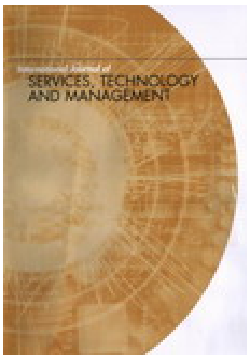

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An analysis of the research trends and collaboration strategy of university and industry on digital twin technology

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An analysis of the research trends and collaboration strategy of university and industry on digital twin technology

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Abstract: The rapid transition to digitalise all processes in the manufacturing field has promoted the introduction of new manufacturing technologies. However, few have focused on how to create synergies in R&D through university-industry collaboration (UIC) in the relevant fields. To fill the research void, in this study, we analysed the research trends of industry and university with a focus on the technological field of digital twins (DTs), which has recently attracted attention, and we explored partner selection for effective UIC strategies in the field. The results suggest that the university focuses on intelligent production systems using AI technology, whereas the industry focuses on industrial digitalisation platforms for condition monitoring and predictive maintenance. The methodology proposed in this study can be applied to other industrial fields that require the UIC strategy. The research findings provide useful guidelines concerning UIC for industry practitioners and academic researchers in DTs.

Keywords: digital twin; university-industry collaboration; UIC; type of collaboration; text mining; bibliometric analysis; portfolio analysis.

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1 Introduction

As the Industry 4.0 era emerges, the manufacturing technology paradigm is rapidly shifting to digitisation. Among various technologies, digital twins (DTs) are gaining attention and popularity in both the university settings and industry as a breakthrough technology that can change future manufacturing environments (Enders and Hoßbach, 2019). The application of DTs to all aspects of manufacturing is a strategic priority for modern manufacturing companies (Lasi et al., 2014), and research at universities has actively responded to these industries' needs.

Despite such an interest in DTs, the inconsistent application and divergence of DT technologies have hindered universities and industries from collaborating in technology development (Fuller et al., 2020) for numerous reasons. First, the closed manufacturing strategy in industry causes a gap in perspectives between universities and industries (Skinner, 1996). Second, universities and industries have not agreed on the definition of DTs yet (Moyne et al., 2020) given that DTs are in an early stage of development. Finally, DTs are converging technologies. A wide range of technological fields [e.g., simulation, data analysis, and artificial intelligence (AI)] affect them, and they several industries apply them (e.g., aerospace and automobiles) (Zheng et al., 2018).

Furthermore, numerous studies on university-industry collaboration (UIC) that were conducted in different contexts with different goals generally concluded that such collaborations can be beneficial but it is hard for them to be successful (Gulbrandsen et al., 2011). This requires a new approach to developing a UIC strategy for DT technologies, one characterised by converging technologies at an early stage of development with the knowledge gap between industry and universities. Innovation patterns in DTs resemble those in autonomous vehicles; automobile manufacturers have pursued aggressive collaborations with firms in other sectors to cope with rapidly changing environments, where competition is accelerated and technologies are converged (Attias and Mira-Bonnardel, 2016). Selecting an appropriate collaboration partner from a corporate management perspective is indispensable to introduce new technologies, which requires understanding the collaboration ecosystem in the target field, that is, DTs in this study. Accordingly, we addressed the following research questions. First, which type of research fields does DT consist of, and on what research fields are universities and industries focusing? Second, what strategies and partners do UIC need in those research fields?

To answer those questions, in this study, we aimed to examine empirically the technological fields that focus on universities and industries through DT-related literature analysis, as well as possible collaboration partner candidates for research cooperation. In general, most assume that companies are not aware of potential collaborating partners of the technology with which they want to collaborate. To find a collaboration partner that can provide great synergy, companies need to analyse massive amounts of quantitative data (Geum et al., 2013). Considering the number of scientific and technological publications has increased recently, numerous studies have used bibliometric analysis to identify technological trends, establish technological strategies, and select collaboration partners (Ran et al., 2020; Kulkarni et al., 2018). Finding a suitable partner requires careful screening, which can be a time-consuming process (Dacin et al., 1997). In addition, the business environment's complexity increases due to the technology paradigm's rapid change; scientific literature can be meaningful support for practitioners' decision-making in a company. Recently, as interest in DT technology increases, the scientific literature is rapidly increasing, and much of the research been derived through collaboration between universities and industries (Liu and Nee, 2022). Therefore, we investigated these data as follows. First, we used the text-mining method to analyse DT-related technical and scientific literature. Through this, we identified various research fields applied to DT. Second, we analysed each research field's technical and cooperation capabilities to explore the types of collaboration. In addition, to develop DT technology, we selected partner candidates that could collaborate. Finally, we verified whether the proposed approach helped companies that developed DT technology and we derived our policy implications. The research findings help to understand the major trends in university–industry DT research and to provide useful information for future UIC research directions by indicating the DT technological fields that lack research collaboration.

The remainder of this paper is organised as follows. Section 2 reviews the existing literature on the knowledge gap between universities and industries and the selection of potential partners. Section 3 presents the research methodology used for the entire technological field and collaboration plan, and Section 4 suggests the major technological fields and UIC strategies based on the analysed results. Section 5 discusses the validation and implications of this study's results. Finally, Section 6 concludes with limitations and future research directions.

2 Literature review

2.1 Research fields of universities and industries on DT technology

A DT is broadly defined as a type of cyber physics system (CPS) that connects virtual and physical space. While CPS is a conceptual technology that enables sharing virtual and real data, a DT is a technology that can further monitor and synchronise real-time activities in a virtual space (Negri et al., 2017). The DT system is a new paradigm for future manufacturing information systems, that focuses, on data and models through ultra-high fidelity simulation (Zheng et al., 2018). Considering DTs have huge economic and social potential in many industrial fields, including aerospace (Glaessgen and Stargel, 2012), shipbuilding, and marine fields (Hribernik et al., 2013), large investments in the relevant technologies are being made worldwide. Currently among these, the manufacturing industry is most actively applying DTs, suggesting smart manufacturing and air transportation, social infrastructure, healthcare and medicine, intelligent transportation systems, and robots for services, among others (Gunes et al. 2014; Holler et al., 2016).

With various industrial fields applying DT technology, the amount of academic literature has increased rapidly (Tao et al., 2019). Despite this interest in DT, there are differences in the research characteristics in universities and industries. Universities have not conducted much research on key technologies (DT's simulation and factory platform technologies) applicable to industrial sites that companies need due to the industry's closed information sharing. In contrast, the industry lacks cooperation on key technologies (AI and data analysis technology) to gain a competitive advantage in manufacturing strategies (Kulkarni et al., 2018; Fuller et al., 2020). Although numerous literature reviews have attempted to analyse the research field of industries to which DT technology is applied, there have been no previous studies comparing universities and industries. Existing studies that analyse application fields via reviewing a large selection of literature have limitations and require quantitative analysis as a whole. Therefore, in this study, we collect literature data related to DT by synthesising the sources, periods, and search terms used in existing literature studies, by apply the text-mining method to identify the research field of implied DT. In addition, we analyse the research fields focused on university and industry, and we derive cooperation strategies and partner candidates.

2.2 Knowledge gap between universities and industries and selecting partners

Against increasing international competition and rapid technological change, governments actively encourage collaboration between universities and industries as a means of improving innovation efficiency and creating wealth. However, the stability and contingency of initiating cooperation in response to environmental uncertainty motivates cooperation (Oliver, 1990). Sherwood et al. (2004) argued that universities offer extensive access to a wide variety of research expertise and research infrastructure, while industry offers extensive access to a wide range of expertise. In addition, universities have shifted the UIC strategy from temporary sponsorship to continuous partnerships to respond to rapid environmental changes (Jacob et al., 2000). In particular, the individual' governments universities have greatly supported the growth of new knowledge, and universities have responded through a partnership with the industry to narrow the knowledge gap. Similar to universities, today's transition to a knowledge-based economy is a motivating factor for industry to engage with universities (Santoro and Betts, 2002). Many studies have shown that UIC is a great way to create and stimulate technology-based enterprises, especially new ones for business growth (Klofsten and Jones-Evans, 1996).

Based on previous literature studies, universities can stay ahead of industry in understanding future trends and potential knowledge needs in specific engineering fields. In contrast, industry has more awareness of current needs and often has a deeper understanding of existing technologies. These differences often cause problems in UIC (Rudzajs et al., 2010), including differences in industry's and universities' main objectives, the value of papers and patents resulting from research, the expansion of new knowledge, and profit generation. Perkmann and Walsh (2007) explained that these problems caused a knowledge gap between universities and industries. In addition, based on the previous literature review, various types of interactions were presented to resolve the knowledge gap (Santoro, 2000; D'Este and Patel, 2007). Through their literature review, Schaeffer et al. (2015) identified five variables that could be adopted to characterise and fill the existing knowledge gap between universities and industries: the duration of interaction, the direction of information flow, the level of knowledge involved, the degree of formality, the complexity of interaction, and the actors' absorptive capability. Perkmann and Walsh (2007) proposed a type of collaboration based on research partnerships (joint research activities) and research services (academic publications). Nsanzumuhire and Groot (2020) suggested that among the types of cooperation, three major forms (educational collaboration, academic entrepreneurship, and research-related collaboration) are the best knowledge-transfer methods that maintain continuous interaction. It is important to identify these characteristics and types of cooperation that can help make knowledge levels uniform between universities and industries and to develop available types. We aim to select types of cooperation and partners with high synergy through the strength of technology and cooperation by analysing the research results (patents and papers) of UIC without considering the characteristics of previous studies.

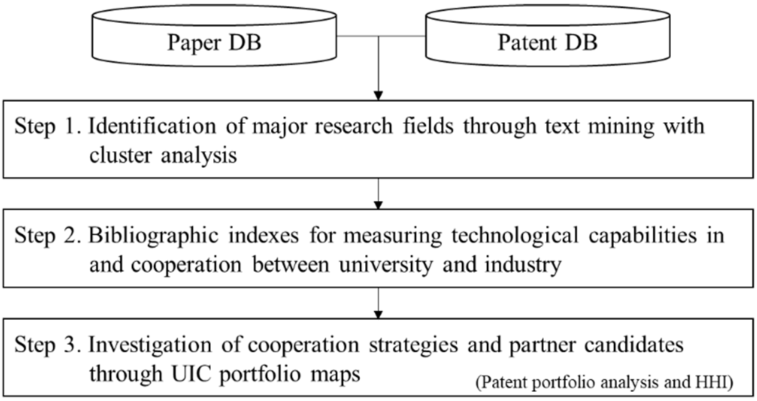
In a typical company, it is difficult to find a partner with high synergy for R&D collaboration. Shah and Swaminathan (2008) found that three dimensions of potential partner selection (partner complementarity, partner compatibility, and partner commitment) related to collaboration performance. In particular, complementarity has been understood from various perspectives, such as technology, governance, clients, and types of activities. Among them, technological complementarity should be carefully considered in R&D collaboration. Firms benefit more from R&D collaboration when partners have moderate, rather than high or weak, technological competency compared to the core company (Sampson, 2007). Despite this importance, methods of finding technically complementary partners have not been studied relatively well.

3 Methodology

In this study, we aimed to identify the university and industry research directions, as well as to explore further UIC strategies via analysing collaboration partners in each research field. The overall research process has four steps (see Figure 1).

First, in step 1, publication and patent data were collected to identify the major DT technological fields in industry and universities, for which we adopted text mining with cluster analysis. Text mining is an approach mainly used to analyse the gap in literature information between science and commercial technology, as well as to predict technology trends. In this study, we identified crucial keywords with potential meanings in many DT-related industry-university documents from 2000 to 2019, and major technical fields were derived based on the similarity between documents. In the process of deriving major technical areas, we combined expert opinions to identify further accurate information and to improve the results (Kostoff and Schaller, 2001). The method involved delivering crucial keywords and key documents to four DT-related practitioners in advance, as well as carrying out naming and convergence in each cluster through individual interviews.

Figure 1 Overall research process



In step 2, we evaluated the technological and cooperation capabilities of the two groups by applying bibliographic analysis indicators to the technological fields. Because technological collaboration is the process of accessing the other's technological resources, it is important to understand each innovator's level of technological competence, as well as the innovator's access to technology (Welsh et al., 2008; Koski and Svento, 2016). López-Martínez et al. (1994) showed that a partner's technical competency is the most valuable cooperation motivator for companies that lack in-house capabilities. In addition, identifying collaboration capabilities between partners results in cost savings related to knowledge creation in new collaboration activities with companies (George et al., 2002).

Recent studies have mainly used literature citation information to analyse partners' R&D capabilities (Geum et al., 2013; Danish et al., 2020). These studies identified complementary technology areas from the company's point of view by specifying objectives for R&D collaboration and selecting partners based on collaboration criteria. Based on previous studies, we identified differences in industry-university perspectives in major technological fields through patent indicators that represent technological capabilities (qualitative and quantitative) and collaborative capabilities.

In general, the patent share and the patent citation measure technology capabilities. First, the patent share measures a company's or university's quantitative technical capabilities in a particular field based on its number of patent applications or documents (Ernst, 2003). Representative indicators include the revealed technology advantage (RTA) and the activity index (AI) (Banerjee et al., 2000; Geum et al., 2013). Both indicators allow the documents' quantitative concept to be applied to a company's or country's relative technical capabilities in each field, but RTA is more commonly used in the corporate analysis (Danish et al., 2020). Second, patent citations measure technology's quality and impact (Thomas, 2001). As a representative indicator, previous studies have widely used the current impact index (CII) or the citation per publication (CPP) (Narin et al., 1992; Geum et al., 2013). Although previous studies have widely used both, it is difficult for the CPP to reflect recent technological trends, thus, we used the CII in this study. Finally, we used various indicators to measure collaboration ability. For example, the number of joint publications (Ernst, 2003), the similarity in technical interests (Breitzman and Mogee, 2002), and the number of researchers' technical exchanges (OECD, 2005), among others, have been studied in advance. In this study, we aimed to analyse companies' and universities' relative collaboration capabilities. The representative indicator for measuring the strength of relative cooperation is the Salton Index (Ding et al., 2001), which uses the number of joint documents to identify partner candidates.

Finally, in step 3, we explored the cooperation strategies and partner candidates through a UIC portfolio map. Organisations often use the patent portfolio to assess technology capabilities among competitors and to advance further technology strategies (Kronemeyer et al., 2020). The portfolio composition utilises the competency differences between industry and universities based on the three indicators measured in step 2. Quantitative and qualitative differences regarding universities' and industry's technological capabilities represent technological capabilities and influence (Jeong and Ko, 2016). In addition, the differences in collaboration ability can determine whether they are actively collaborating in the relevant field (Ding et al., 2001). Each indicator's values were placed on the quadrant's map, and the four types of cooperation were presented as interactions. The *x*-axis was the difference in industry's and universities' technical and technological capabilities, and the *y*-axis confirmed industry's and universities' collaboration capability. The bubble's size indicated the technological influence of the patents that each group held. The point where the two axes intersected indicated the technological strength and collaboration level of industries and universities, and it suggested a cooperative strategy accordingly.

We selected collaboration partner candidates according to the cooperation type. Partner selection involves analysing the countries and institutions' research concentration based on their number of research documents (Selvamani and Arul, 2021). The type of collaboration on the UIC portfolios map was the difference in the relative strength of industries and universities, and it indicated the strength of potential competition. We used the Herfindahl-Herschman Index (HHI) as a representative index for measuring competition (Sutton, 1998). We aimed to select partners that could create synergy without overlapping technological capabilities for companies that wanted technical cooperation (Makri et al., 2010; Parahoo et al., 2020). Previous studies mainly involved selecting partner candidates via measuring indicators' characteristics (Geum et al., 2013; Jeong and Ko, 2016), but they did not consider potential competition risks.

3.1 Identification of major technological fields

The first step was to identify the technological fields focused on universities and industries through text mining with cluster analysis. The method involved three stages:

Stage 1: data collection and pre-processing

Publications and patents have long been regarded as valuable sources of technological knowledge, and thus, have been widely used to investigate technology development and applications trends. However, publications present research activities largely from universities and research institutes, whereas patents show development activities from not only these sources but also companies. Hence, it is difficult to analyse accurately the differences between universities and industries through only one specific data type because the universities' proportion of publications is high (Tao et al., 2019) and companies focus on strategically applying for patents to protect their technologies. Unlike the existing studies focusing merely on one data type, either publications or patents, this study used both data types to examine the differences between industry and universities. Collecting data on DTs is important for obtaining reliable analysis results. For data collection, the search terms were created by referring to DT-related papers (Table 1). Using the terms, we collected publications between 2000 and 2019 from the SCOPUS database; we collected USA patents through the commercial website WISDOMAIN (http://www.wisdomain.com).

Table 1 Selection of search keywords for data collection

Reference	*Search keywords*
Holler et al. (2016)	Digital twin, product avatar, cyber-physical equivalence, product shadow, and information mirroring model
Negri et al. (2017)	Digital twin
Kritzinger et al. (2018)	Digital twin, digital twin in manufacturing, and digital twin in maintenance
Lim et al. (2019)	Digital twin, virtual twin, and cyber twin
Tao et al. (2019)	Digital twin, digital twin design, digital twin manufacturing, and digital twin control
Enders and Hoßbach (2019)	Digital twin, product avatar, product agent, product shadow, information mirroring model, and cyber-physical equivalence
Lu et al. (2020)	Digital twin

Stage 2: text mining for classifying key terms

After we analysed the collected documents via text mining, we extracted all terms related to DTs; the removal of stop words, word tokenisation, and stemming were then performed sequentially. The document was then integer-encoded into a vector based on word frequency. For extracting the key terms, the important weights of words were calculated using term frequency-inverse document frequency (TF-IDF) analysis.

Stage 3: cluster visualisation

To build a document cluster, an index is needed for measuring the similarity between documents containing key terms. We adopted cosine similarity, which has been used as a representative index for measuring the similarity between documents. Then, we identified the clusters through modularity analysis, which is one of the most commonly used approaches. A cluster is composed of subgroups called modules; modularity refers to the degree to which a node is close to a specific cluster and far from other clusters. Here, the larger the value of modularity in the positive direction, the higher the possibility that a community structure exists in the cluster.

Stage 4: cluster convergence

Similar clusters that algorithms converged did not divide with the opinions of experts with domain technical knowledge (Rezaeian et al., 2017). The experts consisted of four people (engineers and researchers), and the naming of clusters and fusion work on similar clusters were carried out.

3.2 Bibliographic indexes

The second step was to evaluate the level of technological capabilities of universities and industry along with the degree of interaction between them to establish their differences in perspective. In this study, we evaluated the technological capabilities of two innovators via quantitative and qualitative analysis, and we evaluated their accessibility was evaluated based on the current degree of cooperation.

Patent distribution, based on the number of patent applications or registrations, has been effectively used to measure a company's technological capability in a specific field, and thus, conceptually, it can secure a company's competitiveness in R&D. Among these, the most representative patent-based quantitative and qualitative analysis indicators are the RTA and CII. The RTA provides information on what technological areas a particular group focuses on compared to other groups. The CII provides information on the technological impact of the technological innovation that the group has achieved during the past five years. Finally, the degree of cooperation indicates how actively the group has engaged in cooperation activities, which the Salton Index can measure, called technology collaboration strength (TCS). This measure evaluates the strength of various types of cooperation, such as inter-state cooperation, inter-regional cooperation, and inter-agency cooperation. Table 2 provides the operational definitions of the three indexes we customised for this study.

Table 2 Operational definitions of indexes

Index	*Operational definition*	*References*
Revealed technology advantage (RTA)	$RTA = \dfrac{D_{ij} \big/ \sum_i D_{ij}}{\sum_i D_{ij} \big/ \sum_{ij} D_{ij}}$ where *RTA* shows the related quantity advantage of the *j* group (industry or university) in *i* technological field; $D_{ij}/\Sigma_i D_{ij}$ is the proportion of the number of documents (patent and publication) of *j* group in *i* technological field to total documents of all groups; and $\Sigma j D_{ij}/\Sigma_{ij} D_{ij}$ is the ratio between the number of all communities (industry and university) in *i* technological field and all groups in all communities.	Mahmood and Singh (2003)
Current Impact Index (CII)	$CII = \dfrac{100\, C_i \big/ \sum_i C_i}{100\, D_i \big/ \sum_i D_i}$ where C_i represents the number of times a document of group *i* has been cited in a certain year from the previous five years. D_i is the number of documents group *i* produced in the past five years.	Narin et al. (1992)

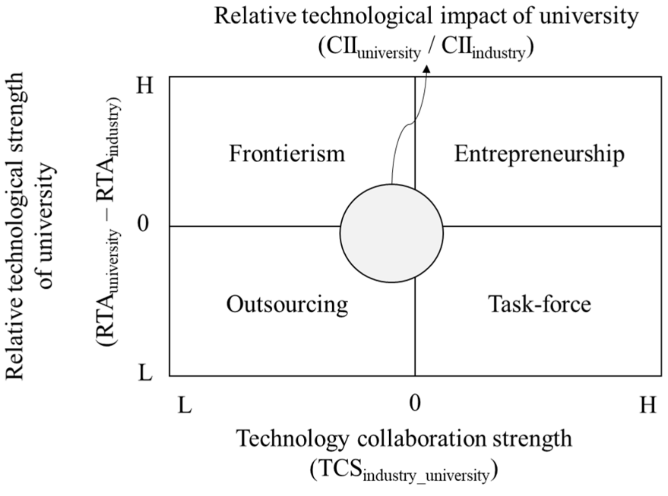
Table 2 Operational definitions of indexes (continued)

Index	*Operational definition*	*References*
Technology collaboration strength (TCS) (Salton Index)	$TCS = \frac{D_{ij}}{\sqrt{D_i D_j}}$ where D_{ij} is the number of joint research of i and j; D_i is the number of joint research studies of university i; and D_j is the number of joint research studies of industry j.	Ding et al. (2001)

3.3 *Investigation of cooperation strategies and partner candidates through UIC portfolio map*

The third step was to explore cooperation strategies between industries and universities through a UIC portfolio map. We based our proposed UIC portfolio on the difference between universities' and industry's technical capabilities and degree of cooperation. For this, we used the RTA, CII, and TCS values, which indicate the quantitative value, qualitative value, and degree of cooperation, respectively. For visualisation, the difference between universities and industries was highlighted in addition to the degree of collaboration between them, based on which the technological areas were positioned in one of the portfolio's four quadrants (see Figure 2).

Figure 2 UIC portfolio map



In Figure 2, the x-axis represents the degree of cooperation between universities and industries for joint R&D based on the TCS values. The y-axis indicates the relative technological strength (RTS), which the difference value is obtained by subtracting the industry RTA values from the university RTA values. A positive RTS value indicates universities' high technological strength, whereas a negative RTS value indicates industries' high technological strength. Finally, the size of the point indicated by the x and y coordinates indicates the CII ratio; the technological advantage is expressed as a ratio by dividing the values of industry from the values of universities. A value higher than 1 indicates the university's higher technological impact, whereas a value lower than 1 indicates the industry's higher technological impact. The RTS and TCS values for the *x*- and *y*-axes were normalised based on the mean values.

The UIC portfolio map has four categories of technological fields along with appropriate types of cooperation according to the relative technological strength and technology cooperation strength. The first type is entrepreneurship. Here, the university leads knowledge creation, the cooperation with industry is actively taking place, and the focus is likely to be on using university R&D achievements (Franco and Haase, 2015; Wen, 2019). The second type is frontierism. Here, the university governs knowledge creation, there is little cooperation with industry observed, and thus, steps need to be taken to make knowledge at universities available in industry. The third type is outsourcing. Here, industry governs the knowledge flow, but cooperation with universities does not actively take place; universities' advise is requested only on a few topics (Seppo and Lilles, 2012; Santoro, 2000). The last type is taskforce. Here, industry governs the knowledge flow while cooperation with universities actively takes place; the focus is on developing companies' commercial technology (Narin et al., 1997; Gulbrandsen et al., 2011).

The following are designed to help identify organisations as potential collaboration partner candidates for each UIC type. Numerous studies have been conducted to analyse the factors used for selecting an appropriate R&D partner (Pidduck, 2006). For example, Beers and Zand (2014) analysed whether the diversity of partners (concentration) affects R&D cooperation and innovation performance using the HHI. The HHI originally assessed the market's monopoly status and competitive strength, and using patent data provides useful information about the technological monopoly situation and the technological competition's strength. In this study, we analysed the technological concentration for partner selection using the HHI regarding countries and organisations for each technological field. They were expressed as:

$$HHI = \sum_{i=1}^{n} S_i^2$$

where S_i denotes the concentration ratio of documents of relevant countries or research institutes.

4 Results and cooperation trend

4.1 Major technological fields

In total, we analysed 1,140 publications and 92 patents using text mining; 6,797 terms were selected based on the TF-IDF score. Among them, 854 key terms were selected as key DT terms under the following criteria (Zhang et al., 2014):

1. TF-IDF values of seven or more
2. cosine similarity values of 0.25 or more.

Then, with the key terms, we performed clustering analysis, generating an initial 12 major clusters and the corresponding key terms. Although the clustering method has an advantage as an exploratory analysis method, the results are difficult to interpret because there is no purpose given in advance (Tseng and Yang, 2001). In addition, because DT technologies have convergence technology characteristics, classifying them only with algorithms is difficult. For clear classification, we performed naming and convergence work for each cluster together with manufacturing engineers and researchers who apply DT technology and finally identified six major research areas (see Table 3). After reviewing the major DT fields in universities and industries through the number of documents, we found that universities conduct research activities in all technical fields except cluster 2. The main technology of cluster 2 is monitoring and predictive analysis of industrial digitalisation platforms. Because it is difficult for universities to access a company's unique information (equipment data, sensors, information on anomalies, etc.), research activities in specific research fields may not be active. However, confirming whether universities and industries require technology research in other fields to be studied is difficult. In Subsection 4.2, we analysed the technology and cooperation capabilities of universities and industries through each cluster's technical and cooperation strengths.

Table 3 Six DT technological fields and key terms for universities and industries

Clusters	*Technological fields*	*Group (number of documents)*	*Key terms*
1	Interaction framework based on VR, AR, and MR	University (21)	Augmented reality (AR), virtual reality (VR), virtual spaces, mixed reality (MR), and 3D modelling
		Industry (17)	Augmented reality system, augment reality content, avatar cloning system, cloud computing, and real-time processing
2	Industrial digitalisation platform for condition monitoring and predictive maintenance	University (33)	Preventive maintenance, condition monitoring, machine learning, big data visualisation, and human-machine interface (HMI)
		Industry (55)	Industrial internet of things (IIoT), predictive analytics, predictive maintenance, condition monitoring, and diagnosis
3	Simulation-based systems engineering	University (51)	Computer architecture, computational model, simulation platform, multi-body simulation, model and simulation
		Industry (26)	3D simulation, model-based systems engineering (MBSE), finite element analysis (FEA), and virtual test beds
4	Digital twin-driven product smart manufacturing system	University (31)	Big data, data fusion smart manufacturing, digital factory, production system, operation procedure, and internet of things (IoT)
		Industry (27)	Industrial internet of things (IIoT), architecture, operation paradigm, embedded system, management system, and factory design
5	Digital twin and AI	University (39)	Machine learning, data mining, cloud platform, internet of things (IoT), and autonomous manufacturing
		Industry (29)	Data mining, intelligent manufacturing, artificial intelligence (AI), robot learning, and intelligent products

Table 3 Six DT technological fields and key terms for universities and industries (continued)

Clusters	*Technological fields*	*Group (number of documents)*	*Key terms*
6	Digital twin in air force operations, commercial airports, plane airframes, and the aerospace industry	University (20)	Fleet management systems, predictive analysis and fault diagnostics, wind turbine, blade system design, and data reduction
		Industry (18)	Principal component analysis (PCA), failure prediction, composite materials, and autonomous unmanned aerial vehicles (UAVs)

4.2 Bibliographic analysis results

Patents and publications may have different focus areas. Whereas publications emphasise the research process and results, patents emphasise the research's technological applications and their market value. Therefore, both data sources are worth considering. We also need to consider the quality of a publication and a patent; the citation frequency is generally used as a proxy for quality, and thus, we proposed the following index to produce the adjusted document number:

$$wD = w \times D = \frac{C}{C_t} \times D$$

where w is measured by the citation frequency (C) of the target patent (publication) compared with the average citation frequency (C_t) of all patents (publications) published in the same year. Then, we assigned all documents to technological fields (see Table A1). Using the adjusted document number, Table 4 presents the bibliographic analysis results.

Table 4 Bibliographic analysis results

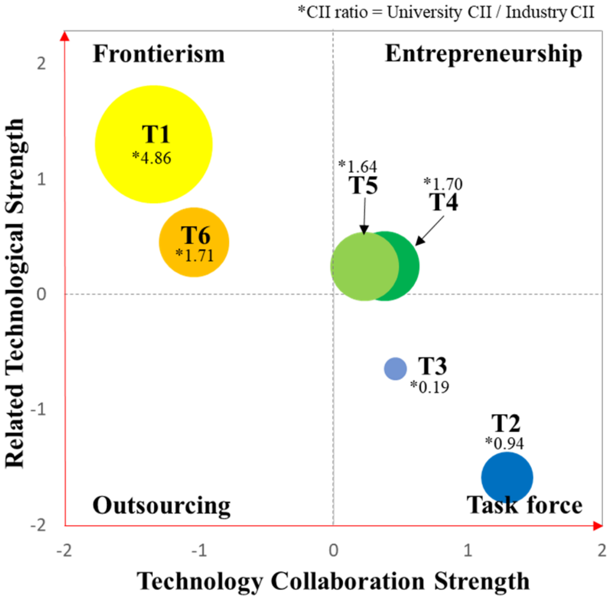
Technological fields	*Group*	*RTA*	*RTS*	*CII*	*CII ratio*	*TCS*
T1	University	1.28	0.91	2.24	4.86	0.17
	Industry	0.37		0.46		
T2	University	0.67	–1.03	0.81	0.94	0.51
	Industry	1.70		0.86		
T3	University	0.87	–0.4	0.37	0.19	0.41
	Industry	1.27		1.87		
T4	University	1.06	0.21	2.00	1.7	0.37
	Industry	0.85		1.17		
T5	University	1.09	0.24	1.74	1.64	0.36
	Industry	0.85		1.06		
T6	University	1.10	0.34	0.89	1.71	0.21
	Industry	0.76		0.52		

First, the RTA and RTS results indicated that academics focus on technological fields 1, 4, 5, and 6, whereas industry focuses on technological fields 2 and 3. In technological field 1, technological outputs were produced four times more at universities (1.28) than in industry (0.37). Second, the CII and CII ratio results showed that universities (2.24) in technological field 1 have an approximately five-times-higher technological impact than that of industry (0.46), whereas universities (0.37) have a five-times-higher technological impact than that of industry (1.87) in technological field 3. However, the RTA and CII results generally exhibited similar patterns. Finally, the TCS results showed that technological fields 2 and 3, which industry drives, were more cooperative than technological fields 1, 4, 5, and 6, which university drives. This indicates that industry governs UIC activities in DTs more than universities do; the technological areas of interest to the industry bring more UIC opportunities because the research funding for such collaboration tends to rely on the industry.

4.3 UIC portfolio and selecting partner candidates

Figure 3 shows the DT technological fields and their positions on the UIC portfolio map. Finally, we analysed the technological concentration (which the HHI measures) by the country for selecting collaboration partners in each of the DT technological fields (see Tables 5 and A2).

Figure 3 UIC portfolio (see online version for colours)



First, technological fields 4 and 5 (smart manufacturing systems and AI technology, respectively) were included in the *entrepreneurship* type, which includes technological fields that universities lead in cooperation with industry. In addition, China, Germany, and the USA (in the order of research intensity) have produced numerous patents and publications, and the leading research institutes are Beihang University and Siemens AG. Second, the *frontierism* type included technological fields 1 and 6 (VR, AR, and MR; and aerospace industry technology, respectively), which universities lead with little cooperative research with industry. The USA, China, and Russia have active R&D activities. In addition, the leading research institutes are General Electric Company and the Skolkovo Institute of Science and Technology. Third, technological fields 2 and 3 (industrial digitalisation platform and simulation-based systems engineering, respectively) were included in the *taskforce* type, where industry leads research and leads collaboration with universities. Hence, the technological impact of industry is much higher than that of universities. Furthermore, the USA, China, and Russia have active research activities, and the leading research institutes are General Electric Company and Siemens AG.

Finally, no DT-related technological fields were found for the *outsourcing* type. Industry can strategically suppress the publication of joint research results to protect the company's proprietary technology from competitors, which may result in no technological fields of this type.

Overall, the USA, Germany, and China have driven advances in DT technologies with the representative organisations in those countries. The country-concentration ratio was relatively high in the technological field 4, indicating that only a few countries dominate this field. In contrast, the organisation-concentration ratio was relatively high in technological field 2, meaning that a few major research institutes have advanced this field.

Table 5 HHI analysis results by country

Type	*Clusters*	*HHI*	*Top 3 countries*
Entrepreneurship	4	0.1879	China, USA, Germany
	5	0.1695	Germany, USA, Sweden
Frontierism	1	0.1129	USA, China, Germany
	6	0.1606	USA, Russian Federation, France
Taskforce	2	0.1383	USA, Germany, China
	3	0.1156	Germany, USA, UK

5 Discussion

5.1 Findings and validations

In this paper, we identified the major DT research areas that universities and industries focus on, and we selected and presented the types of cooperation and strategic partners. Section 5 verifies that our approach can be used in general companies and it suggests policy implications. We conducted two analyses to present the usability of the proposed approach. In the first analysis, we used a target firm, firm S, in which DT technologies are widely used as part of its business, and we developed its collaboration strategy using the proposed approach. In total, 65 DT-related patents and publications belong to this firm, particularly in the areas of smart manufacturing, simulation, AI, and industrial IoT, which correspond to T2, T4, and T5 (see Table 3). Focusing on T5, we obtained the firm's RTA value of 0.55, CII value of 0.68, and TCS value of 0.13, which are smaller than the averages of different industries (see Table 4). We also found that universities have higher technological capabilities than industry does in T5. Nevertheless, the target firm is not active in collaboration with others for T5. Consequently, the firm's T5 is positioned in the UIC portfolio map's second quadrant (frontierism), whereas T5 of industry is in the first quadrant (entrepreneurship). The potential partners for research collaboration in T5 include the University of Stuttgart and Chalmers University of Technology. We concluded that Firm S could consider collaboration with universities to benefit the development of T5. Nevertheless, note that we base the proposed approach only on public databases to explore UIC trends and potential partners for collaboration. More factors need consideration for establishing a collaboration strategy. For example, prioritising short-term goals may delay UIC for long-term innovation (Dutrénit et al., 2010).

In the second analysis, we conducted interviews with four experts; two were in charge of UIC project manager and the other two were in charge of R&D in the automotive industry. More specifically, we provided the research findings to the interviewees to ask about those findings' implications along with the usability of the proposed approach and the relevant needs from the user's perspective. We conducted the interviews based on the four stages. In stage 1, we identified potential interviewees and selected the target interviewees considering their expertise in DTs and experience with UIC. In stage 2, we designed questionnaires for the interviews to help evaluate the proposed approach's strengths and weaknesses from the user's perspective. In stage 3, we conducted semi-structured interviews; we provided the analysis results to the interviewees for review before the interviews were conducted. Each interview lasted for two hours on average. In stage 4, we collected and analysed feedback from the interviewees.

The interviewees generally agreed that the analysis results offered an overview of research trends at universities and in industry, particularly different perspectives of the two parties. One of the interviewees (a director in the R&D planning department of an automotive manufacturing company) said, "In some areas, a research gap in terms of direction is so big that finding a way to fill the gap should be the first step in initiating UIC. A joint body of university and industry to communicate their research trends can be beneficial."

The interviewees were particularly interested in the partner selection process. The proposed approach assists with developing an expert pool for DT technologies, which can serve as a useful reference for a UIC project by increasing the reliability and objectivity of technology planning. It also enables establishing collaboration modes suitable for target areas. Moreover, it is expected to offer significant value for global UIC, as one of the interviewees (a UIC project manager) argued: "This will be greatly useful in identifying collaboration partners abroad and their research trends. Once the key countries are acknowledged, our resident employees in those countries can collect more information about the candidate partners and set up a collaboration."

However, an in-depth analysis of candidate partners and countries, specifically regarding their previous projects, would be required for choosing a final partner through the interviews. An internal agreement on the UIC areas and modes seems necessary as well. Consequently, the interview results generally indicated that the proposed approach can be a useful tool for UIC strategies, whereas more effort could be made by combining the proposed tool with other technology planning and intelligence tools within an organisation.

5.2 Managerial and policy implications

Understanding the research trends both at universities and in industries is essential not only for initiating UIC but also for producing successful UIC outcomes, particularly in areas such as DTs and AI. Organisations are closed in their innovation processes, technologies are converging, and significant technology gaps between universities and industries exist in sub-areas. The proposed approach can be applied to any sector of similar characteristics with DTs in developing their UIC strategies. It can also be used to design government-funding programs for facilitating UIC to advance DT technologies.

The proposed approach offers valuable policy implications for designing UIC programs. First, the government should play the role of a control tower in facilitating UIC for DT advances by identifying the areas in which universities and industries can work together to create synergistic value and intermediate them. Although an organisation specialised for UIC is established (e.g., technology collaboration, open innovation team), it remains difficult for an individual firm or university to collect information to understand UIC trends and identify potential collaboration partners. In particular, the risks from the collaboration partners' opportunistic behaviours can be reduced through the government's involvement.

Indeed, in newly emerged areas such as DTs, identifying potential partners that have strong technological capabilities and offer various collaboration opportunities is important for facilitating industry development. The Korean Government has been involved in the Advanced Manufacturing Technology Consortia program, which aims to grow advanced manufacturing in the USA. This program's purpose is to develop a technology roadmap for advanced manufacturing through collaboration between small and medium-sized firms and universities. Despite such activities, further collaboration for technology development was not undertaken due to the differences in their research interests. Before designing government-funded UIC programs or entering into global collaboration programs, investigating the technological areas that are complementary to each other among potential collaboration partners and assessing their capabilities will help improve such a collaboration's performance. A systematic tool for this purpose is urgently needed.

Finally, the focus should be on the technology transfer from universities to industry by facilitating basic and applied research that can meet industry needs. A wide range of sub-technologies needs to be converged to introduce DTs in industry applications, which requires various collaborations, including UICs. The UIC best practices along with the need for technology collaboration are worth sharing.

6 Conclusions

In this study, we aimed to investigate the focus of universities and industries on DT technologies, as well as propose strategic UIC partner candidates to facilitate collaboration between industry and universities. To achieve this aim, we first collected DT-related publications and patents, and then we investigated their content through text mining, which produced six technological fields. Then, we designed three indices, the RTA, CII, and TCS, to investigate each field's characteristics regarding technological strength, technological impact, and collaboration level. Finally, we designed a portfolio map to investigate the relative strength of universities and industries, and to propose the four possible types of cooperation (entrepreneurship, frontierism, outsourcing, and taskforce). We also used the HHI to analyse the degree of the technological concentration of each technological field.

The proposed approach creates value for UIC strategies in the sector at an early stage of development, particularly characterised by converging technologies and closed innovation, where industry development can be fostered via facilitating vigorous interactions among innovation actors. Methodologically, the proposed portfolio map with three indices will be useful for understanding the technological strengths and weaknesses of universities and industries, and thus, finding a way to produce synergistic effects from UIC collaboration, which facilitates industrial growth. Practically, the research findings help with understanding the technology trends in DTs observed in publications and with patents. Centred on the fourth industrial revolution, DTs are innovative tools for developing manufacturing strategies, and thus, their trends are worth exploring. Recognising the potential value of DTs, previous studies have introduced the DT concept and application areas. Nevertheless, the concept is not yet set, with numerous technologies being fused around DTs, which makes it difficult to grasp DT technological trends at a glance. Furthermore, unlike most previous studies that adopted the qualitative approach to investigate the latest trends, applications, and research issues of DT technology, this study introduced a systematic bibliometric analysis method using publication and patent data. In practice, we expect the research findings to provide valuable insights for selecting partners to researchers and practitioners who are responsible for collaboration between universities and industries in DT technological fields.

However, despite the aforementioned contributions, this study has several limitations. First, although we proposed possible collaboration strategies for each type of DT field, the final selection of collaboration modes depends on various other decision-making factors. From this, the proposed approach needs to be elaborated as a tool for guiding a specific UIC strategy. Second, the analysis target was limited to publications and patents in this study. Considering not all technologies are published in the form of publications and patents, further study is needed to identify other data sources for analysis besides publications and patents. Finally, we conducted only a static analysis in this study given the small data size. A dynamic analysis may offer further valuable insights for monitoring technological trends. Future research will address these issues.

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Appendix

Table A1 Adjusting the value of publications and patents

	Cluster 1	*Cluster 2*	*Cluster 3*	*Cluster 4*	*Cluster 5*	*Cluster 6*	*Total*
Number of publications	32	52	69	46	58	32	289
Number of patents	6	36	8	12	10	6	78
Cited number of publications	65	306	186	365	458	55	1425
Cited number of patents	25	18	54	26	15	6	144
Number of weighted publications	21.2	46.9	47.2	50.7	66.8	16.5	249.3
Number of weighted patents	5.5	27	9	6	5	4.5	57
Total number of weighted documents in the university	57.6	40.1	41.5	79.7	94.7	23.2	326.8
Total number of weighted documents in the industry	7.6	46.2	27.6	29.2	31.1	7.27	148.9

Table A2 HHI analysis results by research institutes

Type	*Clusters*	*HHI*	*Top 3 research institutes*
Entrepreneurship	4	0.0371	Beihang University Siemens AG Shanghai University
	5	0.0177	Bremen Institute for Production and Logistics GmbH University of Stuttgart Chalmers University of Technology
Frontierism	1	0.0283	Beihang University Shandong University Technical University of Munich
	6	0.0474	General Electric Company Skolkovo Institute of Science and Technology South Ural State University
Task force	2	0.0558	General Electric Company Siemens AG University of Auckland
	3	0.0309	RWTH Aachen University Airbus Akselos.inc