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The Status of University-Industry Collaboration in China, EU and USA——A Comparative Research on Co-authored Publications

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Abstract

The type of this paper is research. Policymakers and industry strategists in developing countries are increasingly considering initiatives that foster university-industry collaboration (UIC), such as those implemented in developed economies over the past decades. Their goal is to enhance the capabilities and efficiency of innovation systems by leveraging the roles of universities as generators and disseminators of valuable knowledge, which is still highly concentrated in the academia of these nations. In this study, UICs in China, the European Union (EU), and the United States (US) are analyzed in terms of co-authored publications indexed in the Web of Science (WoS). We conducted sample comparison and regression analysis of data from the CWTS Leiden Ranking and the Times Higher Education World University Rankings. The results show a wide gap between China and the EU/US: (1) Chinese universities are much less active in collaboration with industry in terms of both publication productivity and collaboration intensity. (2) In selecting local and foreign industrial partners, however, greater variation is found among Chinese universities than among EU and US universities. The Chinese system is almost exclusively domestically oriented and the US system is oriented both nationally and internationally, whereas the EU system internationally oriented. Thus, the EU research system is possibly more open than those of the US and China. (3) In the EU, the level of university-industry collaboration is determined by the quality of the research, but in China, large research universities with strong ties to domestic industry play central roles in national publication systems.

Keywords: University-Industry Collaboration; Bibliometric Comparison; China; EU; US

Introduction

Universities are commonly regarded as influential agents in the context of a knowledge-intensive economy [1], [2]. The impact of their engagement with innovation systems is likely to be felt on regional and national levels [3]-[5]. This perception has received substantial attention from decisionmakers in both the public and private sectors who attempt to foster closer connections between academic institutions and businesses in an environment increasingly defined by open innovation [6]-[8]. For example, the increase in industrial funding of academic research in recent decades has illustrated the increasing relevance of university-industry collaboration (UIC) for innovation [9].

UIC refers to interactions between any part or parts of the higher education system and industry that are mainly aimed at encouraging knowledge and technology exchange [10], [11]. UICs have had a long history as a means of building organizations' knowledge stock [12]. These collaborations have recently increased substantially in the United States (US) [13], Japan [14], Singapore [15], and the European Union (EU) countries [16], [17]. This increase has been attributed to a combination of pressure on both industry and universities [18], [19]. For industry, rapid technological change, shorter product life cycles, and intense global competition have radically transformed the current competitive environment for most firms [20], [21].

Universities have experienced a growth in new knowledge and the challenges of rising costs and funding problems, which have led to enormous resource burdens. Thus, they seek relationships with firms to enable them to remain as close as possible to the forefront of research [22]. In addition, societal pressure is growing for universities to be engines for economic growth rather than fulfilling their previous broader social remit (i.e., education and generating knowledge) [23], [24]. Thus, pressures on both parties have led to an increasing stimulus to develop UICs that aim to enhance innovation and economic competitiveness at the institutional level (e.g., countries and sectors) via knowledge exchange between academic and commercial domains [25]. UICs have also been widely perceived as a promising tool for enhancing organizational capacity in open innovation, when an organization uses external networks to develop innovation and knowledge [26], as complementary to traditional internal R&D [27].

However, less attention has been paid to the context of developing countries, which face constraints in terms of innovation-oriented entrepreneurship [28]. Their levels of human capital are limited and often concentrated in universities [29]. The innovation systems of such countries are typically characterized by weak, inefficient ties between agents, thus making UIC externalities that may translate into further academic entrepreneurial capabilities additionally important. The research in this area mainly focuses on co-authorship in academic papers.Some scholars have used the number of co-authored publications to analyze university-industry collaboration in a given country [30], while others use the data to explore the differences between countries [31]. And we take this perspective to examine university-industry co-authored publications to address the following questions regarding China, the EU, and the US. How do the macro-level UIC-based results relate to the systemic differences among these three regions? How do the meso-level UIC-data, at the university level, relate to data on research income/expenditure? Which region is most "efficient" in terms of output and input?

Data and Methods

This study uses 2018 UIC data from 2013 to 2016 (available at http://www.leidenranking.com/ranking/2018). (The data is updated every four years, so the 2013-2016 data is newest at the time of writing..) The publication productivity of UICs of the 938 largest research universities in the world are listed in the CWTS Leiden Ranking 2018, which is also a data source for our study. The relevant data were downloaded and processed for our research objectives.

The indicators include UIC productivity, UIC intensity, and indexes that describe various types of collaboration. UIC productivity is defined as the number of publications that include both university and industrial addresses, and UIC intensity (i.e., %UIC) is the percentage of UIC productivity relative to the total number of publications of a university indexed in the Web of Science (WoS).

The UIC data of the Leiden Ranking enables quantitative studies of university-industry collaboration in terms of academic publication activities at both the macro- and meso-levels for countries, regions, and individual research institutions. Most of the indicators are effective and can be used independently, except UIC intensity: universities with a high UIC intensity are not necessarily active in collaborating with industry, and vice versa. Nonetheless, when taken together with UIC productivity, UIC intensity still has its value: a university with high values on both indicators will be more active in collaborating with industry than those with only a high productivity value.

UIC can be divided into UIC Local and UIC Foreign, depending on the physical distance between a university and its partner. UIC Local (%Local) measures the percentage of UIC publications of a university collaborating with industry within a 100-km radius from the center of the city in which the university (or its main campus) is located. This indicator can reflect the relative propensity to engage with partners nearby or within the same urban agglomeration. The UIC Foreign (%Foreign) is the percentage of UIC publications that involve a partner located abroad, which reflects the internationalization of a university in its collaborations.

The 2018 data cover 148 universities in China, 308 in the EU, and 175 in the U.S. The publications are classified into five broad fields: "Biomedical and Health Sciences," "Life and Earth Sciences," "Mathematics and Computer Science," "Physical Sciences and Engineering," and "Social Sciences and Humanities." Each publication in the Web of Science database was assigned to one of these seven fields by a computer algorithm. More details can be found at http://www.leidenranking.com/information/fields.

Not all 148 Chinese, 308 EU, and 175 US universities are active in publishing with industries in all seven fields. For example, no UIC Social Sciences and Humanities papers are indexed in the WoS in 2013-2016 for one of the US, two of the Chinese, and three of the EU universities covered by the Leiden Ranking of 2018. No Mathematics and Computer Science papers are indexed for one of the Chinese and five of the EU universities, respectively. In the Life and Earth Sciences, all EU, Chinese, and US universities are active in collaborations with industry, except the Medical University of Silesia from the EU, which does not have any UIC papers in the studied period.

To enhance reliability, we focus on fields that provide sufficient UIC publications among the universities. "Biomedical and Health Sciences" and "Physical Sciences and Engineering" satisfy this condition. Publications in the "All sciences" category reflect the overall UIC performance of a country, and thus are also analyzed. The study is based on the 2018 UIC data, so Chinese, EU, and US universities not yet included in this data are not discussed. Financial factors play a significant role in UICs [32], so industry-related income and expenditure of universities are used for linear regression analysis. We use the World University Rankings 2015-2016, which provides various data on industry income, research influence, learning environment, and staff size.

This paper mainly uses two research methods, namely, comparative analysis of samples and regression analysis. Comparative analysis of samples is often used to compare the similarities and differences between different subjects, such as countries [33]. By using the method of sample comparative analysis, the data of China, the US and the EU in different disciplines were compared to study the UIC situation of the three countries in different disciplines. And multiple linear regression is a common research method in data analysis, which is used to analyze the influence of multiple independent variables on dependent variables [34].We use the regression analysis method to find the main influencing factors of UIC in China, the US and the EU. Stata 15.1 is used for statistical analyses.

Findings

The 2018 Leiden Ranking covers 938 universities, with 148 from China. This accounts for only 5.78% of the 2,560 higher education institutions in China (National Bureau of Statistics of the People's Republic of China, 2016. Available at http://www.stats.gov.cn/tjsj/ndsj/2016/indexch.htm). This low inclusion rate implies that Chinese universities have a long way to go in terms of publishing internationally, even though China has been the second-largest producer of international publications for some years [35].

UIC in all sciences

Publication productivity

Harvard University is in the first position for all sciences, with publication productivity being nearly twice that of the University of Toronto in the second position worldwide (Table 1). Of the Chinese universities, Shanghai Jiao Tong University takes the lead, with 1,051 publications more than Zhejiang University in second place. In the EU, half of the 10 most productive universities are from the UK, and the level of variation in publication productivity among them is lower than that of the Chinese and US universities.

When comparing the leading universities of the three regions, the differences in the total numbers of publications have gradually reduced, except Harvard University. In particular, the publication productivity gap between the US and Chinese universities at the same domestic rank reached 1.3 times on average, but was at least 1.6 times 10 years before. At the same level, the gap between China and the EU is smaller than that between China and the US.

In the US, Harvard University keeps the first position throughout, Johns Hopkins University drops one spot, and the University of Michigan is replaced by Stanford University. As in China, three of the 10 high-producing US universities—Columbia University, the University of Pennsylvania, and the University of California at Berkeley—are replaced by the University of California at San Diego, the Massachusetts Institute of Technology, and the University of California at San Francisco when rated in terms of publishing with industry partners.

Table 1: Top 10 Universities in Domestic Ranking in publications in "All Sciences"

Rank	University（China）	P[1]	University（EU）	P	University（USA）	P
1	Shanghai Jiao Tong University	33,169	University of Oxford	33,973	Harvard University	71,634
2	Zhejiang University	32,118	University College London	33,708	Johns Hopkins University	37,273

3	Tsinghua University	29,130	University of Cambridge	29,490	University of Michigan	36,152
4	Peking University	28,874	Sorbonne University	28,554	Stanford University	33,653
5	University of Chinese Academy of Sciences	27,041	Imperial College London	27,057	University of Washington	33,290
6	Fudan University	22,738	University of Copenhagen	24,452	University of California, Los Angeles	30,377
7	Sun Yat-sen University	20,991	Katholieke Universiteit Leuven	22,692	Columbia University	28,914
8	Huazhong University of Science and Technology	19,980	Utrecht University	21,737	Duke University	28,722
9	Shandong University	19,659	University of Amsterdam	21,698	University of Pennsylvania	28,534
10	Sichuan University	19,431	University of Manchester	20,842	University of California, Berkeley	26,707

1 "P" is the abbreviation of publications, similarly hereinafter.

In the EU, there is little difference in the top three universities between the UIC figures and publication productivity, in which Imperial College London places first, and the former top three of the University of Oxford, University College London, and the University of Cambridge each drop one spot. Cambridge, in fact, drops out of the top three. Thus, in Europe, UK universities showed the most enthusiasm for UIC. Compared with the leading universities of China and the US, the leading EU universities do better in their collaborations with industry. Only two of the leading universities—the Sorbonne and the University of Amsterdam—are replaced by Karolinska Institutet and Freie Universität Berlin (Tables 1 and 2). In a single region or country, the gaps in UIC between universities are small, with the data reporting differences of about 200 to 300. Harvard and Stanford Universities are the exceptions.

Table 2: Top 10 Universities in Domestic Ranking in UIC productivity in "All Sciences"

Rank	University（China）	P(UIC)	University（EU）	P(UIC)	University（USA）	P(UIC)
1	Tsinghua University	1,581	Imperial College London	2,192	Harvard University	4,998
2	Shanghai Jiao Tong University	1,416	University of Oxford	2,156	Stanford University	2,967
3	Zhejiang University	1,323	University College London	2,040	Johns Hopkins University	2,671
4	Peking University	1,162	University of Cambridge	2,013	Duke University	2,488
5	Fudan University	875	University of Copenhagen	2,005	**University of California, San Diego**	2,446
6	**China University of Petroleum Beijing**	844	Katholieke Universiteit Leuven	1,824	University of Washington	2,389
7	Huazhong University of Science and Technology	809	**Karolinska Institutet**	1,707	University of California, Los Angeles	2,255
8	**Xi'an Jiaotong University**	786	University of Manchester	1,705	University of Michigan	2,236
9	University of Chinese Academy of Sciences	726	Utrecht University	1,604	**Massachusetts Institute of Technology**	2,211
10	**Tianjin University**	720	**Freie Universität Berlin**	1,592	**University of California, San Francisco**	2,061

By parallel comparison, in terms of UIC productivity, the enthusiasm of the leading Chinese universities seems significantly lower than those of their European and American counterparts. The numbers of UIC publications for each of the leading US universities are at least twice that of the leading Chinese universities at the same domestic rank. For example, Tsinghua University, the largest UIC publication producer of China, published 1,581 papers, which is comparable with that of the University of Minnesota at Twin Cities (with 1,576 UIC papers) between 2013 and 2016, which occupies 15th position on the list of 175 US universities in the 2018 Leiden Ranking. In first position in China, Tsinghua University is approximately equal to Freie Universität Berlin, which is in the 10th position in the EU.

Table 3: Top 10 Universities in Domestic Ranking in UIC intensity in "All Sciences"

Rank	University (China)	P(UIC)	%UIC	University（EU）	P(UIC)	%UIC	University（USA）	P(UIC)	%UIC
1	**China University of Petroleum Beijing**	844	25.3%	Eindhoven University of Technology	950	15.4%	Colorado School of Mines	282	11.6%
2	Southwest Petroleum University	395	22.8%	Semmelweis University	408	12.8%	Missouri University of Science & Technology	229	10.9%
3	China University of Petroleum East China	443	13.8%	Graz University of Technology	362	12.6%	Icahn School of Medicine, Mount Sinai	1,195	9.6%
4	Shenyang Pharmaceutical University	173	8.4%	Chalmers University of Technology	764	12.5%	Rensselaer Polytechnic Institute	299	9.3%
5	China University of Geosciences	609	8.1%	University of Tampere	454	12.0%	University of Maryland, Baltimore	857	9.2%
6	China Pharmaceutical University	293	7.9%	Luleå University of Technology	244	11.9%	**University of California, San Diego**	2,446	9.2%
7	University of Science and Technology Beijing	586	7.6%	Budapest University of Technology and Economics	290	11.3%	Oregon Health & Science University	742	9.1%
8	Jiangnan University	446	7.5%	Technical University of Denmark	1,202	11.2%	Thomas Jefferson University	431	8.9%
9	Beijing University of Posts & Telecommunications	253	6.1%	Cranfield University	244	11.2%	**University of California, San Francisco**	2,061	8.9%
10	North China Electric Power University	204	5.9%	Delft University of Technology	1,097	11.0%	Georgia Institute of Technology	1,114	8.8%

Table 4: Collaboration Distance of Top 10 Chinese Universities in UIC Productivity in "All Sciences"

Rank	University（China）	P(collab[1])	%Foreign	%Local	University（EU）	P(collab)	%Foreign	%Local	University（USA）	P(collab)	%Foreign	%Local
1	University of Chinese Academy of Sciences	26,641	21.6%	20.4%	University College London	28,465	**73.5%**	17.5%	Harvard University	59,953	**58.0%**	16.7%
2	Peking University	22,649	46.8%	20.9%	University of Oxford	27,869	**79.8%**	10.7%	Johns Hopkins University	30,489	**51.0%**	10.7%
3	Shanghai Jiao Tong University	22,540	43.4%	24.2%	Sorbonne University	27,133	**67.4%**	17.1%	University of Washington	27,418	46.9%	9.1%
4	Zhejiang University	21,297	43.4%	17.6%	University of Cambridge	24,014	**80.7%**	9.1%	University of Michigan	27,321	47.7%	6.2%
5	Tsinghua University	20,917	46.9%	20.7%	Imperial College London	22,534	**79.4%**	13.5%	Stanford University	27,064	**53.5%**	9.8%
6	Fudan University	16,315	41.7%	25.0%	University of Copenhagen	19,737	**78.8%**	16.5%	University of California, Los Angeles	24,660	**51.7%**	9.4%
7	Sun Yat-sen University	15,430	37.3%	22.1%	Katholieke Universiteit Leuven	18,805	**80.5%**	21.3%	Duke University	24,440	47.6%	9.9%
8	Nanjing University	14,407	39.8%	18.6%	University of Amsterdam	18,710	**66.9%**	23.4%	Columbia University	24,142	**52.8%**	11.5%
9	Shandong University	13,612	34.1%	20.1%	Utrecht University	18,481	**65.4%**	26.8%	University of Pennsylvania	22,725	42.6%	11.2%
10	Huazhong University of Science and Technology	13,289	39.2%	20.2%	Karolinska Institutet	17,484	**75.2%**	16.0%	University of California, Berkeley	21,991	**59.5%**	8.7%

1 "Collab" is the abbreviation of collaborations, similarly hereinafter.

UIC intensity is measured by the percentage of UIC publications in the total number of publications of a university indexed in the WoS (%UIC), and a different list of universities emerges (Table 3). The use of the UIC intensity generated different results from those based on UIC publications. Most of the Chinese universities leading in UIC productivity disappear from the top 10 list in terms of UIC intensity, except China University of Petroleum Beijing. This implies that this university performs relatively well in both UIC productivity and intensity. In addition, the top three leading Chinese universities in terms of UIC intensity are all petroleum universities, which reflects their close collaboration with industry, due to specific industrial attributes and historical backgrounds. A similar situation can be observed for US universities, as most of those leading in UIC productivity no longer appear on the top 10 list of UIC intensity, with the exception of the University of California San Francisco and the University of California San Diego, which perform well in terms of both UIC productivity and intensity. Interestingly, the list for the EU is completely different, with 70% being technical universities. Thus, for the leading EU universities, UIC productivity is not increasing in parallel with publication productivity, and technical universities were found to have relatively more enthusiasm for UIC.

Compared to the EU and the US, although each of the top three Chinese universities performs better on UIC intensity, the inequality is still obvious for the UIC intensity list (Table 3). Fourteen US universities and 31 EU universities included in the 2018 Leiden Ranking have a UIC intensity greater than 8.4%, which is the level of Shenyang Pharmaceutical University, which ranks 4th among Chinese universities. Thus, except for the top three, the UIC intensity of the Chinese universities is significantly lower than those of the EU and the US.

Collaboration distance

Each of the Chinese universities that lead in collaboration publications collaborates more with domestic than foreign partners, and the variation is high. Not surprisingly, the University of Hong Kong, the Chinese University of Hong Kong, and Hong Kong University of Science and Technology have strong ties (>50%) with foreign partners due to their specific locations and historical backgrounds. Central China Normal University also collaborates with foreign more than domestic partners (i.e., within mainland China). Most partners of the leading Chinese universities are located further than 100 km from the center of the city in which the university (or its main campus) is located (Table 4), which implies that geographical distance is less important in determining domestic collaborations in China. In contrast to the finding that leading Chinese universities have different preferences in their collaborations with domestic and foreign partners, a high percentage of the leading universities in the US, and particularly in the EU, collaborate with foreign partners. As in China, distance is not particularly important in establishing collaborations.

UIC in Biomedical and Health Sciences

Publication productivity

The US universities dominate the field of Biomedical and Health Sciences, with eight on the list of the top 10 most productive worldwide. The first position in the Biomedical and Health Sciences is, by a significant margin, held by Harvard University which is the only one with more than 50,000 publications, with 51,076 publications: nearly twice that of the Johns Hopkins University in the second position worldwide (Table 5). In China, Shanghai Jiao Tong University is still top with nearly 3,000 publications more than that of the second (Fudan University). Each of the first five Chinese universities, Shanghai Jiao Tong, Fudan, Sun Yat-sen, Peking, and Zhejiang, produced more than 10,000 papers during the period 2013-2016. In the EU, each of the top 10 universities published more than 10,000 papers.

The productivity of the leading EU and US universities is higher than that of Chinese universities at the same rank. China's first position university has less productivity than the 13th university in the US. Variation in the publication productivity of the top 10 US universities is higher than that of the universities in China and the EU. As the largest publication producer, Harvard University published 33,400 papers more than the University of Texas Health Science Center at Houston, at the 10th position, whereas the publication difference between the first and 10th universities in China and EU is only 8,087 and 7,518, respectively.

Table 5: Top 10 Universities in Domestic Ranking in publications in the "Biomedical and Health Sciences"

Rank	University（China）	P	University（EU）	P	University（USA）	P
1	Shanghai Jiao Tong University	15,843	University College London	19,661	Harvard University	51,076
2	Fudan University	12,939	Karolinska Institutet	17,683	Johns Hopkins University	27,779
3	Sun Yat-sen University	11,522	University of Oxford	14,970	University of California, San Francisco	20,678
4	Peking University	10,858	University of Amsterdam	13,519	University of Pennsylvania	20,001
5	Zhejiang University	10,228	University of Copenhagen	13,226	University of Michigan	19,908
6	Capital Medical University	9,191	Utrecht University	13,181	University of Washington	19,873
7	Sichuan University	8,682	Imperial College London	12,997	Duke University	19,577
8	Shandong University	8,401	King's College London	12,687	University of Pittsburgh	18,116
9	Peking Union Medical College	8,215	Erasmus University Rotterdam	12,296	Stanford University	18,059
10	Nanjing Medical University	7,756	Heidelberg University	12,143	University of Texas Health Science Center at Houston	17,676

University-industry collaboration (UIC)

In the field of Biomedical and Health Sciences, the most productive universities have not yet shown that they are particularly interested in collaborations with industry. Of the leading publication producers in China, only two, Shandong University and Nanjing Medical University, are not present in this list, replaced by Huazhong University of Science and Technology and the Chinese University of Hong Kong in the top 10 list of university-industry collaboration. The situation is similar in the US: two universities, the University of Michigan and the University of Pittsburgh, are replaced by the University of California at San Diego and the University of California at Los Angeles. In the EU, three leading publication producers are not present and are replaced by Freie Universität Berlin, Humboldt-Universität zu Berlin, and Katholieke Universiteit Leuven. Nevertheless, the gap between Chinese universities and

EU/US universities is wide. For example, the first UIC producer of these three regions, Peking University, produced only 502 UIC papers in 4 years (2013-2016), whereas Karolinska Institutet has over three times more. The UIC publication rate of Harvard University was nearly eight times higher than that of Peking University. As the 10th UIC paper producer of China, the Chinese University of Hong Kong only generated 229 UIC papers, far fewer than that of the 10th UIC paper producer of the EU and the US (i.e., Utrecht University and the University of California at Los Angeles, respectively) (Table 6).

In terms of UIC intensity, a completely different list of universities is produced, particularly for China and the EU (Table 7). None of the EU and Chinese leading universities in university-industry collaboration publication lists are present in the list of UIC intensity, which also means that their rate of publication productivity and collaborations with industry is not consistent. Furthermore, among the leading Chinese universities in terms of UIC intensity, local colleges occupy the dominant positions, which implies that there are strong ties between these colleges and industry, due to specific industrial attributes and historical backgrounds. Compared to the EU and China, the US universities do relatively well in terms of UIC intensity, with three leading universities, the University of California at San Diego, Duke University, and Stanford University, holding their positions in collaborations with industry both in productivity and intensity. The UIC intensity of the leading Chinese universities again lags far behind their EU and US counterparts, and the situation is worse than in "All Sciences". Of those included in the Leiden Rankings, 22 US universities and 87 EU universities have a UIC intensity larger than 8.6%, which is the level of Shenyang Pharmaceutical University that ranks first among the Chinese universities.

Table 6: Top-10 Universities in Domestic Ranking in Collaborations with Industry in the "Biomedical and Health Sciences"

Rank	University(China)	P(UIC)	University（EU）	P(UIC)	University（USA）	P(UIC)
1	Peking University	502	Karolinska Institutet	1,569	Harvard University	3,952
2	Fudan University	464	University College London	1,332	Johns Hopkins University	2,104
3	Shanghai Jiao Tong University	452	University of Copenhagen	1,327	Duke University	1,986
4	Peking Union Medical College	396	**Freie Universität Berlin**	1,312	University of California, San Francisco	1,871
5	Sun Yat-sen University	322	**Humboldt-Universität zu Berlin**	1,250	Stanford University	1,766
6	Zhejiang University	299	University of Oxford	1,247	University of Washington	1,590
7	Capital Medical University	280	Heidelberg University	1,232	**University of California, San Diego**	1,567
8	Sichuan University	236	Imperial College London	1,225	University of Pennsylvania	1,553
9	**Huazhong University of Science and Technology**	234	**Katholieke Universiteit Leuven**	1,140	University of Texas Health Science Center at Houston	1,512
10	**Chinese University of Hong Kong**	229	Utrecht University	1,090	**University of California, Los Angeles**	1,494

Collaboration distance

As in the outcomes for "All Sciences", each of the leading Chinese universities collaborates domestically in the Biomedical and Health Sciences. However, domestic collaboration in terms of the distance between a university and its partners varies greatly: 17.8% of the UIC papers of Sichuan University are local collaborations, whereas that of Peking Union Medical College is 55.4% (Table

8). Similarly, nearly all of the US universities that lead in collaboration publications collaborate more with domestic than foreign partners, with Harvard University (55.9%) and the University of Texas Health Science Center at Houston (50.2%) publishing more papers with foreign than with domestic partners. Conversely, the other eight universities publish more with domestic than with foreign partners, with the University of Pennsylvania as the extreme. In terms of the domestic partners of the leading universities, more than 10% are located at most 100 km from the center of the city in which the university (or its main campus) is located, with the University of Michigan as the exception (Table 8). In the Biomedical and Health Sciences, however, most university-industry collaborations of the leading EU universities are foreign, and the variation in the foreign collaboration percentage among the leading universities is much greater than that among Chinese and US universities. As for the distance of domestic collaboration, most industrial partners of the leading EU universities are located more than 100 km from the center of the city in which the university (or its main campus) is located.

Table 7: Top 10 Universities in Domestic Ranking in UIC Intensity in the "Biomedical and Health Sciences" (2013–2016)

Rank	**University (China)**	**P(UIC)**	**%UIC**	**University（EU）**	**P(UIC)**	**%UIC**	**University（USA）**	**P(UIC)**	**%UIC**
1	Shenyang Pharmaceutical University	117	8.6%	Budapest University of Technology and Economics	63	18.8%	Missouri University of Science & Technology	25	18.7%
2	Guangdong University of Technology	12	8.2%	Eindhoven University of Technology	140	16.9%	University of Rhode Island	79	13.4%
3	China Pharmaceutical University	200	8.1%	Chalmers University of Technology	91	14.7%	Baylor University	150	11.5%
4	University of Science and Technology Beijing	13	7.9%	Technical University of Denmark	239	14.1%	Georgetown University	343	11.2%
5	Tianjin Polytechnic University	11	7.9%	University of Natural Resources and Life Sciences, Vienna	68	13.6%	Massachusetts Institute of Technology	819	10.8%
6	Zhejiang University of Technology	31	7.7%	University of Tampere	396	13.6%	Colorado School of Mines	13	10.6%
7	Changzhou University	11	7.7%	Semmelweis University	360	12.6%	**University of California, San Diego**	1,567	10.3%
8	Jiangnan University	84	7.4%	Kiel University	402	12.0%	**Duke University**	1,986	10.1%
9	Yunnan University	23	7.2%	University of Szeged	184	11.7%	Icahn School of Medicine, Mount Sinai	1,126	9.8%
10	University of Shanghai for Science and Technology	14	7.0%	Graz University of Technology	62	11.7%	**Stanford University**	1,766	9.8%

Table 8: Collaboration Distance of Top 10 Universities of China in UIC Publications in the "Biomedical and Health Sciences" (2013–2016)

Rank	**University (China)**	**P(collab)**	**%Foreign**	**%Local**	**University（EU）**	**P(collab)**	**%Foreign**	**%Local**	**University（USA）**	**P(collab)**	**%Foreign**	**%Local**
1	Shanghai Jiao Tong University	10,723	36.4%	30.3%	University College London	16,875	**71.2%**	20.6%	Harvard University	42,424	**55.9%**	19.5%
2	Fudan University	9,251	37.7%	29.4%	Karolinska Institutet	15,415	**75.9%**	15.7%	Johns Hopkins University	22,595	48.8%	11.4%
3	Peking University	8,203	41.4%	24.7%	University of Oxford	12,802	**76.1%**	12.9%	University of California, San Francisco	17,344	46.3%	10.6%
4	Sun Yat-sen University	8,142	32.9%	25.3%	University of Amsterdam	11,872	**61.6%**	26.2%	Duke University	16,806	44.3%	11.8%
5	Zhejiang University	6,787	36.6%	22.3%	Utrecht University	11,401	**60.8%**	29.3%	University of Washington	16,781	42.3%	11.4%
6	Capital Medical University	6,744	37.4%	29.6%	Freie Universität Berlin	11,191	**54.0%**	10.7%	University of Pennsylvania	16,272	38.9%	12.9%
7	Shandong University	6,000	28.3%	24.6%	Imperial College London	11,173	**76.0%**	17.8%	University of Michigan	15,195	40.9%	8.0%
8	Peking Union Medical College	5,863	32.7%	55.4%	Humboldt-Universität zu Berlin	11,041	**53.8%**	10.9%	Stanford University	14,997	47.8%	10.3%
9	Nanjing Medical University	5,627	25.7%	27.1%	King's College London	10,899	**70.3%**	21.6%	University of Texas Health Science Center at Houston	14,365	**50.2%**	10.9%
10	Sichuan University	5,109	35.8%	17.8%	Erasmus University Rotterdam	10,464	**65.2%**	24.6%	University of California, Los Angeles	14,303	45.4%	11.4%

UIC in Physical Sciences and Engineering

Publication productivity

The outcome is again different in the field of Physical Sciences and Engineering. The US universities no longer dominate the list of publication productivity, and the Chinese universities have seven universities in the list of the top 10 most productive universities worldwide. Among the Chinese universities, Tsinghua University takes the absolute lead, with 3,788 publications more than the second, the University of Chinese Academy of Sciences. Unlike the field of Biomedical and Health Sciences, the productivity of the leading universities in China is significantly higher than that of US and EU universities and has a high level of variation. The number of publications is at least 1.2 times of those of US and EU universities at the same domestic rank. In the EU and the US, the gap at the same domestic rank is small (Table 9).

Table 9: Top 10 Universities in Domestic Ranking in publications in "Physical Sciences and Engineering"

Rank	University（China）	P	University（EU）	P	University（USA）	P
1	Tsinghua University	16,807	University of Cambridge	10,482	University of California, Berkeley	11,289
2	University of Chinese Academy of Sciences	13,019	Sorbonne University	10,367	Massachusetts Institute of Technology	11,089
3	Zhejiang University	12,303	University of Oxford	8,591	Harvard University	8,980
4	University of Science and Technology of China	11,274	Imperial College London	8,232	California Institute of Technology	8,185
5	Shanghai Jiao Tong University	11,228	Paris-Sud University	8,105	University of Michigan	7,745
6	Peking University	10,868	Université Grenoble Alpes	7,543	Stanford University	7,322
7	Harbin Institute of Technology	10,615	Karlsruhe Institute of Technology	7,485	University of Texas at Austin	6,849
8	Jilin University	9,964	University College London	6,517	Pennsylvania State University	6,662
9	Nanjing University	9,327	University of Manchester	6,398	University of Maryland, College Park	6,487
10	Xi'an Jiaotong University	9,281	KTH Royal Institute of Technology	6,009	University of Illinois, Urbana-Champaign	6,405

University-industry collaboration (UIC)

In Physical Sciences and Engineering, Tsinghua University still performs well in coauthoring with industry, with many more than those of other universities in China and in the EU. Among the 10 most productive Chinese universities, the University of Science and Technology of China, Jilin University, and Nanjing University are replaced by Petroleum Beijing, the University of Science and Technology Beijing, and Tianjin University when rated in terms of publishing with industry. Similarly, of the 10 most productive EU universities, Sorbonne University, Paris-Sud University, and University College London are replaced by Eindhoven University of Technology, the Technical University of Denmark, and Delft University of Technology when rated in terms of publishing with industry. Of the leading productive US universities, California Institute of Technology, the University of Maryland at College Park, and the University of Illinois at Urbana-Champaign are replaced by Princeton University, Georgia Institute of Technology, and Purdue University at West Lafayette when rated in terms of publishing with industry (Tables 9 and 10).

Of the leading Chinese universities collaborating with industry, the China University of Petroleum Beijing and the University of Science and Technology Beijing (Table 10) also take the lead in terms of UIC intensity, which implies that these universities perform relatively well in both UIC productivity and intensity. Furthermore, among the leading Chinese universities in UIC intensity, the top three universities are the China University of Petroleum Beijing, Southwest Petroleum University, and China University of Petroleum East China, which implies the close collaboration between the petroleum universities and industry due to specific industrial attributes and historical backgrounds. Similar situations are also found in the EU and the US, as most of the universities leading in UIC productivity no longer appear on the top 10 list of universities in terms of UIC intensity, with the exception of Eindhoven University of Technology in the EU, but with none in the US. Thus, the UIC productivity of most universities is not growing in parallel with intensity, and among the leading US universities in UIC intensity, Icahn School of Medicine at Mount Sinai takes the second position with a UIC intensity of 13.7%, although its UIC productivity is only 17.

Table 10: Top 10 Universities in Domestic Ranking in UIC productivity in "Physical Sciences and Engineering"

Rank	University (China)	P(UIC)	University（EU）	P(UIC)	University（USA）	P(UIC)
1	Tsinghua University	781	University of Cambridge	674	Massachusetts Institute of Technology	797
2	Shanghai Jiao Tong University	630	Karlsruhe Institute of Technology	596	University of California, Berkeley	661
3	Zhejiang University	571	KTH Royal Institute of Technology	589	Stanford University	655
4	**China University of Petroleum Beijing**	507	Imperial College London	576	University of Texas at Austin	563
5	**University of Science and Technology Beijing**	497	**Eindhoven University of Technology**	569	**Princeton University**	545
6	**Tianjin University**	478	**Technical University of Denmark**	566	**Georgia Institute of Technology**	540
7	Xi'an Jiaotong University	472	**Delft University of Technology**	557	University of Michigan	536
8	Harbin Institute of Technology	434	University of Oxford	501	**Purdue University, West Lafayette**	494
9	University of Chinese Academy of Sciences	375	Université Grenoble Alpes	460	Pennsylvania State University	492
10	Peking University	355	University of Manchester	443	Harvard University	482

Collaboration distance

The collaboration distance of Chinese universities obviously varies, and each of the leading Chinese universities collaborates more domestically in the field of Physical

Sciences and Engineering. For example, Shanghai Jiao Tong University mainly (49.2%) collaborates with foreign partners, whereas some (e.g., University of Chinese Academy of Sciences) have relatively weak (15.6%) ties with foreign partners. Most of the partners of the leading Chinese universities in UIC productivity are located farther than 100 km from the center of the city in which the university (or its main campus) is located (Table 12). In contrast to the leading Chinese universities, which have different preferences in their collaborations with domestic and foreign partners, a high percentage of the leading universities in the EU/US collaborate with foreign partners, and particularly in the EU. Besides, the percentage of partners of the EU/US universities leading in UIC productivity located farther than 100 km from the center of the city in which the university (or its main campus) is located is higher than that of China.

Table 11: Top 10 Universities in Domestic Ranking in UIC intensity in "Physical Sciences and Engineering"

Rank	University (China)	P(UIC)	%UIC	University（EU）	P(UIC)	%UIC	University（USA）	P(UIC)	%UIC
1	**China University of Petroleum Beijing**	507	22.6%	University of Tampere	29	28.6%	George Mason University	123	18.9%
2	Southwest Petroleum University	290	22.2%	Universität zu Lübeck	26	22.0%	Icahn School of Medicine, Mount Sinai	17	13.7%
3	China University of Petroleum East China	322	14.8%	Semmelweis University	35	20.8%	University of California, San Francisco	51	11.9%
4	Hebei Medical University	17	13.0%	**Eindhoven University of Technology**	569	16.7%	Colorado School of Mines	145	11.0%
5	China University of Geosciences	212	8.7%	University of Natural Resources and Life Sciences, Vienna	77	14.4%	Oregon State University	134	10.6%
6	Shanghai University of Traditional Chinese Medicine	14	8.1%	Luleå University of Technology	144	14.2%	University of Nevada, Reno	74	10.4%
7	**University of Science and Technology Beijing**	497	8.1%	Graz University of Technology	208	13.8%	University of Colorado, Denver	41	10.2%
8	China Pharmaceutical University	76	7.7%	University of Gothenburg	107	13.5%	Baylor College of Medicine	17	9.9%
9	Shenyang Pharmaceutical University	42	7.7%	Medical University of Innsbruck	14	13.3%	University of California, San Diego	475	9.7%
10	Northeastern University	275	7.5%	Aalborg University	128	13.3%	Rensselaer Polytechnic Institute	174	9.7%

Table 12: Collaboration Distance of Top 10 Chinese Universities in UIC Productivity in "Physical Sciences and Engineering"

Rank	University (China)	P(collab)	%Foreign	%Local	University（EU）	P(collab)	%Foreign	%Local	University（USA）	P(collab)	%Foreign	%Local
1	University of Chinese Academy of Sciences	12,819	15.6%	19.7%	Sorbonne University	9,910	**73.4%**	13.7%	University of California, Berkeley	9,526	**69.1%**	6.8%
2	Tsinghua University	11,528	43.3%	21.9%	University of Cambridge	8,455	**87.2%**	5.0%	Massachusetts Institute of Technology	8,870	**71.3%**	6.5%
3	Peking University	8,692	44.1%	20.7%	Paris-Sud University	7,550	**74.6%**	13.4%	Harvard University	8,023	**75.3%**	7.3%
4	University of Science and Technology of China	8,295	42.0%	15.7%	Université Grenoble Alpes	7,180	**70.9%**	13.6%	California Institute of Technology	6,965	**75.8%**	2.5%
5	Zhejiang University	7,590	43.8%	14.8%	University of Oxford	6,973	**85.6%**	7.1%	University of Michigan	5,778	**68.0%**	3.2%
6	Shanghai Jiao Tong University	7,307	49.2%	20.0%	Imperial College London	6,522	**83.1%**	9.2%	Stanford University	5,650	**71.1%**	11.0%
7	Nanjing University	7,156	38.0%	16.9%	Karlsruhe Institute of Technology	5,963	**74.9%**	7.9%	University of Maryland, College Park	5,376	**67.5%**	11.2%
8	Harbin Institute of Technology	6,552	39.1%	14.0%	University College London	5,581	**81.9%**	10.1%	Pennsylvania State University	5,161	**67.2%**	1.6%
9	Jilin University	6,083	29.6%	21.9%	Paris Diderot University	5,438	**81.6%**	9.6%	University of Texas at Austin	4,942	**67.2%**	2.3%
10	Tianjin University	5,832	31.0%	34.9%	Claude Bernard Lyon 1 University	5,405	**64.3%**	11.0%	Princeton University	4,876	**70.1%**	4.8%

Regression analysis

To establish the drivers of UIC, we performed linear regression with UIC as the dependent variable. Only large research-active universities that satisfy the following conditions are included in this analysis. First, the university should be listed in the Leiden Ranking 2018. Secondly, due to data source limitations, we must use another source for the input (funding) data of Chinese, EU, and US universities. The input data (funding) from the Times Higher Education World University Rankings 2016 includes more than 1,250 universities, so this article uses the data as one of the independent variables. In total, 40 Chinese, 175 EU, and 64 US universities (Appendix) satisfy the above conditions and are used in the regression analysis (Table 13). K-S nonparametric test of standardized residuals was carried out, and it's found that there was no significant difference between standardized residuals and standard normal distribution, so it can be considered that the residuals meet the prerequisite of linear model.

Table 13: Linear Regression Results of "all science"

	China	**USA**	**EU**
(Constant)	-4.47***	-4.44**	-4.83***
	(0.71)	(0.34)	(0.40)
Total research publication output	1.08***	1.03***	0.98***
	(0.08)	(0.04)	(0.05)
Income from industry	0.22*	0.28***	0.38***
	(0.13)	(0.08)	(0.07)
MNCS	-0.50	0.20	0.53***
	(0.33)	(0.13)	(0.14)
R-squared	0.89	0.95	0.83
F value	100.72***	485.60***	283.26***
VIF	1.01~1.47	1.21~1.86	1.06~1.47

Note: ①***P<.001; **P<.05; *P<.1; ②Dependent variable: University-Industry Collaboration; ③The numbers in brackets are standard errors.

In these countries, the total research publication output appears to be the main determinant of UIC productivity. The cause of this phenomenon is also evident that the UIC publication is part of the research publications. In addition, the income from industry also has a significant positive impact on UIC, but the research quality variable of a university is less relevant. And the EU and the USA research system are found to be more financially driven than in the Chinese. In other words, for each additional income from industry, the Chinese universities' UIC productivity is increased less than that in EU and USA universities.

A significant difference among the Chinese, EU, and US universities is found in terms of the research quality variable; that is, the average number of citations of the publications of a university, normalized for field differences and publication year (MNCS). The results suggest that UIC intensity is also determined by research quality determinants in the EU but not in China and the US. This implies that strong positive correlations were found between UIC productivity and MNCS in EU universities, which does not occur for the 40 Chinese and 64 US universities.

Discussion and Conclusion

The universities most productive in academic publishing are not by definition the most active in collaborations with industry. However, strong positive correlations were found between these two factors. Publication productivity correlates highly with research collaboration, including university-industry collaboration, but does not necessarily result in high UIC intensity. Universities with high publication productivities may have low UIC intensity even though their UIC productivity is high, and conversely, those with low numbers of publications may have high UIC intensity even though their UIC productivity is lower than those of large producers, due to size effects. We also found that the large research universities with strong ties to industry typically have high UIC intensity rates. And the large research universities with strong links to domestic industry play critical roles in a national research system.

The publication productivities of most of the leading US universities are significantly higher than those of Chinese and EU universities at the same domestic ranks. This difference is more pronounced in "Biomedical and Health Sciences" than in "All Sciences." US universities are much more active in collaborating with industry than their EU and Chinese counterparts, which implies that they have more involvement in the national research system. Field variation is also found: the distance between Chinese and EU/US universities in collaborations with industry is narrower in "Physical Sciences and Engineering." Thus, Chinese universities are relatively more active in knowledge transfer in this field.

An important difference is also found among these three regions in selecting partners: the Chinese system is almost exclusively domestically oriented and the EU system internationally oriented, whereas the US system is oriented both nationally and internationally. Thus, the EU research system is perhaps more open than that of the US and China. One possible explanation is that the EU is made up of a group of countries that work together to produce a greatly higher %Foreign for the EU than for China or the US. Some Chinese universities prefer domestic industries and some are more involved with foreign industries. A university with a greater focus on collaboration with foreign industry may be less vigorous in establishing domestic partnerships, and vice versa. Interestingly, in "Physical Sciences and Engineering" most of the US universities give more attention to foreign than domestic partners. Therefore, the national orientation of university-industry collaboration in the US may imply that the US research system is more self-contained.

Another significant difference is found among these three regions: UIC productivity is partially determined by research quality (MNCS) in the EU but not in China or the US. Thus, strong research ties with industry are concentrated in EU universities with high-quality research environments. The Chinese UIC is less financially driven than those of the US and the EU, but it appears to be more a consequence of academic publication.

Limitations

This article has the following limitations: (1) The regression analysis is based on publication data of "All sciences," which cannot sufficiently reflect field variations. Even in the same field, the cost versus output of different UIC projects may vary notably. (2) The expenditure/income data used in this study are taken from another source, which may affect data consistency. (3) Publication is only a form of university-industry collaboration, in addition, there are talent training, technical contracts and other forms. This paper is only from a point of view to analyze the collaboration between industry and university, the following can consider other forms. (4) Because patents and publications are the important output of university-industry collaboration, the conclusions of this study may not reflect the complete picture, particularly in fields like medical sciences, computer science, and engineering, in which patents are a major part of the output. Further studies should research more fields and take patents into account in specific fields.

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