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ANALYSIS OF GLOBAL COMPETITIVENESS OF ENGINEERING MODELING AND SIMULATION TECHNOLOGY FOR NEXT-MANUFACTURING INNOVATION: USING QUANTITATIVE ANALYSIS OF PATENTS AND PAPERS

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Abstract. *To overcome the manufacturing crisis of Korea during the 4th industrial revolution, the nation's design competence should be improved to enable it to become a leader in manufacturing innovation. In this study, we examined Engineering Modeling and Simulation (Eng. M&S) technology from the viewpoint of next-generation manufacturing innovation, and used patent and dissertation information to analyze the technical competitiveness of global manufacturing competitors. We confirmed that Eng. M&S technology is currently leading the US and European countries; Korea competitiveness is 73.9% of that of the United States. Developed countries are implementing various policies to foster the technology for manufacturing innovation, and Japan and China have their own policies for Eng. M&S. We suggest that Eng. M&S technology should be used in Korea as the basic manufacturing technology to increase the design capacity of Korean manufacturing companies. To realize this adoption, the recognition of M&S is most important, and policies should be set up at the national level.*
Keywords: Engineering modeling and simulation, Technology competitiveness, Patent and paper analysis

1. **Introduction.** The 4th industrial revolution entails innovation in the entire manufacturing industry [1]. In the OECD's view of the 'convergence between new digital technology and process' of the 'Next Production Revolution' [2], Engineering Modeling & Simulation (Eng. M&S) has been mentioned as a core technology to enable manufacturing innovation.

Manufacturing engineering is a crucial factor that affects the competitiveness of manufacturing industry as the manufacturing environment changes. In other words, it plays a key role in supporting the creation of new value and demand in a rapidly changing manufacturing environment, such as revitalization of industrial interdependence and reduction of product life cycle. Accordingly, manufacturing engineering is expected to lead to technological innovation of manufacturing industry by systemic linkage and structural acceleration of manufacturing industry [3].

M&S technology, which is mainly used in the product design process of the whole manufacturing engineering activities, is located in the initial stage of the manufacturing value chain and creates high added-value. In addition, computer-based production methods have been commonly used and design and manufacturing methods of products have became smart, Eng. M&S technology is recognized as an indispensable technology in manufacturing [3].

Eng. M&S uses virtual design (Modeling) and numerical analysis (Simulation) methods, especially during the design process of product development. Eng. M&S minimizes the need to develop physical prototypes and reduces the number of errors during the design process, and can thereby reduce the time and cost of development [4]. 'Digital Design and Simulation' is one of the core technologies to strengthen manufacturing competitiveness [5].

In Korea, manufacturing industry is a major part of a whole nation's economy and accounts for about 32% of GDP, which is much higher than those of developed countries in the manufacturing industry such as Germany, Japan, and the United States. However, Korea has recently suffered the first negative growth rate in the manufacturing industry in the past 53 years [6]. To overcome this crisis manufacturing industries need to have an innovative approach for the product design and development process. In this regard, Eng. M&S technology is important to increase concept and basic design capability which are lacking in Korea. To systematically promote this technology, a national technological competitiveness assessment is needed; however, relevant policy research activities are insufficient.

Therefore, in this study, we analyze global competitiveness of Eng. M&S technology by a quantitative method using patents and research papers information, and identify policy implications. Section 2 presents related studies on the meaning and role of Eng. M&S in the manufacturing innovation, and the research method. Section 3 introduces the research method in detail. Section 4 presents the results of Eng. M&S competitiveness including information of data collection, and the final section presents conclusions and implications.

2. **Related Research.**

Modeling and Simulation (M&S) is a field that has its own knowledge system, theory and research method [7], but the academic definition of M&S has not yet been clearly defined. Given the importance of M&S in industrial application, M&S concepts, related terms and the scope must be defined comprehensively [8].

The US Department of Defense defines M&S as a simulation that implements a physical, mathematical, and logical model that represents a system, entity, phenomenon, or process; this is currently the most commonly-used definition [9]. The National Science Foundation defines M&S with the engineering view as 'establishing a model for an engineering system and using it to predict physical events or responses using computational methods'. Engineers can use Eng. M&S to modify designs to see results immediately, and to compare and evaluate alternatives without creating expensive prototypes or taking risks [10].

Combining Eng. M&S technology with manufacturing enables building and evaluation of virtual prototypes, instead of physical models. Therefore, R&D activities based on real tests, and experiments based physical prototypes can be replaced by Eng. M&S that uses virtual product design (Modeling) and engineering analysis (simulation); this substitution reduces the time and cost of product development. Eng. M&S is additionally defined as a technology that uses Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) to predict problems and to provide optimal design during the product-design stage which mainly contributes to the increase of product performance.

Manufacturing innovation refers to a change of manufacturing paradigm [12]. Several global consulting firms have identified Eng. M&S as a technological alternative to replace the existing manufacturing process [12] and also as a key technology for preparation to change manufacturing paradigms. However, M&S has not been classified as one definite field, so little research has been conducted to evaluate it.

Advanced countries have actively developed CAD/CAE techniques [13], which dramatically improve the productivity and reliability of manufacturing processes in these countries. In contrast, currently Korea merely imitates the technologies of developed countries, and is therefore at a relatively inferior level of manufacturing innovation [13]. Thus, because the manufacturing environment is becoming increasingly complicated, Eng. M&S should be introduced nationally to improve Korea's manufacturing competitiveness. However, the previous research cannot be applied to the current situation in manufacturing innovation; to understand current technology competitiveness, new research is needed.

To systemically nurture a specific technology of national importance, the technological competence of the country should be analyzed. This analysis has been performed [14] by consulting experts and international trends but this qualitative method has limited accuracy. This qualitative method can be objectively complemented by quantitative data analysis, which can measure technological competitiveness from the viewpoint of 'accumulated knowledge' [14].

Patent information has been used as an index of innovation in industry science, and technology as a reliable measure of a nation's capacity to innovate [15]. Bibliometric empirical research based on research papers also contributes strongly to establishing effective science and technology policies [16]. Combined analyses of patents and research consider both technical (practical) and scientific (basic research) trends, and thereby increase the accuracy of measurements of the levels of science and technology in a country or industry.

However, recent analyses that consider patent or paper information separately to compare the technology competitiveness of countries have been dominated by studies that use country-specific characteristics based on some specific indicators [17-20]. To eliminate the limitations of this restricted analysis, an integrated technology level analysis that uses both patents and papers has emerged. Recent research has developed a model that evaluates composite technology level by considering representative individual indicators [21-24].

In the case of the most recent study [24], a composite evaluation model considering both patents and paper information is proposed. The researchers solved the multi-collinearity problem of the past models and confirmed the possibility of empirical analysis of the software field to replace the Delphi method. In this study, we will follow the technology level evaluation model given in [8], because Eng. M&S is similar to the software (SW) field, which includes SW technology related to CAD and CAE, and because the model has been validated.

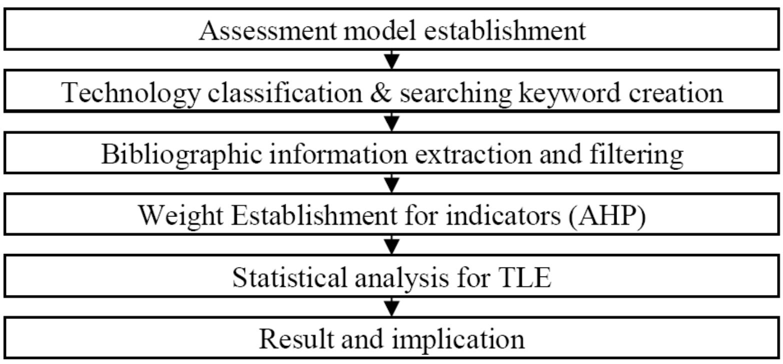

Figure 1. Research framework

3. **Research Method.** Previous research to evaluate the technology level by using the information of patents and papers has established a six-step process as shown in Figure 1 [24]; we followed this process. (1) We set up a model that uses patent information to measure national competitiveness. (2) We consulted a pool of experts who each had more than 10 years of experience in a field related to Eng. M&S; based on their insights we developed a classification of Eng. M&S technology, and developed keyword sets for searches. (3) We assembled analysis data by consulting application/publication patents in USPTO and bibliographical information in SCOPUS, and refined missing parts of the retrieved data. (4) We performed Analytic Hierarchy Process (AHP) analysis to derive the weight of each indicator. (5) We stabilized the data by applying basic statistics, then calculated individual indices; and then standardize the value multiplied by the index weight to derive the final technical competitiveness score. (6) We extracted results and implications.

3.1. **Definition of target technology: Engineering M&S technology.** Eng. M&S has been largely divided into modeling part and simulation part, and mesh generation step has been considered as a separate part: preprocessing for solving. First, a formal definition for 'Computational Geometry Modeling' is 'computer-based representation, analysis, synthesis (design) and computer-controlled manufacture of two and three-dimensional shapes' [25]. Solving is used to create a real world of complex features prediction and evaluation. Meshing is commonly regarded as a preprocessing step to derive the overall numerical value of a concept image by dividing a model into a polygonal or polyhedral model on a computer and assigning a calculation formula per lattice [26]. The related terms are summarized in Table 1.

Table 1. Technology classification and keywords of Eng. M&S

Technology	**Classification**	**Process**	**Related keywords**
Engineering Modeling & Simulation	Modeling	Geometry Modeling	Wire-frame modeling, Surface modeling, Solid modeling, Half-space, topological method, CSG, B-rep, Feature-based...
	Simulation	Meshing	Mesh topology first, Nodes first, Adapted mesh template, mesh smoothing, topology decomposition, node connection, grid-based, geometry decomposition, triangulation, quadrilateral, tetrahedron, hexahedron...
		Solving	Structural analysis, Fluid dynamics analysis, FEM, FDM, FVM, DSMC, LBM, SPH, PIC, PPM, PEM, LES, DNS...

3.2. **Patent and paper indicators and composite TLE model.** According to Cho and Lee [24], the composite TLE model consists of two models that represent patent and paper information each. The patent-based competitiveness model is defined as 'Patent AMC', the paper-based model as 'Paper AC' and the integrated technology level evaluation model as 'Composite TLE' (3), which can be calculated as following Equations (1)-(3). W, T, and Z in Equations (1) to (3) represent weights, and PAI, PMI, PCI, BAI, and BCI refer to indices of patents and papers. Analysis of patents considers activity (PAI), marketability (PMI) and number of citations (PCI). Papers have no market power, so they are analyzed based on current frequency of citation (BAI) and total number of citations (BCI). Detailed descriptions for the indices of patents and papers are given in Table 2 and Table 3 [23,24].

$$\text{Patent AMC} = W \times P' = (W_1 \times PAI) + (W_2 \times PMI) + (W_3 \times PCI) \quad (1)$$

$$\text{Paper AC} = T \times B' = (T_1 \times BAI) + (T_2 \times BCI) \tag{2}$$

$$\text{Composite TLE} = Z \times U' = (Z_1 \times \text{Patent AMC}) + (Z_2 \times \text{Paper AC}) \tag{3}$$

Table 2. Patent indicators for Patent AMC

Term	Statistics	Definition	Technical meaning
PAI	Patent activity	Patent applications (PA) of nation i in technological field (TF) $F \Rightarrow \text{PA}_{iF}/\text{PA}$ for all competitors in F	Extent of R&D expenditure by i in F (interest of i in F) or competitive technological position of i in F (quantitative)
PMI	Patent market-power	Size of patent family (PF) and share of patents for triad (US, JP, EPO) PA_{ik}	Economic quality of i's PA (international scope of protection)
PCI	Patent citation	Average citation frequency of PA_{ik}:PC_{iF}	Economic quality of i's PA (competitive technological strength of i in F)

Table 3. Paper indicators for Paper AC

Term	Statistics	Definition	Technical meaning
BAI	Bibliometric Activity	Paper publications (PP) of nation i in technological field (TF) $F \Rightarrow \text{PP}_{iF}/\text{PP}$ for all competitors in F	Extent of R&D expenditure by i in F (interest of i in F) or competitive technological position of i in F (quantitative)
BCI	Bibliometric Citation	Bibliometric citations (BC) of nation i in technological field (TF) $F \Rightarrow \text{BC}_{iF}/\text{PP}$ for all competitors in F	Scientific quality of i's PP (competitive scientific strength of i in F)

3.3. **Determination of weight for TLE model.** As the importance of the individual indicators depends on the technical characteristics and the situation of the time, weights for each indicator and model can be different. In this study, the weights for each indicator were derived using AHP, which compares qualitative variables with each other and draws priorities. AHP analysis was conducted by 12 experts for Eng. M&S or quantitative analysis in academia and research institutes (Table 4).

Table 4. The AHP analysis result for determination of weight for indicators of TLE

TLE (1.000)	Patent AMC (0.623)	PAI (0.356)/PMI (0.232)/PCI (0.412)
	Paper AC (0.377)	BAI (0.214)/BCI (0.786)

3.4. **Data stabilization and standardization.** Seo [21] suggested that appropriate transformations should be made to compensate or prevent the standard variability and distorted distribution of the indicators measuring the level of technology, and standardization should be done through the re-scaling method. In this study, we used the square root transformation for raw data that is collected to improve the stability of data processing. To ensure data comparability, data for the highest-ranking countries were defined as 100%, and then data for the remaining countries were expressed as a percentage of that value [21,24].

4. **Results and Discussion.** The countries considered were South Korea, USA, Japan, France, Germany, UK and China. The search period was 2001.01.01 to 2016.12.31; the databases consulted were the USPTO for patents and SCOPUS for papers. After data cleansing, 907 patents and 2,551 papers were used (Table 5).

Table 5. Overview of analysis data

	Patent	**Paper**
Target technology	Eng. M&S (Geometry Modeling, Meshing, Solving)	
Target country	Korea, USA, Japan, France, Germany, UK, China	
Period	2001.1.1∼2016.12.31 (by application year)	2001.1.1∼2016.12.31 (by publication year)
Data type and DB	A1, B1, B2 in USPTO DB	Published papers in SCOPUS
The number of documents	907	2,551
Analysis time point	April 17, 2017 ∼ May 28, 2017	

Composite TLE scores (Table 6, Figure 2) of the countries were calculated as percentages of the country with the highest technological competitiveness. USA has the highest M&S technology competitiveness, followed by Germany and the UK ∼90% of the USA level. France's competitiveness is similar to the average of the seven countries. Japan and Korea had similar levels with about 70% of US competitiveness. China had the lowest competitiveness, about 60% of that of the US.

Table 6. Aggregate patents and papers statistics in Engineering M&S, 2001-2016

※ The most competitive country = 100 (%)

Technology	Korea	USA	Japan	France	Germany	UK	China	Average
M&S	73.9	100	75.2	78.3	90.5	89.8	60.5	81.2
Geometry Modeling	78.8	92.9	89.6	78.3	76.4	100	56.7	81.8
Meshing	51.0	100	82.1	82.8	97.4	94.0	27.4	76.4
Solving	72.7	100	69.2	79.5	91.6	83.2	63.3	79.9

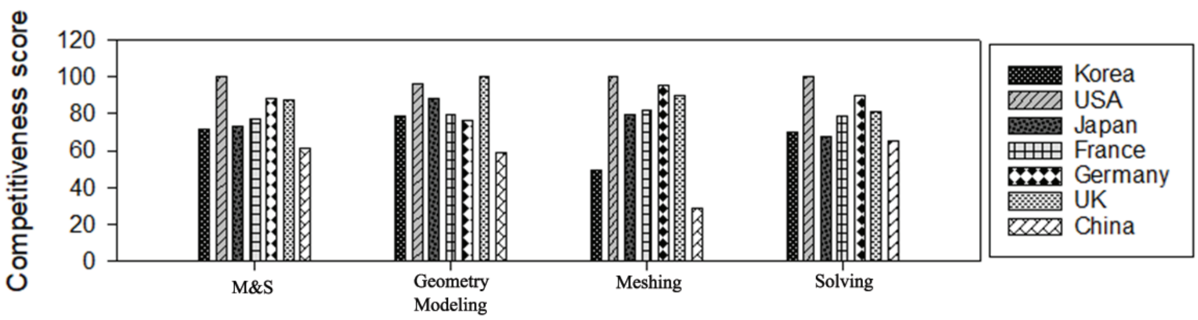

Figure 2. Comparison of TLE score in Eng. M&S by countries, 2001-2016

The United States, with the most advanced Eng. M&S technology, operates DMDII, a manufacturing innovation organization, to encourage utilization and distribution of Eng. M&S as a part of the 'National High-tech Manufacturing Strategy (2012)'. The United States is now looking beyond the importance of technology adoption to the efficient use of technology [27]. Europe is at the top of Eng. M&S competitiveness and has been promoting a public-private community for M&S support project, for example using FORTISSIMO to expand the use of M&S to small and medium enterprises. Also, 'Simulation' is one of the nine essential technologies for the implementation of Germany's 'Industry 4.0' and 'Factories of the Future' [28].

In Japan, the modeling competency is excellent, but competitiveness in the solving field is relatively lower. However, Japan's Science and Technology Innovation Strategy 2015 is striving to nurture the technology nationally by giving top priority to development of optimal design technology by high-speed simulation [28]. China, which has the lowest score, seems to be trying to nurture design technology centered on CAE technology rather than on CAD already developed in advanced countries. China has established 'China manufacturing 2025', and set the digital R&D design tool penetration rate as one of four major projects in the field of IT manufacturing convergence [28]. Korea is currently more competitive than China, but can be caught by that country, which is promoting to M&S technology in the national level. Clearly, all of these competitors are acutely aware of Eng. M&S as a means of increasing their capacity for manufacturing innovation, whereas Korea has an insufficient recognition of the importance of Eng. M&S technology.

5. **Conclusion and Implications.** The 4th industrial revolution is stimulating a big change in the manufacturing methods and value chain of the manufacturing industry, and M&S is one of the key technologies to produce innovations to adjust to the new paradigm. This trend means that the national economy should be revitalized to increased manufacturing competitiveness by fostering M&S technology and applying it to the manufacturing industry. In this study, we evaluated the competitiveness of Eng. M&S technology in major countries by using a quantitative method based on analysis of information about patents and research papers. Analyses considered manufacturing innovation. An integrated evaluation model was developed to consider key indicators that represent activity level, market power, and impact power. With research results, we compared political efforts of the competitors to increase adoption of Eng. M&S. The countries that have high competitiveness in Eng. M&S technology did it by setting up the relevant political infrastructure early at the national level, and have been actively supporting the use of Eng. M&S S/W in the private sector of manufacturing. Also, because China has set up a policy to promote Eng. M&S and thereby threatens to overtake Korea competitively, Korea must hurry to develop and implement a plan to develop and apply the technology to the manufacturing industry at a national level. Eng. M&S is globally recognized as a key technology for manufacturing innovation; accordingly, we suggest that Eng. M&S technology should be used in Korea as the basic manufacturing technology to increase the design capacity of Korean manufacturing companies. To achieve this goal, the importance of Eng. M&S as a method of manufacturing innovation should be recognized, and policies should be developed to nurture and distribute the technology at the national level. Second, the government should actively set up a consortium to facilitate development and diffusion of Eng. M&S technology and to accept opinions from manufacturing companies in various fields. Lastly, to lead the next manufacturing innovation with Eng. M&S technology, it should be fostered in the manufacturing environment in Korea from the fundamental level by imposing appropriate policies. To reach this goal, realistic alternatives must be developed by further research into the status of Eng. M&S use in the manufacturing environment of Korea.

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