast Asia and South Asia, scientific publications made by the EU and the US are more relevant than those that these regions published collaborating with China (Burke et al., 2022; Leydesdorff et al., 2014). Apart from this higher impact, the US and the EU benefit from each other's specializations in the different scientific fields (Burke et al., 2022). In addition to this, European countries have also benefited from the rivalry between China and the US, attracting more collaborations between the US and the EU (Cai et al., 2021; Schüller & Schüler-Zhou, 2020; Wagner & Cai, 2022).

Chinese–European collaborations

The EU and China are the countries where most Science and Engineering articles are produced in the world, producing more publications than the US (White, 2019). In recent years, the collaboration between them has grown fast, turning the European Union into the second biggest partner of China in science and technology research (Li & Chang, 2014). This collaboration tendency between the EU and China varies among the EU former countries. However, it represents only more than 20% of total Chinese collaborations (Wang et al., 2017; Yuan et al., 2018). Previous findings indicate that the proportion of Chinese scientists living abroad is significantly higher in the USA compared to the EU. However, the flow of researchers from these destinations coming back to China has been more pronounced from the EU than the USA, which can increase international collaboration with countries from the EU (Cao et al., 2020). That trend, summed with political reasons can be the cause of that Chinese researchers still wanting to collaborate with EU institutions instead of US institutions (Schüller & Schüler-Zhou, 2020; Silver et al., 2020; Wagner & Cai, 2022).

Analysis

In this section, we first present the dataset used and then show the results obtained based on its analysis. We have divided our findings into three different subparts: *Number of collaborations*, *Impact in research outcomes*, and *Researched Topics*.

Dataset

Multiple data source alternatives are available for obtaining the bibliometrics information for this study. Starting with the Microsoft Academic Knowledge Graph (MAKG),[2] a large RDF data set containing more than 238 M publications on the 28th of May of 2023. It is

[2] https://makg.org/.

based on the discontinued Microsoft Academic Graph (MAG)[3] and it provides information about scientific publications as well as related entities (Färber, 2019). Similar to the MAKG, we examined OpenAlex[4] as a fully open scientific knowledge graph (SKG) (Priem et al., 2022). OpenAlex is also based on the MAG, although it had 245 M works in its database on the 28th of May of 2023, increasing the number of publications that can be analyzed in the study. In addition to this, ArXiv[5] was also examined, but it was quickly discarded due to its low amount of papers, containing just 2.2M of publications.

In the end, we decided to go forward with OpenAlex as the data source. Apart from the larger size, OpenAlex allows using filters in advance, setting thresholds to the search, and therefore reducing the processing time. Its simplicity and easy integration with Python were also relevant for the final decision, making this dataset the best option for our case.

Data collection

In the following section, we discuss the process we followed for the data collection.

We gathered information on the works by utilizing OpenAlex API, using various filters. First, we filtered works by the "computer science" concept, and we only considered published journal articles for better analysis of citations within the different subfields. We also limited the publication years to range from 1990 to 2021, both inclusive. In addition to this, we filtered retracted publications.

Data preprocessing

We first preprocess the raw data. As the scope of our research is to analyze the collaboration patterns between different countries/regions, papers written by just one author were removed. OpenAlex associates each article with its authors and links each author to their affiliated institution, where the country location can be obtained. We only analyzed papers whose all authors were linked to institutions with available country information. As authors can be affiliated with different institutions, in those cases we considered all the institutions' locations for the study as countries participating in the published research paper. Country name normalization was not required, because the data was following ISO 3166-1 Alpha-2 format, so no different names for the same country could occur. We only considered publications whose all authors were affiliated with an educational or company institution, therefore, not considering those papers in which any of the authors were affiliated with other types of institutions[6] or when the institution's type was empty, however such cases were the minority. There were also works that did not have their DOI code attached, neither the number of citations, which we then also removed. To categorize the publications, we added a tag to mark each work based on the institutions' type that participated in the collaboration. Therefore, works where all participants were affiliated with educational institutions, such as universities, were categorized as "educational", works where all participants came from profit-oriented private corporations were categorized as "company", and papers authored by both were marked as "mixed". In our analysis, for simplicity, we considered as

[3] https://www.microsoft.com/en-us/research/project/microsoft-academic-graph/
[4] https://openalex.org/
[5] https://arxiv.org/
[6] https://docs.openalex.org/api-entities/institutions/institution-object#type

Table 1 Number of publications per collaboration type

Collaboration type	CN-only	EU-only	US-only	CN–EU	CN–US	EU–US	CN–EU–US	Total
All	692,924	727,151	835,456	26,267	73,420	84,701	3277	2,443,196
Education	672,256	678,427	748,132	24,024	65,978	68,861	2648	2,260,326
Company	4064	16,015	31,420	92	153	1375	9	53,128
Mixed	16,604	32,709	55,904	2151	7289	14,465	620	129,742

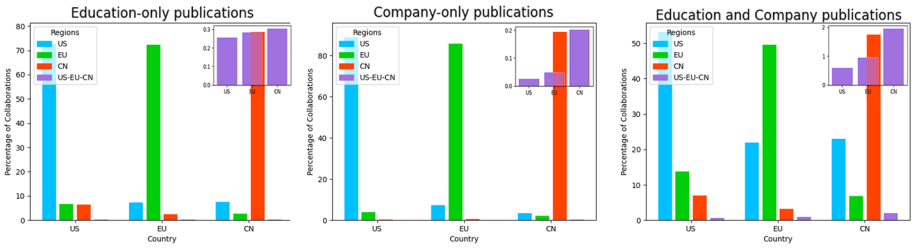

Fig. 1 Collaboration percentage by collaboration type

Table 2 Relative collaboration rates per country

Country	With CN (%)	With EU (%)	With US (%)	All 3 regions (%)
CN	76.75	2.91	8.13	0.36
EU	2.57	71.15	8.29	0.32
US	6.27	7.23	71.33	0.28

EU publications the ones published by the EU27 as well as the UK, and China publications published by "China Mainland". It resulted in a dataset composed of 2,443,196 research papers.

Results for the number of collaborations

As we can see in Table 1, the nation that published the highest number of publications was the US (835,456) followed by the EU (727,151) and lastly China (692,924). If we look into the number of journal articles written as a result of a collaboration between the regions, we can see that the EU and the US collaborated the most, having a total of 84.701 publications done together. It is followed by the number of collaborations between the US and China (73,420), China and the EU (26,267), and finally, the least common collaboration was between the 3 regions (3277).

In all the cases, the co-authorship between authors from the same region represents more than 70% of their total co-authored articles as shown in Table 2. China has the highest rate, with 76.75% of their collaborations being only within the country, followed by the US with 71.33% of self-collaboration and finally the EU with 71.15%. These results suggest that Chinese authors have been more isolated in terms of collaboration opportunities than others. This can also be observed in the importance the

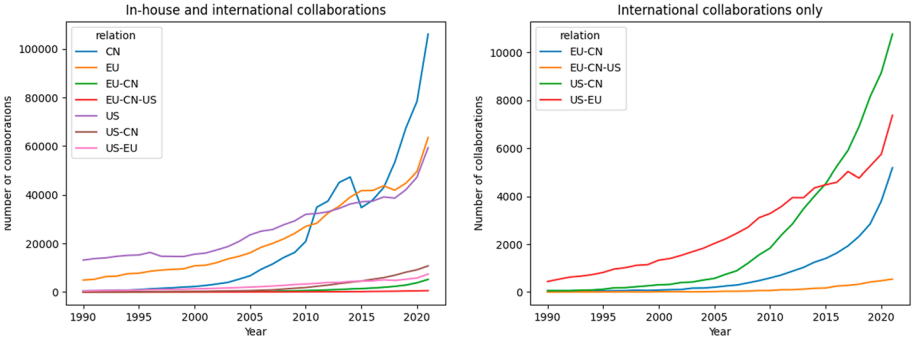

Fig. 2 Number of collaborations between regions by year

different countries have given to others. Both the EU and the US have prioritized each other. Thus, the number of co-authored papers published between the EU and the US represents 8.29% of the total published papers for the EU, and 7.23% for the US, while collaborations with China represent only 2.57% of the total for the EU and 6.27% for the US. It also suggests that China has prioritized collaborating with the US. Joint collaborations between the three regions have been minor for each concerned region, with rates between 0.28% for the US the 0.36% for China.

We have next analyzed the impact of the collaboration type, that is if the collaboration was between educational institutions, companies, or both. Although the collaboration patterns remain equal in all cases, when collaboration is done between public and private institutions, the internationalization rate is higher.

In Fig. 1, we can observe how the countries go from 77.56%, 72.38%, and 72.58% of self-collaboration for China, the EU, and the US respectively in the case of education-only co-authorship to a rate of 52.48%, 49.52%, and 53.17% in the case of collaborations between mixed institution types. In addition to this, the percentage of papers published in collaboration with institutions from the US increased either for China or the EU, going from 7.61% and 7.35% for China and the EU in the case of educational institutions only, to 23.04% and 21.90% in the cases of mixed institution types.

Although in a long-term perspective, the EU and the US were the most productive regions in terms of the number of papers published, in Fig. 2 we can observe that China became the most publishing country in 2017, followed by the EU and the US. Regarding the articles published in collaboration, the EU and the US used to be the most productive pair, but in 2014, the number of papers published by China and the US together surpassed the number of published articles coauthored by institutions from the EU and the US, becoming the two most productive publishers as we can see in Fig. 2.

It's important to note that the patterns of collaboration between these countries vary significantly. Collaborations between China and the EU and China and the US have exhibited an exponential positive tendency, indicating a rapid increase in joint publications over the years. This growth has been particularly notable, especially during the last five years. In contrast, collaborations between the EU and the US follow a different pattern. Their collaboration history appears more irregular and linear, with a less pronounced exponential trend, although in recent years, there has been a noticeable shift towards a more exponential increase in joint publications.

Table 3 Average number of citations per collaboration type

Collaboration type	CN-only	EU-only	US-only	CN–EU	CN–US	EU–US	CN–EU–US	AVG
All	13.32	21.64	37.24	24.14	27.89	38.12	32.88	27.89
Education	13.41	21.84	37.41	24.44	27.83	38.86	32.66	28.06
Company	6.41	15.4	31.95	19.59	15.87	17.8	11.11	16.88
Mixed	11.43	20.56	38.04	21.04	28.64	36.53	34.12	27.19

The number of co-authored articles between China and the EU has also been steadily increasing, with a positive tendency, similar to the one noted during the last five years between China and the US. Finally, we can observe that the number of collaborations between the three territories has been increasing, especially since 2015. This dynamic evolution in collaboration patterns underscores the shifting landscape of scientific cooperation on a global scale.

Results for the Impact in research outcomes

Apart from the articles themselves, we have measured the number of citations as the outcome of the published articles. In an overall comparison, we found that the papers published through the collaboration between the EU and the US obtained the highest citation rate with an average of 38.12 citations per paper as we can see in Table 3. It is followed by publications done by the US only with a 37.24 citation on average, and by the publications where the three regions collaborated with 32.88 average citations. The rest of the results are below an average of 30 citations per research paper. The least cited papers were those published only by Chinese institutions, with an average of 13.32 citations per paper, far from the second least cited publications, the EU only with an average of 21.64. However, China appears to have increased its rates by collaborating with the US and the EU, which also helped the EU to increase its own rates. Therefore, the collaboration between China and the US resulted in an average of 27.89 citations, as well as the collaboration between China and the EU resulted in an average of 24.14 citations, increasing the rates for both regions, China and the EU, compared to their in-house rates. We applied the ANOVA statistical method, and the result indicates a statistically significant difference among the groups: $F(6, 835449) = 2430.78$, $p = 0.000$.

Taking a closer look at the average citation counts across different collaboration types, papers authored by individuals affiliated with private companies, exhibit lower citation rates, with an average of 16.88 citations per paper. In works published by US-linked authors only, the average number of citations was 31.95, and for EU-linked authors, this number dropped to 15.4, 52% less. In China's publications, this average plummets to 6.41 citations per paper. In collaborations between the regions, the US dropped its citations when collaborating with both, China and the EU, with 15.87 and 17.8 respectively. However, from China's and Europe's perspectives, the collaborations with the US increased their rates. Also, Chinese and European collaborations brought a higher average citation rate for these countries, suggesting that the results of their partnerships tend to be more relevant than those works done within the regions.

We also analyze how the number of participants from each region affects the final number of citations. To measure it, we compute the number of participants from a region over

Table 4 Spearman correlation test results for the number of citations and the participation ratio per collaboration type

Collaboration type	CN		EU		US	
	r	*p*-value	*r*	*p*-value	*r*	*p*-value
Education	− 0.18	< .05	− 0.06	< .05	− 0.01	< .05
Company	− 0.14	< .05	0	0.63	0.07	< .05
Mixed	− 0.19	< .05	0.01	0.04	0.08	< .05
All	− 0.18	< .05	− 0.06	< .05	0	< .05

the total number of participants in the paper, obtaining a participation ratio. Then we use the Spearman Correlation Rank test to analyze if there is a correlation between the country participation ratios and the number of citations obtained. We can see in Table 4 that the number of authors publishing from the US participating in the research articles may not have an impact on the total number of citations. On the other hand, results suggest that there might be a weak negative correlation between the number of Chinese or European-affiliated authors participating in the research and the final number of citations. While for the UE, Spearman's rank correlation between the two variables is −0.06 with a corresponding p-value of < 0.05, for China this coefficient is three times higher, with a corresponding p-value of < 0.05.

Focusing on the different co-authorship types, we find that China has negative correlation values in all cases, the highest of those occurring in collaborations between Chinese companies and public institutions, where there is a negative correlation between the two variables, r (31641) = −0.19, p = < 0.05. On the other hand, the EU has no significant correlation results in all cases but education, where it obtains a negative correlation of −0.06 with a corresponding p-value of < 0.05. Finally, the US obtains positive correlation results in the collaborations between companies and between companies and public institutions, obtaining a positive correlation of 0.07 with a corresponding p-value of < 0.05 and a positive correlation of 0.08 with a corresponding p-value of < 0.05, respectively.

Results for researched topics

In this section, we analyze the main topics researched by the different regions using as input the keywords of the published scientific papers. We try to find tendencies over the years and know better in which areas the different countries are focusing.

For measuring the most studied topics during the years, we have obtained the keywords of every publication used in our study, and we have considered them as the topics of the research. As we can see in Fig. 3, in China and the UE, as well as in the case of their inter-collaborations and the collaborations with the US, some topics have grown more than others. China appears to be giving preference to fields such as "Artificial Intelligence," "Physics," "Mathematics," and "Engineering" over other disciplines. Consequently, these subjects dominate internal collaborations in terms of publications. Moreover, China seems to share an interest in these fields with the EU and the US, resulting in these four fields being the most frequent in the publications written in cooperation with each of them. Within these topics, the results suggest that China is particularly focusing on "Artificial Intelligence", which is a topic that has been more researched in the last few years. Internal

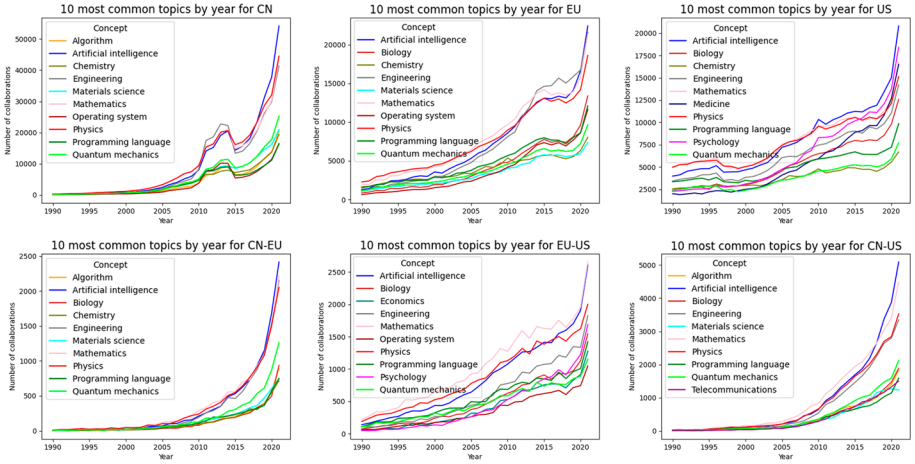

Fig. 3 Most researched topics by collaborating regions

collaborations within the EU also have those 4 topics as the most researched. However, the EU is not only focusing on artificial intelligence. In contrast to the Chinese case, the EU patterns are not repeated when collaborating with the US, being in this case less grouped. The US does not have the clustering tendency we observed in the others. Although they are also researching more in "Artificial Intelligence", it seems that they are also working on other fields such as "Psychology" or "Medicine", relating them to the topic "Computer Science". These topics are also observed when the US works with the EU, but not with China, suggesting that these are fields that may be more interesting for both.

As described in "Results for the number of collaborations", we can also see different patterns between the collaborations in Fig. 3. The patterns shown in Chinese partnerships with the EU and the US have an exponential tendency. On the other hand, the pattern drawn by the EU and US collaborations has a more linear tendency, although it has increased its tendency positively in the last few years. The different patterns are repeated within the different topics, suggesting that the publication of journal articles is stable for the different regions, being more impacted by other factors than the popularity of the topics themselves.

Discussion

In this section of the paper, we explore the meaning and significance of the research results. In addition to this, an evaluation of the results in relation to the previous studies is performed.

First, we found that the *US has been leading the research efforts in the field of Computer Science in the long term*. However, it changed in recent years, when first *China surpassed the US* in 2011, only being exceeded by the US again in 2015, and second when the EU also surpassed the US in 2013. These results provide a narrower view of the results provided by the National Science Foundation placing China and the EU as the top-most productive regions in terms of the number of publications in science and engineering (Burke et al., 2022). Because of this increase in Chinese publications, *the number of co-authored articles between China and the US surpassed the previous*

leading collaborator partners, the EU and the US, in 2014. This change leaves China and the US as the top collaborators in Computer Science.

Taking a deeper look into the different results obtained when analyzing the data based on the type of institutions that worked together, we observed that *education-company collaborations tend to be more internationalized, having a higher percentage of collaborations between the regions compared to educational and company-only co-authorships*, whereas in-home collaborations have a higher percentage of the total regions' collaborations. Locations of company headquarters or offices around the world could explain this higher internationalization rate, but it could also be a consequence of collaborator selection. Both institutions would try to find the best partner for their projects, finding it in other regions.

Second, we study the impact of the different regions when publishing their investigations, we found that those co-authored by *the EU and the US tend to have the highest number of citations*, suggesting that their findings tend to be more relevant than the others. In addition to this, results suggest that collaborating with the US also brings more citations for Chinese publications, obtaining twice as many citations than the country obtains when publishing alone. These results, added that US-only papers obtained the second-highest average number of citations, indicate that the *US has a big impact on their publications*, either when the publication is done alone or with institutions from other countries, which can be an important reason for the other countries to collaborate with the US. On the other hand, China and the EU benefit from collaboration between them too, both increasing their publication share when collaborating, compared to their works published when working within their countries only.

Our results also indicate that *articles published by Chinese companies were the least cited*, suggesting that they might not be as relevant to other researchers as those published by colleagues from the EU or the US. In collaborations within the private sector, the US stands out as the most relevant contributor, receiving an average of 39% more citations compared to the next most cited entity, which are the papers published by China and the EU together. In all cases, the average citations of company-only papers were lower than the average citations obtained by those were education and education-company collaborated, suggesting that *company-published articles have less relevance and impact*. Several factors contribute to this trend. In general, private companies often conduct research with specific industry-oriented goals, which may not align with the broader interests of the academic community. Moreover, private company research may have limited visibility within academic networks, resulting in fewer citations. Additionally, research from private companies may be published in industry-specific venues or proprietary reports, which are less accessible to academic researchers and receive fewer citations. If we analyze the case of China in particular, divergences in peer review processes, language proficiency, funding sources, and cultural influences may contribute to this disparity. While these factors impact citation rates, it's important to note that lower citation rates for private-sector research do not necessarily reflect its quality or significance, as it often serves different purposes and audiences. On the other hand, education institution authored papers obtained similar results to mixed articles with 0.87 more citations on average. Although these results can help US to understand the impact of the works published by research associated with the different territories and organization types, we need to highlight that there might be more aspects that can have an impact on the number of citations, such as the subfield, publication date, citation culture (Waltman, 2016). For example, Chinese lower citation rates could be also explained by the novelty of their works.

Lastly, we found that in *all cases but in the collaborations between the EU and the US, "Artificial Intelligence" was the most researched topic in the field of computer science*. This finding supports the conclusions drawn by Fiala and Tutoky where they conclude that this subfield is the most productive in computer science Fiala and Tutoky (2017). Focusing on the different regions, China and the EU have been prioritizing "Artificial Intelligence", "Physics", "Mathematics", and "Engineering" over others. This can also be seen when they have collaborated between themselves and the US. In contrast, *the US has had not such a clear aim. Its research topics have been broader, including topics such as "Psychology" and "Medicine"*. The EU has benefited from this wider approach by also collaborating with the US on these topics, bringing it the opportunity to work on more articles in those fields. The differences in patterns of collaboration between regions could be the consequence of different policies taken by the governments as well as different historical relationships and research capabilities. China is a relatively new scientific power, and the exponential growth of its published works could be explained by the efforts of the Chinese government to become a large R &D producer (Băzăvan, 2019; Suttmeier, 1997; Xiwei & Xiangdong, 2007). However, as mentioned by Cao and Suttmeier in their research, this intention of "technological catch-up" with the historical scientific powers rather than actual innovation might have led to a large production strategy instead of quality production (Cao & Suttmeier, 2017). Although there might be other aspects that could impact the number of citations that papers receive, this "produce more, not better" strategy could also support our results showing the low citation rates for Chinese publications. In addition to this, the difference in the collaboration patterns between China-EU/US and the EU-US might be influenced by an older and more stable relationship between the Atlantic powers. As reported in the result section, the EU and the US are the regions with the highest number of collaborations in the field of Computer Science. It indicates that the chances for building more bridges between the countries that result in more works is limited since those bridges are already built (Krige, 2008; Schmidt, 2017).

Conclusion

In this study, we aimed to analyze the collaboration patterns and tendencies in the field of Computer Science over a long time, focusing on China, the EU, and the US to provide a context on the status, benefits, and pitfalls of those collaborations.

We can draw different conclusions for the three regions. First, while China produces the greatest number of scientific articles about Computer Science, their impact is relatively low. Hence, as observed in our study, China could benefit from collaborating with the EU and the US by obtaining more relevance in the scientific community and getting more quality in their publications. Its collaboration with the EU, whose interests seem to be aligned with China's, can bring more, better, and more diversified studies for both partners.

The EU can also take advantage of co-authorship with China by accessing the most productive region, in terms of the number of published papers, and keep developing the computer science subfields the EU is interested in. However, those collaborations might not be as relevant as those produced in-house or with the US. On the other hand, collaborating with the US can bring the EU high-quality knowledge about different topics than those studied within the region and with China, gaining more relevance in other fields and broadening its expertise.

Lastly, the US can take advantage of collaborating with both China and the EU by accessing highly specialized research institutions, and in particular with the EU by creating high-impact publications, increasing the relevance and importance of their institutions. For the US, collaboration with China has similar benefits and pitfalls as for the EU, allowing the possibility of collaboration with the most productive region, but obtaining a lower impact on their publications.

Despite all the benefits for all the actors, the realm of international collaborations can be significantly influenced by economic and geopolitical decisions, that are not necessarily designed to encourage scientific collaboration and development. Therefore, we will see in future years which steps these countries decide to follow.

Limitations

Limited Data Source Analysis: This study primarily relied on papers from OpenAlex for its analysis. While OpenAlex is one of the largest academic databases, it's essential to acknowledge that different results might emerge when analyzing data from other sources. As mentioned in "Analysis" section, various data sources were examined. Still, there is potential for variations in findings when using alternative databases or sources. We recognize that our choice of data source could introduce some bias into the results, and future research might consider a more diverse set of sources to enhance the study's robustness. In addition to this, we have only analyzed journal articles for our dataset because we consider publishing in scientific journals a general practice among the different subfields of computer science, and journal articles also represent mature and trustworthy work. This selection is also justified by its potential to facilitate future research. Comparing current results with other knowledge areas, where standard publication methods may differ (e.g., proceedings papers or posted content), opens doors for valuable insights.

Geographical and Cultural Barriers: The study treated the UE27 as a single entity for simplification, which could raise concerns regarding the oversimplification of international collaborations. Existing literature has demonstrated that various barriers to collaboration, such as geographical, cultural, and political distances, can significantly impact the collaborative process (Cerdeira et al., 2023). While geographical distances might not differ significantly within Europe compared to the vast territories of China and the U.S., cultural and political distances could have a more pronounced effect on collaborations within Europe. The diversity of countries within Europe can create unique challenges in terms of international research partnerships.

Neglecting the Influence of Political and Cultural Factors: Political and cultural factors play a pivotal role in international collaborations. However, this study did not focus extensively on these aspects. Future research should consider a more in-depth investigation of the influence of funding and politics on international collaborations. For instance, exploring how a country's financial support to foreign researchers can attract talent and foster partnerships with its national research institutions is an area that could be further explored. Additionally, analyzing the impact of political factors, such as restrictive or permissive laws, on research associations can provide valuable insights into the dynamics of international collaboration. For example, restrictive laws that make obtaining visas difficult or economic incentives for international research institutions can significantly affect collaboration patterns.

Heterogeneity of Collaborations within Europe: Collaborations within Europe are subject to a unique set of challenges due to the heterogeneity of the region. The study did not extensively address these disparities, which can impact collaboration dynamics. Cultural, linguistic, and political diversity within Europe can create complexities that are distinct from collaborations within more culturally and politically homogenous regions. These complexities should be acknowledged when discussing and interpreting the results.

In summary, while this study has made valuable contributions to the understanding of international collaborations, it is important to recognize these limitations. Addressing the potential impact of data source selection, acknowledging the significance of geographical, cultural, and political distances, considering the influence of funding and politics, and acknowledging the heterogeneity of collaborations within Europe are essential for a comprehensive evaluation of the study's findings. These limitations should be clearly discussed in the study's results and limitations sections to provide a more nuanced interpretation of the research outcomes.

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Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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