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A Diagnosis and Evaluation Method for Strategic Planning and Systematic Design of a Virtual Factory in Smart Manufacturing Systems

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Technology developments are ushering in the introduction of smart manufacturing (SM) systems, unmanned production lines and sustainable production. SM will minimize human intervention and allow systems to control sites intelligently. To realize such an era, many global manufacturers are trying to develop different SM methods. The virtual factory is a digital-manufacturing-based SM system that predicts, solves (improves) and manages (controls) problems with overall production tasks by linking them to the actual sites, in a virtual environment. This paper proposes a strategic plan and a systematic design for the efficient implementation and application of the virtual factory to real manufacturing companies. In addition, an efficient and systematic means of introducing the virtual factory is presented via diagnosis, analysis and establishment of the strategy, implementation plan and system design case with an electronic parts manufacturing company.

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1. Introduction

In manufacturing companies, different types of production have been developed based on diverse production strategies and differentiated technologies. Fig. 1 shows the production types, differentiating factors and manufacturing strategies by era.[1] The most important factors in manufacturing companies evolved from mass production in the 1970s to quality and efficiency in the 1980s. In the 1990s and 2000s, production types were developed to respond flexibly to customer demand, and mass production capacity was established to produce products according to diverse customer requirements.

Technology developments are supporting the gradual introduction of smart manufacturing (SM) systems, unmanned production lines and sustainable production. SM is expected to minimize human intervention and allow systems to control the sites intelligently. The SM method is already being used in some industries.

One of the technologies that makes SM possible is the virtual factory. A virtual factory is a concept (system) that predicts, solves (improves) and manages (controls) problems with overall production tasks by linking them to the actual sites in a virtual environment.

The virtual factory is a fusion technology that combines diverse IT technologies related to manufacturing, based on digital manufacturing technology. As shown in Fig. 2, the virtual factory is divided into infrastructure and technologies, which include the module design, process design, line design, logistics analysis, ubiquitous and virtual reality, and system integration technologies. Via system integration, they are integrated with diverse heterogeneous systems such as enterprise resource planning (ERP), supply chain management (SCM), product lifecycle management (PLM) and manufacturing execution systems (MES).

2. Background

Global companies are trying to establish digital-manufacturing-based SM systems, including virtual factories, and reporting success by using relevant technologies. Extensive research related these technologies have also been published.[2-15]

In the aviation industry, there is an innovation case of Boeing using a 3D-model-based design/production system. In the car industry, there

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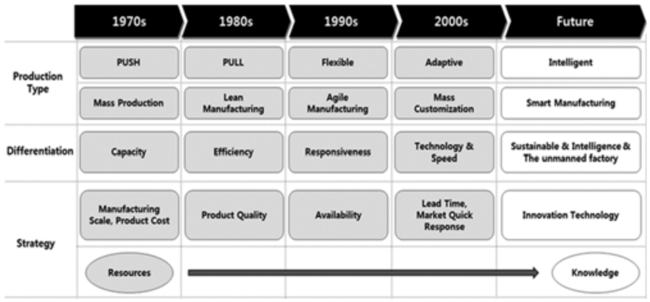


Fig. 1 Development of the production system

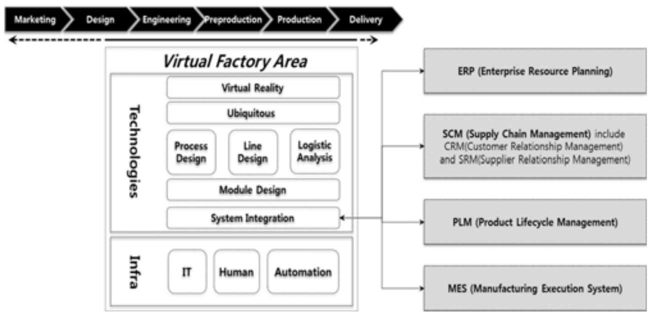


Fig. 2 Virtual factory concept

are R&D cases of digital virtual production in GM, Ford, Daimler, and Toyota. HKMC in Korea is also innovating using the PLM-based digital virtual production system.

In Korea, shipbuilding technologies are being significantly developed. The big three companies in this field (HHI, DSME and SHI) are conducting research on 3D design, the PLM digital virtual production environment, and mobile-based digital shipyards. New information technologies are being used in actual sites. The U.S. Navy reduced its costs by $370 million via simulation and modeling technologies and innovative activities during the design stage.[16] POSCO, a steel company, is developing a technology for establishing a virtual factory in collaboration with a global PLM company, and establishing a mobile-based smart plant.

In the electronics industry, the establishment of a virtual factory using modeling and simulation technologies is an important issue. SEMCO developed a strategic road map for the innovation of the production environment and is implementing detailed processes for the development of an intelligent factory.

CIM data analyzed the effects of the application of digital manufacturing to 12 car, aviation and shipbuilding companies in the U.S., Europe and Japan. Table 1 shows the results.[16]

Application cases of a virtual factory are introduced and observed problems are summarized in the Table 2.

Grieves (2005) stated that the use of full digital manufacturing technology rather than of digital manufacturing point solutions, the use of digital manufacturing in connection with PLM rather than by itself, and the use of PLM with ERP, SCM and customer relationship management (CRM) rather than by itself, are expected to result in more effective innovation.[17]

As Grieves mentioned, a virtual factory is a concept that can lead to

Table 1 Effects of the digital manufacturing application (CIM data)

Overall Effect	- Lead time to market: 30% decrease - Overall productivity: 15% increase - Overall production cost: 13% decrease
Design	- Product design time: 10% decrease - Tool design: 30% improvement - Communication/ collaboration: 35% improvement - Design change: 65% decrease
Process Planning	- Cost reduction due to the improved quality according to the pre-production process verification: 15% - Cost reduction due to the shortened production process planning time: 40%
Work Planning and Production	- Cost reduction due to the reduced inventory: 10% - Cost reduction due to the optimized layout design: 25% - Cost reduction due to the improved worker's work sharing rate: 30% - Cost reduction due to the optimized logistics/material flow: 35% - Cost reduction due to the reduced working equipment: 40%

more powerful innovation. However, many manufacturing companies are having difficulty in its development, implementation and application.

This indicates that a strategic and systematic approach is required to successfully establish the virtual factory. The present study develops the framework and a diagnostic evaluation method for the virtual factory in order to present guidelines by strategically connecting the required technologies to the relevant infrastructure.

3. Virtual Factory Application Strategy

For the successful establishment of a virtual factory, the top-down-approach (with the CEO's active support) must be implemented simultaneously with the bottom-up approach (through the gradual development of detailed technologies).

3.1 Top-down approach

The top-down approach involves investments in the establishment of the company-wide virtual factory from the managerial viewpoint.

Companies are introducing the evaluation tools called key performance indicators (KPIs) to measure and manage financial and non-financial performance. KPIs do not reveal the past performance of a company such as its sales or profit, but are key factors that determine the company's future performance.[18]

As aforementioned, the virtual factory is a digital-manufacturing-based SM system that predicts, solves (improves) and manages (controls) problems that may occur in the overall product production by linking them to the actual sites. The virtual factory establishment level can be managed by applying it to a non-financial performance indicator. For example, the virtual factory allows site monitoring measurement, which can be used to calculate the productivity improvement, failure rate/failure reduction rate, plant operation rate, workforce reduction rate, faster delivery rate and claim rate. This indicates that the site can be controlled in real time to predict and solve the productivity problems.

In addition, the virtual factory is closely related to enterprise control

Table 2 Observed problems at the virtual factory application

Case	Description	Observed problems
Heavy Industry Company	They verified the functions of the relevant solution through the benchmarking test of a global PLM company based on a global IT company's suggestion before it implemented the system. However, after the system was established and used in the actual work process, the resulting outcome measured against the initial investment was poor, which generated negative awareness of the virtual factory. The vague expectation that the virtual factory would solve all production problems in itself caused a problem.	Difficulties in : - Estimation of Investment Cost - Evaluation of the Implement Effects - Key Performance Indicators (KPI)
Parts Manufacturing Company	They introduced a software program that was related to the virtual factory with a small investment and used it in designing and analyzing a new plant. The effect of and the satisfaction with the initial investment were significant, but only the pertinent experts could use the system and the relevant data suffered low reusability, which caused difficulties in supporting many projects. Despite attempts to train professionals in-house, they were not enough. Thus, although the virtual factory technology did generate some benefits, some resulting problems could not be addressed by the frequent production plan changes.	- Lack of Experts - Difficulty of Training
Electronic Company	They sought to innovate its production using plant operation and logistics simulation, but the solution's high cost and the extensive time needed to train professionals became obstacles. In addition, much time and expense was spent in preparing the data and model for use in the simulation.	- Low Reusability - No Standard (Work Process and Interface)

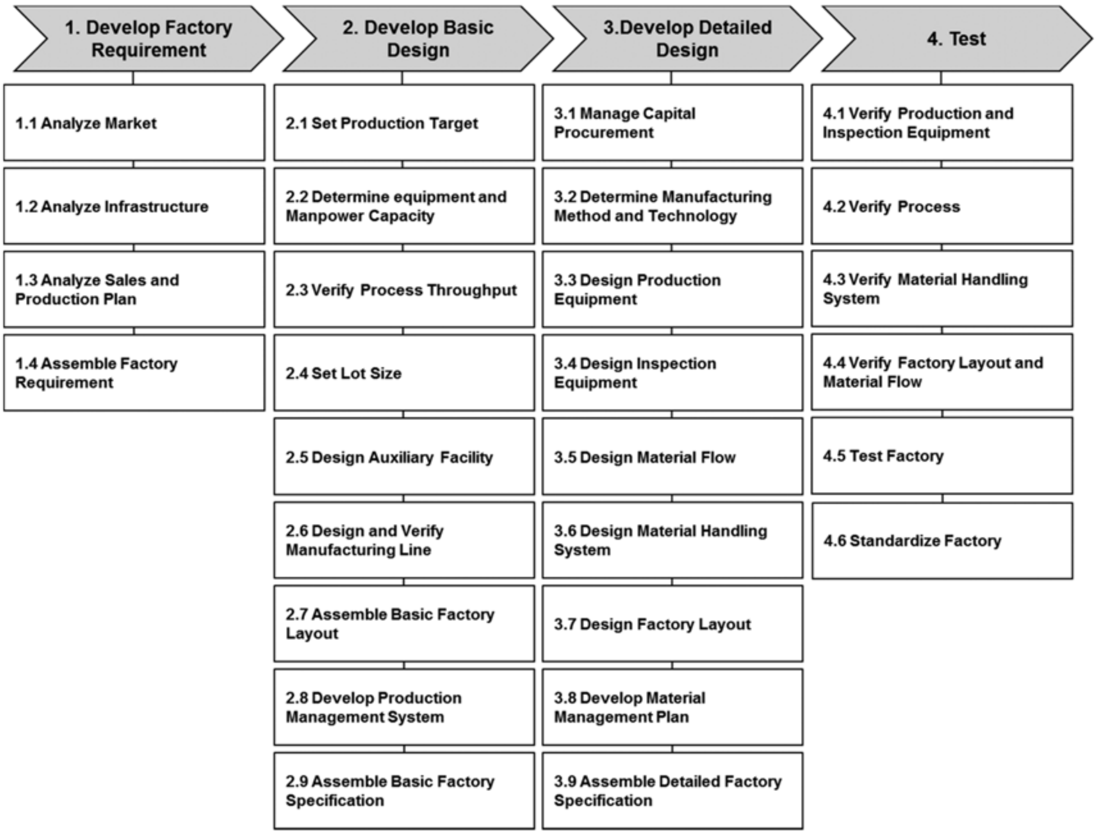


Fig. 3 The work process of the factory design and development

monitoring, automation, unmanned operation, demand/supply prediction and quality improvement through pre-verification.

The virtual factory requires active investment in the necessary infrastructure and required technologies, particularly infrastructure such as IT, workforce and automation. These are the company's IT environment (its hardware, system software, network, security, etc.), the plant's unmanned automation, the presence of an exclusive organization for establishing the virtual factory, and the presence of virtual factory professionals.

3.2 Bottom-up approach

The bottom-up approach extends the coverage of the virtual factory while developing the relevant element technologies.

This chapter describes a work process for factory design and development in manufacturing company and classifies the relevant virtual factory techniques by analyzing each process using IDEF0.

Fig. 3 shows activities and tasks for factory design and development.[19]

Factory design is a very complex process because of the need to determine the manufacturing method, machine, equipment, cell, process

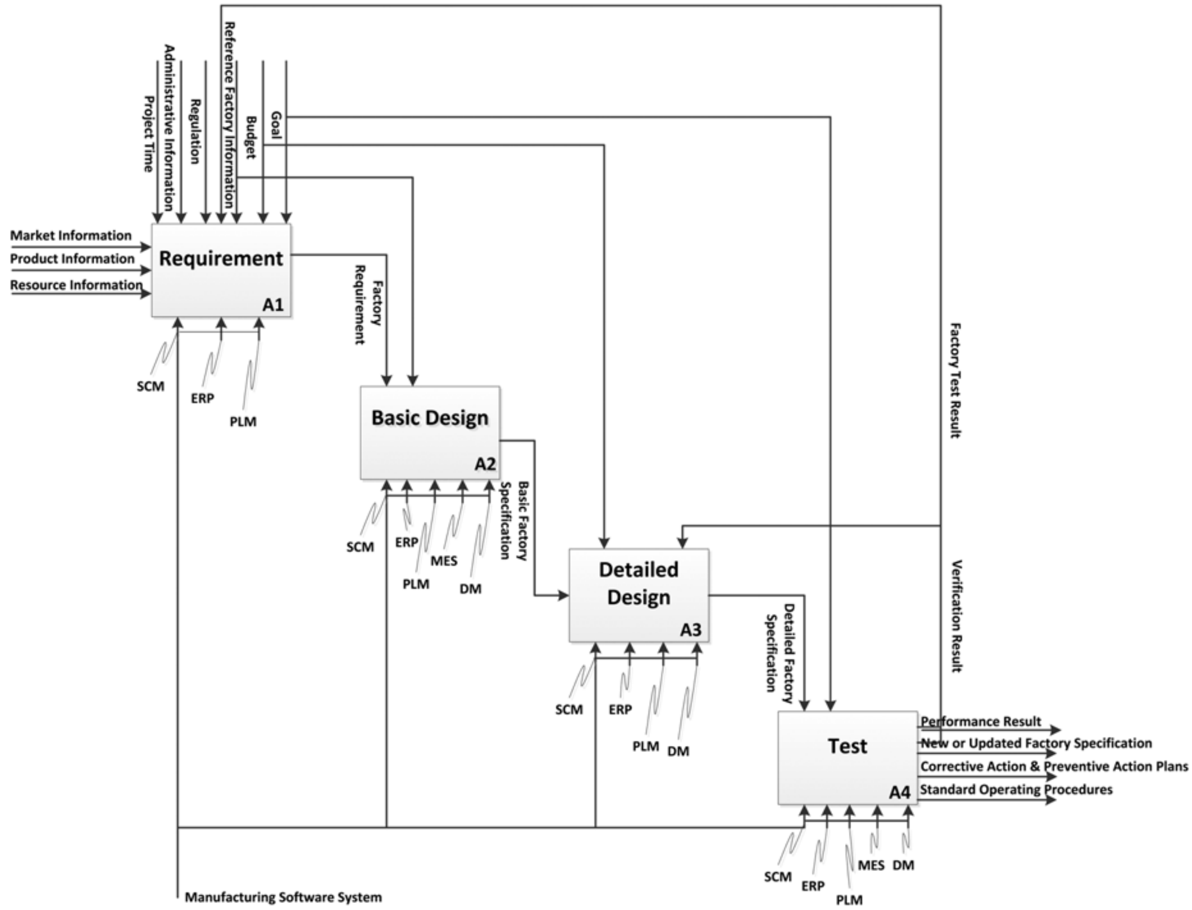


Fig. 4 Analysis of each activity based on IDEF0

and output and utilities with consideration for the overall product lifecycle related to product design, manufacturing and sale.

The factory design and development process consists of Develop factory requirement, Develop basic design, Develop detailed design and Setup and test.[20,21]

• Develop factory requirement: In the plan activity, the customer's needs are reviewed and general plans related to infrastructure, environment, production, sale, budget and schedule are established.[20,21]

• Develop basic design: In the basic design activity, after the production target is set, capacity, equipment and human resources are calculated. The layout design, which is the most important task, is processed next. A more suitable production system is developed via the process layout and utilities design.[20,21]

• Develop detailed design: In this activity, equipment and inspection machines are designed by analyzing manufacturing methods and processes. The material flow between each process, each floor and each factory is designed by referring to the calculated capacity in the basic design activity and manufacturing modules such as loading/unloading, transportation, and container are also designed. The final layout is determined on the basis of the modules, processes, line and material flow design.[20,21]

• Setup and test: In this activity, the manufactured equipment is inspected and arranged on the shop floor, the layout, modules and material flow are verified, and the real manufacturing line is set up and test run. Finally, all processes are established under optimum condition and standardized.[20,21]

Factory design and development are analyzed by IDEF0, as shown in Fig. 4. Table 3 shows the classification under relevant virtual factory technologies and tasks. Fig. 5 shows the seven technologies needed to establish the virtual factory based on digital manufacturing. The next chapter presents cases of diagnosis of the level of the virtual factory establishment in a manufacturing company and application of the resulting strategy to the actual sites.

4. Virtual Factory Level Diagnosis

Michael grieves[17] explained evaluation of PLM system based on Capability Maturity Model (CMM).[22] In order to diagnose the virtual factory, Capability Maturity Model Integration (CMMI)[23] that has superseded the CMM model is referenced. Table 4 shows each level and description of CMMI.

As shown in Table 5, the items needed to evaluate the level of virtual factory in manufacturing companies were arranged based on the observed problems, aforementioned infrastructure and element technologies.

① Module design technology: The important items are the 3D modeling tools such as CAD, the hardware that facilitates the modeling of equipment at the site, the presence of experts and workforce training, and the standardized work process for the module design.

Table 3 Classification of virtual factory technologies

Technology	Description	Relevant Task (Fig. 3)
Module Design (MD)	These refer to the technologies for producing all the data related to the plant (architecture, equipment, KIT) in 3D format. In addition to the 3D CAD modeling that includes kinematics (which is required for process simulation), the reverse engineering technology that utilizes 3D scanning is also being used at present.	#2.5, #2.7, #3.5, #3.6, #4.1, #4.2
Process Design (PD)	These refer to technologies for simulating manufacturing processes and tasks in 3D format. They include the worker analysis technology. There are methods for using the process simulation tools/systems, such as Dassault's Delmia solution and Siemens' Process simulation.	#2.1, #2.2 #2.3, #2.4
Line design (LD)	These refer to the technologies for simulating the LOB (line of balance), the capacity and the optimum required workforce. Commercial line simulation tools, including Dassault's Quest or Siemens' Plant Simulation, can be used.	#2.5, #2.6, #2.7, #3.7, #3.8, #4.3
Logistics Analysis (LA)	These refer to the technologies for analyzing the material mobilization, frequency and load, for the plant. Siemens' Factory Flow and Dassault's Quest are the tools that support these technologies.	#2.4, #2.6 #2.7, #3.5, #3.6, #3.7 #3.8, #4.3
Ubiquitous (UB)	A ubiquitous environment is an information and communications environment wherein the user can connect to networks anywhere without being aware of any network or computer. This technology is being used by manufacturing companies. At any production site, a smart environment that allows operations is established. Ubiquitous technologies are used to enable the interface of man, machine, material, method and environment (4M1E) at the production site.	All (Especially, #2.8, #3.3, #3.4, #3.6)
Virtual Reality (VR)	These refer to the technologies that enable anyone to experience, with his five senses, what it is like to work in an environment that is very similar to a real one. Virtual reality technologies such as tangible display, augmented/mixed reality (AR/MR), hologram and haptics can be used in manufacturing. Virtual reality technologies are used extensively in the manufacturing industry.	All (Especially, #1.4, #2.7, #2.9, #3.7, #3.9, #4.6)
System Integration (SI)	These refer to the technologies for the systematic management of integrated data (on products, processes, resources and plants) via their standardization and linkage to heterogeneous systems. Recently, data/process mining, clouding and virtualization technologies have attracted attention. The integration technology must be linked to the aforementioned element technologies in real time. The data consistency and integrity must be maintained, with flexible scalability to other systems. Thus, the seven element technologies must be organically integrated. The site data should be collected in real time and analyzed, all problems should be pre-simulated in the virtual environment via scientific big-data processing, and the results should be returned for feedback.	All (Especially, #1.1, #1.2, #1.3, #1.4, #2.9, #3.9, #4.5, #4.6)

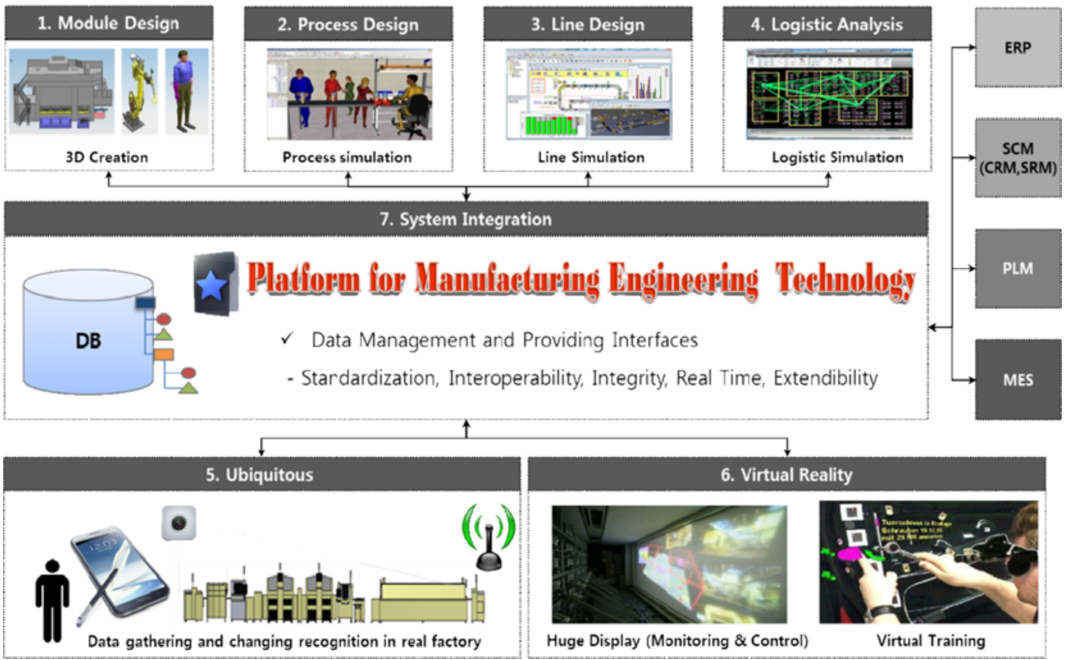


Fig. 5 Architecture of the virtual factory

② Process design technology: The important items are the software for designing and verifying the process in the virtual environment, the presence of experts and workforce training, and the standardized work process for the process design.

③ Line design technology: The important items are the software for designing and verifying the line in the virtual environment, the presence

Table 4 CMMI Levels[23]

Level	Description
1 - Initial	The starting point for use of a new or undocumented repeat process.
2 – Repeatable	The process is at least documented sufficiently such that repeating the same steps may be attempted
3 – Defined	The process is defined/confirmed as a standard business process, and decomposed to levels 0, 1 and 2 (the last being Work Instructions).
4 – Managed	The process is quantitatively managed in accordance with agreed-upon metrics.
5 – Optimizing	Process management includes deliberate process optimization/improvement

Table 5 Virtual factory level diagnosis sheet

Tech	Weight	Classification	Weight	Level				
				1	2	3	4	5
MD	0.129	Tools	0.123	20	40	60	80	100
		Standard	0.258	20	40	60	80	100
		Expert	0.332	20	40	60	80	100
		Training	0.287	20	40	60	80	100
PD	0.135	Tools	0.123	20	40	60	80	100
		Standard	0.287	20	40	60	80	100
		Expert	0.332	20	40	60	80	100
		Training	0.258	20	40	60	80	100
LD	0.151	Tools	0.246	20	40	60	80	100
		Standard	0.197	20	40	60	80	100
		Expert	0.357	20	40	60	80	100
		Training	0.2	20	40	60	80	100
LA	0.156	Tools	0.114	20	40	60	80	100
		Standard	0.216	20	40	60	80	100
		Expert	0.394	20	40	60	80	100
		Training	0.276	20	40	60	80	100
UB	0.125	Environment	1	20	40	60	80	100
VR	0.072	Environment	1	20	40	60	80	100
SI	0.232	Expert	0.142	20	40	60	80	100
		Standard	0.313	20	40	60	80	100
		Environment	0.212	20	40	60	80	100
		MESA MMP	0.333	20	40	60	80	100

of experts and workforce training, and the standardized work process for the line design.

④ Logistics design technology: The important items are the software for designing and verifying the logistics layout in the virtual environment, the presence of experts and workforce training, and the standardized work process for the logistics analysis.

⑤ Ubiquitous technology: The important items are the hardware such as the device, its exclusive application, the environment such as wireless/LTE.

⑥ VR technology: The important items are the hardware such as the specialized display, haptic device and HMD, the software such as the VR authoring tool.

⑦ System integration technology: This includes the establishment of relevant systems (ERP, PLM, SCM, MES), the level of standard information, the standards for linkage to the system and for data exchange, big data processing using the data mining and process mining technologies, and the items related to future-oriented technologies such as the clouding environment and virtualization.

Table 6 Virtual factory level diagnosis results for Company D

	2009	2012
Level	Beginning Level	Growth Level
Total	26.74	37.02
MESA MMP	40	60
MD	29.1	40
PD	25.16	27.62
LD	27.14	31.14
LA	30.16	40
UB	20	20
VR	20	40
SI	29.25	50.9

The weight for each of seven technologies is derived through utilizing of Analytic Hierarchy Process (AHP)[24] based on opinions of experts who are working in factory optimization department of a manufacturing company.

The Standard is included data exchange in each tool, and the system integration and the presence of the standardized process are considered important because the base technology and environment are very important and require significant time, cost and effort to establish. Once the basic environment has been established, the unit technologies (for the module design, process design, logistics analysis, and ubiquitous and virtual realities) can be applied relatively easily.

Among the aforementioned level diagnosis evaluation items, the system integration technology is scored by linking it with the managing manufacturing performance (MMP) defined by MESA. MESA MMP presents six evaluation items and maturity level measurement standards for manufacturing operations: the manufacturing strategy, the manufacturing quality, the supply chain alignment, the data collection, the performance management and improvement, and the manufacturing infrastructure.[25]

In this paper, the evaluation results are divided into five levels. The interval of each level is determined from the general informatization level of 450 Korean manufacturing companies.[26]

Total Score Max ≤ 100

- Global Leading Level: 75 ≤ Score ≤ 100
- Excellent Level: 56 ≤ Score ≤ 74
- Good Level: 44 ≤ Score ≤ 55
- Growth Level: 28 ≤ Score ≤ 43
- Beginning Level: 0 ≤ Score ≤ 27

5. Application Cases and Effect Analysis

Company D is the largest parts manufacturing company in Korea that produces parts ranging from advanced electronic components to mechanical parts. It has three sites in Korea and seven sites abroad. It has 12,000 staff, and produces passive components, printed circuit boards, and wireless connectivity/power/opto and motor products.

A virtual factory level diagnosis evaluation was conducted for Company D in 2009 and 2012. Table 6 shows the diagnosis results of Company D, and Fig. 6 shows its results in a radial chart.

Company D traditionally has a high level of production technology and many production experts with experience of over 20 years. Since

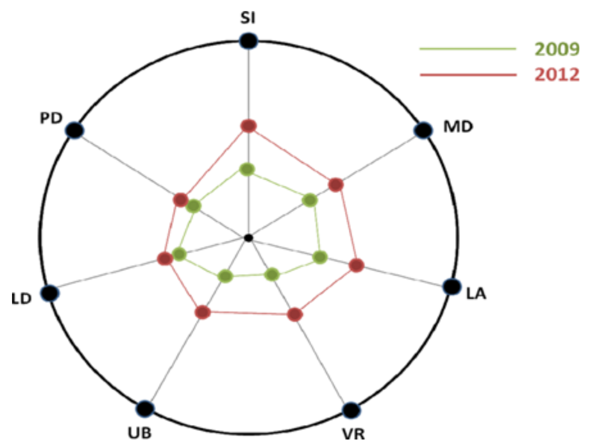
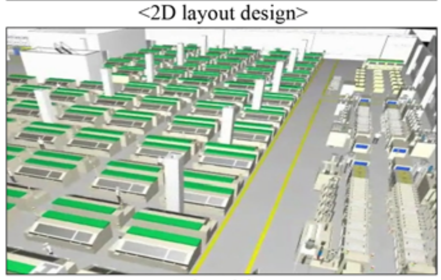
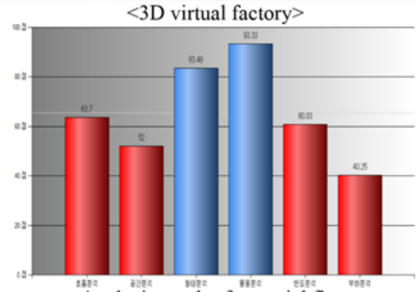


Fig. 6 Diagnosis results for Company D

2000, it has made company-wide investments in IT systems and has established systems related to production technology. The situations in 2009 and 2012 were analyzed using the diagnosis evaluation model that was developed in this study to establish the future virtual factory (intelligent factory) establishment strategy.

In 2009, research and development was conducted on, and investments were made in, system integration, module design and logistics analysis technologies. The utilization of software such as CAD/CAE for product design/analysis increased, and MES, ERP, SCM and PLM were developed and actively used. Experienced experts performed the process design, line design and logistics analysis, and many tasks were conducted using the traditional method with MS Excel files. For the logistics analysis, a commercial software program was used. The ubiquitous and virtual reality technologies were not introduced, and each system was developed and used without considering the system interface. The diagnosis/evaluation results for the 2009 situation recommended that investments should be made in the infrastructure and base systems (MES, SCM, ERP, PLM), and that the process design, line design and logistics design should be studied with the aim of developing corresponding technologies. In addition, user-friendly systems should be developed that can be linked with one another using the integration technology use. By 2012, improvements had been made in most items, except for VR technology. On the whole, the number of professionals had increased due to the training and recruitment efforts, and the increased investment in the system raised its availability. For the module design, equipment for easy site measurement and the 3D scanning modeling technique were developed, which were the improvements from the manual site measurement. For the process design, line design and logistics analysis technologies, relevant software programs were introduced and specialists were trained to ensure an efficient work process. In addition, in relation to the logistics technology, the relevant information was placed in the DB/library so that all departments could simulate the logistics, and a system that would allow anyone who can use MS Office to simulate the logistics was under development.[20,21] This system (e-FEED) is being developed also for the line and process design from 2013, and all these are being developed with consideration for the system integration. The base technology of the virtual factory was applied to the K-Project that is related to the new plant construction in 2013. Table 7 summarizes the project.

Table 7 New plant project

Project Name	K-Project
Purpose	- Optimized production line design that reduces the production L/T by over 50% compared to the current L/T, considering the three core items (job-shop flow, synchronized production and processing point management) - Line design/establishment that minimizes product touching, product movement and handling workforce, via the observation and measurement of, and research on, five manufacturing module kits that are used during the manufacturing process
Method	Design of the optimum manufacturing line, based on which the establishment and evaluation of the actual manufacturing line, 3D layout design and logistics/productivity analysis can be conducted
Duration	January 10 - March 30, 2013
Application effect	Productivity improved by 35% compared to the existing plant Man-hours reduced by 55% compared to the existing layout design Man-hours reduced by 90% compared to the existing design evaluation method Man-hours reduced by 50% compared to the existing logistics/productivity analysis method
Contribution to business	$1.36 million (USD)
Representative image[20]	 <2D layout design>  <3D virtual factory>  <Analysis result of material flow>

The base technology of the virtual factory will be applied to the new plant design and the existing plant expansion and improvement by October 2014, with expected savings of $10.5 million (USD). Table 8 shows the financial performance and productivity analysis results for

Table 8 Financial and productivity analysis

Year		2009	2012
Financial (Unit: billion dollars)	Sales	6,105	8,645
	Operating Income	512	833
Productivity (Unit: %)	Gross Value Added to Sales	17.1	20
	Profit-Sharing Ratio	51.2	60
	Capital Costs to the Gross Value Added	39.7	45
	R&D Investment Rate	5.7	5.7

2009 and 2012. Company D's current credit rating is AAA. Its sales in 2009 of $6,105 billion were increased by over 40% to $8,645 billion in 2012. Its operating profit in 2009 of $512 billion was increased by over 60% to $833 billion in 2012. In view of its productivity, its gross added value to sales seemingly increased by 3%, its profit-sharing ratio by 9%, and its capital costs to its gross added value by 5%.

Company D is striving to attain the best production technology in the world by 2020. With its long-term plan to recruit external experts and train internal experts, it is implementing diverse projects to achieve its original purpose of establishing a virtual factory, which is an intelligent factory with real-time linkage between the site and its virtual reality equivalent. The detailed technologies that are presently being developed or planned for future development are as follows.

① Technologies for ensuring the sustainability of existing studies (e-FEED development)[24]

- Easy-to-use systems that allow anyone to participate in the plant design, evaluation and analysis (logistics/productivity)

The real-time technology required for data management, system integration and linkage to the site

- The MES, SCM, PLM linkage technologies

② Technologies for analyzing standardized manufacturing standard information in real time and using the results for decision-making

- Technology for master data management (MDM) standardization
- Technology for extracting the representative values through scientific big-data processing and for their use in decision-making

③ Ubiquitous and VR technologies

- The clouding and AR/MR-based mobile technologies
- The large-display-based real-time monitoring technology

④ Technologies for optimizing manufacturing considering environmental factors

- Simulation with Korean and worldwide energy/environment regulations

6. Conclusions

Numerous global manufacturing companies are trying to develop smart manufacturing technologies. A virtual factory is a digital-manufacturing-based SM system that predicts, solves (improves) and manages (controls) problems with overall production tasks by linking them to the actual sites in the virtual environment. The present study has described the virtual factory implementation strategy (method) of manufacturing companies and the method of diagnosing/evaluating the virtual factory establishment level of a manufacturing company. In addition, a case study of a manufacturing company in Korea was analyzed using the developed diagnosis/evaluation method.

The application of the developed virtual factory diagnosis/evaluation method is expected to enable manufacturing companies to diagnose the level of their production systems and establish a strategy for investment in and managing the technical development of the virtual factory.

An evaluation model was developed based on the top-level concept of the infrastructure and the required technology. In our future research, we will examine the detailed items concerning the seven technologies mentioned in this study in order to develop an evaluation model for more detailed evaluation.

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