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Research Trends of Cyber-Physical System Technology Applications in the Fields of Buildings and Equipment

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ABSTRACT

Purpose: The purpose of this study is to identify research trends based on a comparative analysis of cyber–physical systems (CPS) application research papers in the fields of domestic and international building and equipment. Papers and recent actual cases were identified to determine the current level and future development potential. **Method:** For this purpose, research papers published in domestic and international journals in the past five years were classified by year, field, topic, and keyword for an in-depth analysis. In addition, domestic and international representative cases were selected, and the applied technologies and performances were analyzed. **Results:** As a result of the research trend analysis, it was confirmed that the research in the fields of CPS and applied building equipment is increasing continuously. Most of the papers were published in the field of the building environment and equipment. In Korea, other fields dealing with policy and spatial psychology were associated with the highest number of papers, followed by the building environment equipment and planning divisions. Overseas, it was found that the number of papers in the fields of the building environment and equipment was significantly higher. Through this study, the level of CPS applications and the potential for development in the field of building and equipment were identified, and the direction and basic technology of the CPS and applied building energy optimization model planned to be developed in future research were confirmed.

KEYWORD
Building System
Cyber-Physical System
Digital Twin

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1. Introduction

1.1. Research Background and Purpose

In the era of the Fourth Industrial Revolution, advancements in information and communications technology (ICT) have led to the provision of smart environments to building users and residents as smart buildings and smart cities industries have become the focal points of the building and equipment fields. A smart environment refers to a new type of environment in which various ICT techniques, such as artificial intelligence (AI), Internet-of-Things (IoT), cloud, big data, mobile, and security are integrated in buildings, thus providing comfort, convenience, safety, and economic benefits in residential environments[1].

An industrial revolution is based on a cyber – physical system (CPS) platform which integrates various ICT types. CPS is a complex system in which a physical environment comprising sensors and actuators is combined with computing elements that control the physical environment in real time by simulating a virtual system[2]. Another term which is frequently mentioned in conjunction with CPS is the digital twin. The reason for which CPS and digital twin are gaining popularity is that they both deliver and utilize the information in the virtual and real worlds[3]. CPS focuses on monitoring and equipment control achieved by using the information of a physical environment, while a digital twin constructs a virtual world resembling the real world based on the information of a physical environment. The relationship between CPS and digital twin is interpreted in different ways depending on applications and research fields, but most perspectives are based on the same concept.

The global CPS market had a value of $6.0 billion in 2018, and is expected to grow at a compound annual growth rate (CAGR) of 9.3 % from 2019 to 2027[4]. According to Gartner Inc., the digital twin market is expected to grow at 45.4 % CAGR from $3.8 billion in 2019 to $35.8 in 2025[5]. Likewise, advancements in ICT are leading to a tremendously rapid growth in the technological development of CPS and market worldwide. The domestic market has been growing steadily from 5.5 trillion Korea won (KRW) in 2016 to 23 trillion KRW

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in 2021[6]. However, the market is concentrated in manufacturing and production industries, and original core technologies are being developed primarily at research institutes or schools. This has resulted in the use of products and technologies from overseas. Specifically, domestic technology applications in the building and equipment fields, such as the use of CPS in smart buildings, is still at a rudimentary step and lags advancements in overseas countries.

Therefore, the purpose of this study is to identify research trends by comparatively analyzing in depth CPS technology application studies as a preparatory step for the development of a building energy optimization model based on CPS applications. Furthermore, the study aimed to identify the current technological level, understand the limitations by analyzing actual cases, and to establish research directions and propose the use of CPS and relevant approaches in the fields of building and equipment. The outcomes of the study can be proven useful as they can be potentially utilized as basic data for research related to the construction of CPS and digital twin.

1.2. Research Method and Procedure

In this study, theoretical considerations and case analysis of various research papers were conducted to analyze current research and application status related to CPS applications in the building and equipment field. Domestic research papers were collected from academic journals published by a variety of societies and websites (Korea Education and Research Information Service, National Digital Science Library, National Assembly Library, and DBpia). Overseas research papers were collected from major academic journals, and from Google Scholar and Science Direct websites.

The papers published in the past five years (from 2017 and 2021) were identified by using several keywords, including “Cyber-Physical System,” “Digital Twin,” “Smart Building,” “Smart Home,” “IoT,” “Building Energy,” and “Architecture” in the paper title, keywords, and abstracts during the search.

Accordingly, only the studies in the building and equipment fields were selected by excluding the studies related to the manufacturing industry, transportation, and health management in which CPS and digital twin were applied. The selected studies were classified by year, field, topic, and keyword for an in-depth analysis, and a comparative analysis was performed for domestic and overseas research trends to derive the conclusion.

2. Theory of CPS

2.1. CPS Definition

CPS refers to a process in which computation, networking, and physical objects are combined such that the sensors embedded in the physical environment are used to communicate with a building information management system installed on a server or a computer through a network framework 〈Fig. 1.〉. CPS can be defined from a diverse perspective owing to a wide variety of applications. CPS is defined in the engineering and control fields related to building and equipment as follows.

- Combination of physical process and computing[7]
- Systems in which features for monitoring and controlling the objects in a physical world are integrated with computing[8]
- Complex systems in which physical elements comprising sensors and actuators are combined with virtual elements controlling the physical elements[9]

A digital twin that has been increasingly mentioned with CPS has evolved to be capable of simulating optimization by virtually implementing various physical objects or processes which exist in the real world. The level of a digital twin can be categorized into level 1 through level 3 as proposed by Gartner Inc. in 〈Fig. 2.〉[10]. The technologies supporting a digital twin have been consistently expanded and have become the main subject in the implementation of massive environments, such as buildings, factories, and cities. A digital twin in the building and equipment fields is implemented by integrating it in apartment complex and building simulations as well as in the design and testing of smart cities and construction sites[11]. CPS is considered as a concept encompassing a digital or an integral body of CPS, and is considered as a digital twin, but certain scholars claim that these two keywords need to be distinguished.

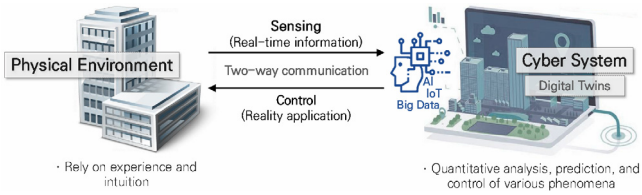


Fig. 1. CPS concept

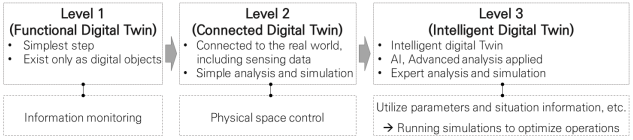
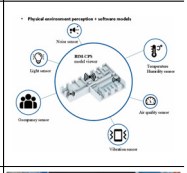
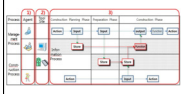
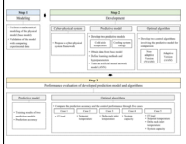
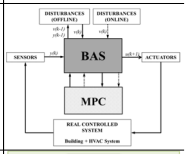
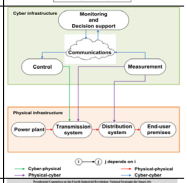
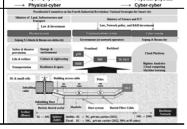


Fig. 2. Definition of digital twin based on a step-by-step process

Table 1. CPS and digital twins of building and equipment field

Field		Main Technology	Main Achievements
Building	Smart building [12]	· Electrical energy prediction and control · Energy and environmental monitoring · CPS platform service	
	Smart factory [13]	· Saving energy and cost · CPS platform service · Data monitoring	
	Smart construction management [14]	· ICT platform for manager support module · IoT connection · Data monitoring	
Equipment	Energy Performance [15][16]	· Data center cooling system control · Cooling energy saving · Sensing and ANN · CPS control platform	
	Efficiency [17]	· MPC method CPS platform · HVAC system efficiency improvement	
City	Smart Grid [18]	· Management cost of energy transfer · Control, computation, communication, security	
	Smart City [19]	· CPS-based smart city service policy	

Abbreviations: CPS: cyber–physical systems, ICT: information and communications technology, IoT: Internet-of-Things, ANN: artificial neural network, MPC: model predictive control, HVAC: heating, ventilation, and air conditioning

2.2. CPS in the Building and Equipment Fields

CPS and digital twin in the building and equipment fields are mostly used for building energy management, automated control of an equipment system, monitoring of internal environments, and for big-data collection, operation, and optimization. Furthermore, they are also applied in various fields, including transportation, energy, and environment from the perspective of smart cities and city planning for multiple building groups instead of a single building.

CPS and digital twin in the fields of building and equipment provide intuitive monitoring screens, automated control instead of manual control, and advanced prediction and control performance inspection features to building managers and residents. Major CPS and digital twin technologies applied in the building and equipment field are listed in 〈Table 1.〉.

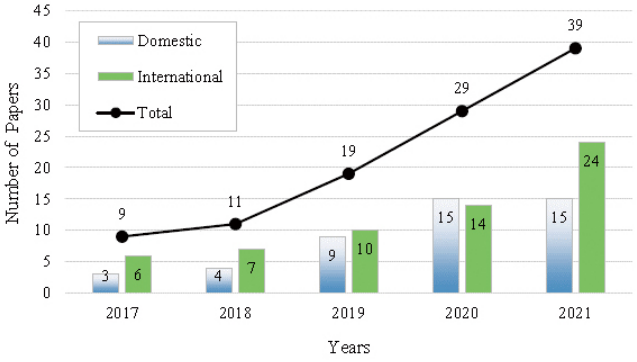


Fig. 3. Chronological trend of CPS publications from 2017 to 2021

3. Research Trend Analysis

3.1. Research Trends by Year

In total, 107 domestic and overseas papers related to CPS applications in the building and equipment field were collected. The number of papers was examined to analyze the research trends by year. As shown in 〈Fig. 3.〉, starting with nine papers, including three papers published in Korean journals and six papers published in international journals in 2017, a total of 39 papers including 15 domestic papers and 24 international papers have been published in 2021.

3.2. Research Trends by Field

The number of research trends by field is presented in 〈Table 2.〉, while the domestic and international research trends by year are illustrated in 〈Fig. 4.〉. The building and equipment field has been further categorized into building environment and system, planning, construction, structure, material, and others. Among the total of 107 domestic and international papers published, the number of papers related to the environment and system was the highest at 60 (59 %), followed by 21 papers related to "others" (20 %), 16 papers related to planning (16 %), four papers related to construction (4 %), one paper related to structure (1 %), and zero papers related to material (0 %). In other fields, research has been conducted on the analysis of previous studies related to CPS applications, building/equipment related policy for CPS applications, and building space psychology for CPS utilization.

In the building and equipment field, CPS application research was most actively conducted in the building environment and system fields. In addition, a growing interest in planning and others fields is also expected. The number of studies in the construction field has been gradually increasing since 2020, whereas no research outcomes have been identified in the material field in the past five years.

Table 2. Number of papers published in the literature classified by field

Field	2017	2018	2019	2020	2021	Total	Ratio (%)
Environment & System	7	7	11	19	20	64	60
Planning	2	2	3	4	6	17	16
Construction	0	0	0	3	1	4	4
Structure	0	0	0	0	1	1	1
Material	0	0	0	0	0	0	0
etc.	0	2	5	3	11	21	20
Total	9	11	19	29	39	107	100

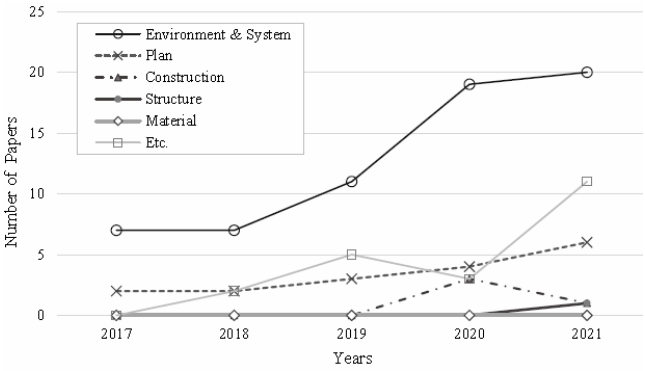


Fig. 4. Research trends associated with the building and equipment fields

3.3. Research Trends by Topic

The research trends by purpose and topic are summarized in 〈Table 3.〉. Research topics were further classified according to the research fields categorized in Section 3.2.

The environment and system field was classified into building energy, air-conditioning (AC) systems, indoor environment, and renewable energy subfields. The number of papers related to building energy was the highest at 35 (33 %), followed by 17 papers related to AC systems (16 %), 12 papers related to the indoor environment (10 %), and one paper related to renewable energy (1 %). In the planning field, 11 papers (10 %) were related to urban planning and six papers (6 %) were related to architectural design. In the structure field, one paper (1 %) was related to optimize structural design. In the construction field, four papers (4 %) were related to process control and no papers related to cost estimation were found. The material field has been excluded from 〈Table 3.〉 because no paper related to CPS applications has been published in the past five years. In other fields, 11 review papers (10 %), five papers on policy (5 %), and five papers on psychology (5 %) had been published.

Table 3. Research trends by topic

Field	Topic	No.	Ratio (%)
Environment & System	Building energy	35	33
	System	17	16
	Indoor environment	11	10
	Renewable energy	1	1
	Subtotal	64	60
Planning	Urban planning	11	10
	Architecture design	6	6
	Subtotal	17	16
Construction	Process control	4	4
	Cost estimation	0	0
	Subtotal	4	4
Structure	Structural optimized design	1	1
	Subtotal	1	1
etc.	Review paper	11	10
	Policy	5	5
	Psychology	5	5
	Subtotal	21	20
Total		107	10

Fig. 5. Keyword word cloud

3.4. Research Trends by Keyword

The outcomes associated with the analysis of the keywords of the studies are presented in the form of a word cloud, as shown 〈Fig. 5.〉. Text sizes of the keywords vary according to their frequency of use. Accordingly, the keywords with a higher frequency are represented with a larger text size.

From the perspective of CPS applications in the building and equipment field, the following keywords demonstrated a strong correlation: building, physical, cyber system, energy, digital twin, virtual, IoT, optimization, management, simulation, intelligent, efficiency, thermal, predictive, deep learning, and data. This result can be interpreted in such a way so that the application of CPS and digital twin in the respective field is mostly focused on IoT, intelligent, predictive, deep learning, and simulator technologies for achieving optimal control of building energy.

3.5. Comparison of Domestic and International Research Trends

The trends of domestic and international papers are presented in 〈Table 4.〉 and 〈Table 5.〉.

In total, 46 papers have been published in domestic journals. Specifically, 13 papers (28 %) have been published in the fields of environment and system and planning. In terms of topics, seven papers were related to AC system control, four papers were related to building energy, and two papers were related to the indoor environment. In the planning field, nine papers and four papers were related to urban planning and architectural design, respectively. Additionally, four papers were related to construction, and one paper was related to structure. No paper related to material has been found. In the material field, CPS applications were considered as part of the building design automation in the building and equipment field, but integration with CPS has not been considered as a core research topic in recent years. Based on the observed trends, research on materials can be developed further in the future with respect to automation and supply network construction by associating efforts with a CPS platform used for the evaluation of environmental and strength characteristics of materials and economic optimization. Among the 15 papers in the others field (33%), five papers were related to space psychology, four papers were related to research trends, and two papers were related to policy.

Table 4. Domestic journal papers in the fields of building and equipment

Field	2017	2018	2019	2020	2021	Total	Ratio (%)
Environment & System	1	1	2	7	2	13	28
Planning	2	2	3	3	3	13	28
Construction	0	0	0	3	1	4	9
Structure	0	0	0	0	1	1	2
Material	0	0	0	0	0	0	0
etc.	0	1	4	2	8	15	33
Total	3	4	9	15	15	46	100

Table 5. International journal papers in the fields of building and equipment

Field	2017	2018	2019	2020	2021	Total	Ratio (%)
Environment & System	6	6	9	12	18	51	84
Planning	0	0	0	1	3	4	7
Construction	0	0	0	0	0	0	0
Structure	0	0	0	0	0	0	0
Material	0	0	0	0	0	0	0
etc.	0	1	1	1	3	6	10
Total	6	7	10	14	24	61	100

A total of 61 papers were published in international journals in which the highest number of papers was on building environment and systems (51 papers in total). Six papers and four papers were related to others and planning, respectively, while no paper has been published on construction, structures, and materials. Unlike the domestic trend of published papers and how these varied in terms of topics, the internationally published papers are mostly focused on the building environment and systems.

The trends of domestic and international papers are shown in 〈Fig. 6.〉 and 〈Fig. 7.〉. The number of domestic papers began to gradually increase since 2019. The building environment and system field with a high number of published papers reached its peak in 2020 but slightly decreased in 2021. At least two papers have been published every year in the planning field over the past five years. In the others field, the number of studies on space psychology and research trends gradually increased; this trend is expected to increase further in the future. Starting with the six papers in the building environment and system fields in 2017, the number of published international papers has consistently increased to 18 in 2021. A slight increase in 2021 was also observed in 2021 in the others field which include planning, policy, and research trends. By contrast, no paper has been published on construction, structure, and material fields over the past five years.

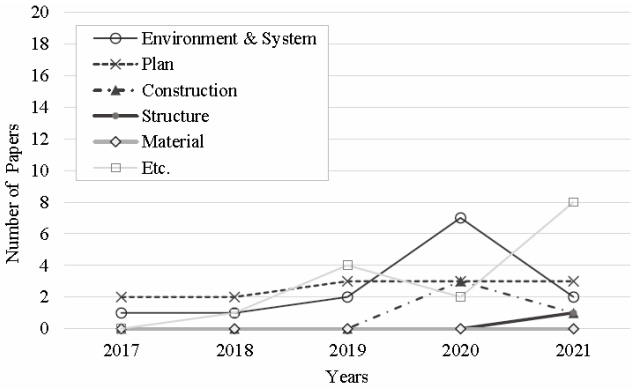


Fig. 6. Domestic journal papers in the fields of building and equipment

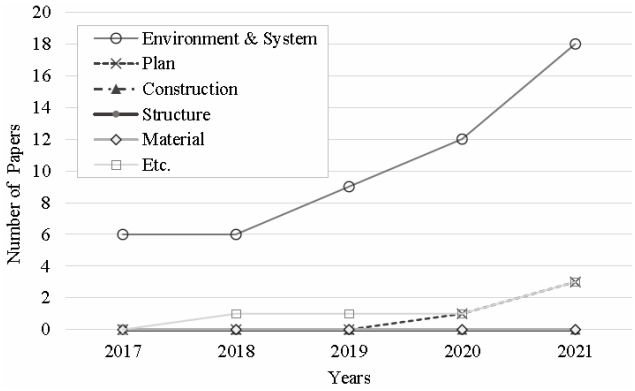


Fig. 7. International journal papers in the fields of building and equipment

4. Case Analysis

In addition to a research trend analysis, both domestic and international cases of applying CPS in the building and equipment field have been investigated and analyzed for the identification of current technological levels, thus establishing future research directions, and proposing CPS applications.

4.1. International Cases

Predix of GE is a cloud platform developed for the integration of the entire software and equipment of the GE group with the industrial internet, as shown in 〈Fig. 8.〉[20]. A digital twin of the GE is constructed by building an application for efficient equipment management from hardware dedicated to the control of various software dedicated to data collection and analysis. Service types are optimized for algorithms for equipment and economic analysis as well as information delivery. For the construction of an environment wherein all the objects can be measured, connected, and controlled, sensors are installed on equipment to collect and analyze data in real time, and algorithms using machine learning are also provided. This technology is applied to various projects, including smart grid and wind power plants.

For instance, real-time monitoring and operation management of power plants are performed at the GE Power M&D Center. The operation status of gas turbines, generators, and other equipment installed around power plants supplying power to 350 million people in nearly 60 countries around the world is monitored in real time based on the use of the digital twin technology. Accordingly, possible situations are predicted in addition to analyses at the most appropriate time for maintenance and optimized power plant operation methods. In particular, a cost loss of approximately $2 million—which incurs in the case of a grid break—could be saved with a priori detection of anomalies. Concurrently, predictability could be improved by employing advanced warning notifications for the problem that may arise from service interruption by applying an asset performance management solution[21].

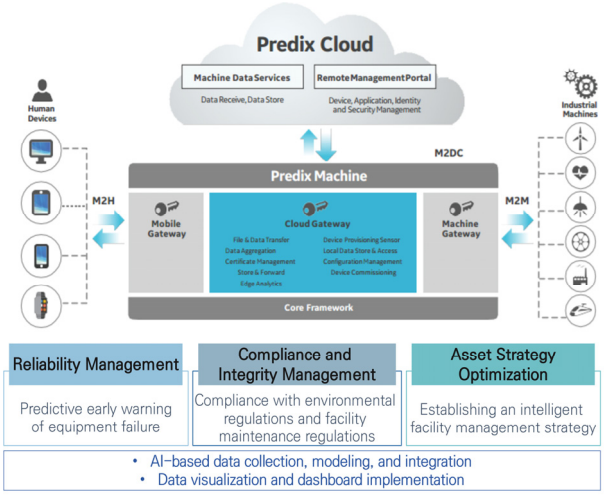
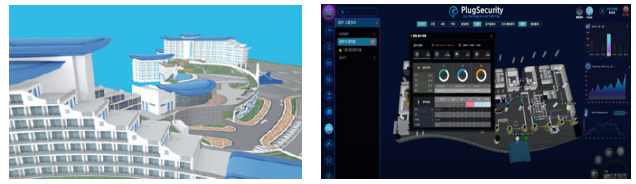


Fig. 8. GE predix cloud concept diagram and applications (AI: artificial intelligence)

4.2. Domestic Cases

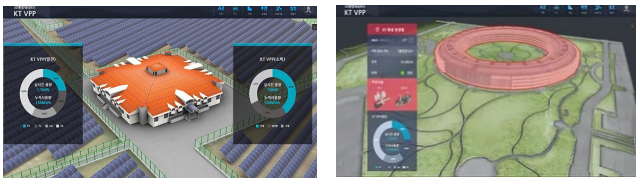
The PLUG Builder is an integrated operation platform based on CPS, digital twin, and a three-dimensional (3D) modeling tool of PLUXITY which is a specialized company in Korea. Real-time monitoring and various simulation features are provided by integrating GIS and BIM data based on a 3D virtual environment of buildings and cities. Different situations can be predicted and prepared for through-simulation features that vary depending on building or service types, thus enabling efficient building design and urban planning[22].

Notable solutions include PLUG Building, PLUG City, and PLUG Energy, as shown in 〈Fig. 9.〉. PLUG Building provides integrated building security and smart building services wherein more intuitive management and immediate response are possible. It has been applied in Daemyung Resort, Seoul Grand Park, and Suwon City Hall. PLUG City is a CPS-based, contactless, integrated city operation solution which provides various features including monitoring of 3D maps of MOLIT, integrated monitoring of linked public data, urban energy monitoring, and closed-circuit television intelligent monitoring. Recently, a variety of simulations required in the building design stage, such as the sunlight, visibility, prospect, and wind path have been studied.



a) PLUG Building

b) PLUG City



c) PLUG Energy

Fig. 9. Representative CPS digital twin technologies of PLUXITY

Several existing cases include the digital twin of Busan Eco Delta Smart City, Busan B-Con development, the autonomous driving project in Daejeon, and a 3D indoor map of Seoul. PLUG Energy solution enables efficient energy management based on real-time power generation measurements for new renewable energy. The process of absorbing, storing, and conversion of solar energy is visualized and simulated to provide statistics and analyses for power generation status and energy usage of each facility. Research is conducted continuously on the development and demonstration of the energy-saving smart lighting platform technology, integrated KT-MEG solar light monitoring system, and construction of a zero light pollution model complex in Seoul.

Furthermore, other solutions, such as PLUG Data, which performs real-time monitoring of temperature/humidity of data centers, panel boards, and the heating statuses of servers, and PLUG Warehouse, which is capable of serving as the distribution center for provision and visualization of information on the indoor environment, automatic calculation of warehouse area, and work status visualization, are provided[23].

In addition to the two cases analyzed above, various platforms utilizing CPS and digital twin technology are launched and applied across a diverse range of fields. The competition in the CPS and digital twin market is intensified owing to fusion of the ICT technology fusion and integration of IoT and simulation technologies. However, despite the outstanding of competencies of various companies and research institutes in basic software and hardware required for the development and operation of CPS and digital twin technologies in an advanced ICT country, the core technology in Korea is still dependent on foreign technologies of overseas companies, while integrated solutions for optimization and prediction through CPS are still insufficient.

Immediate inspection and response to the problems occurring in a CPS and digital twin platform are possible, while energy, air conditioning, safety, and firefighting solutions that have been managed separately in existing systems are now subject to integrated management. Therefore, labor and time required for management and operation can be efficiently saved when compared with existing systems.

To ensure compliance with timelines pertaining to the use and domestic applicability of CPS, of which the necessity and influence are gradually growing, the reinforcement of integrated solutions pertaining to original technology competencies must take precedence for lowering the dependence of domestic companies and research institutes on the CPS technologies of overseas companies. In addition, to expand the applicability of CPS in the building the equipment fields, the issues and limitations of conventional technologies, such as building energy management system (BEMS) and building information modeling (BIM), which are based on a similar concept as that of CPS, must be improved to allow further developments and applications of the services integrated with CPS and digital twin.

5. Conclusions

This study examined the cases of domestic and international papers published over the past five years (from 2017 to 2021) which were related to CPS applications in the building and equipment fields. The following conclusions have been drawn based on comparative analyses of the papers identified based on year, field, topic, and keyword.

A total of 107 papers were examined in this study. Among these, 46 papers were published in domestic journals, while 61 papers were published in international journals. The number of papers has steadily increased from nine (in 2017) to 39 papers (in 2021). It can thus be concluded that the research on CPS application in the building and equipment fields has been expanding.

The building and equipment fields were further categorized into building environment and system, planning, construction, structure, material, and others. The top three fields with the most number of published papers include the building environment and system with 84 papers (60 %), others with 21 papers (20 %), and planning with 17 papers (16 %). In the building environment and system field with the highest number of published papers, most research focused on building energy. Among the papers published domestically, the highest numbers were in policy and space psychology in the others field, followed by the building environment and system field, and the planning field. The papers published internationally had a significantly higher number of papers in the building environment and system fields. Research in Korea is being conducted across several different topics, whereas overseas studies tended to concentrate on the building environment and system fields.

The studies were analyzed by using a word cloud of keywords. The results showed that the application of CPS and digital twin was mostly focused on IoT, Intelligent, Predictive, Deep learning, and Simulator technologies for achieving optimal control of building energy.

This study analyzed the current status of CPS applications in the building and equipment fields based on research trends and case studies. Accordingly, the current level of CPS applications and development potential in the building and equipment field

were proposed, while a) the basic technology was identified, and b) the direction of a building energy optimization model was established based on the anticipated, future CPS applications. Therefore, research with improved efficiency and performance compared with conventional technology is expected to be conducted by applying the advantages of CPS, such as immediate identification of situations, real-time response, and integrated management to a building energy optimization model.

Acknowledgement

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