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Analyzing Consultancy on Production Systems Based on the Digital Triplet Concept

Takaomi Sato [1,2,*], Hiroki Takeuchi [2], Shinsuke Kondoh [3] and Yasushi Umeda [3]

[1] Mitsubishi Electric Co., Ltd., Information Technology R&D Center, 5-1-1 Ofuna, Kamakura 247-8501, Kanagawa, Japan
[2] Department of Precision Engineering, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan
[3] Research into Artifacts, Center for Engineering, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan
* Correspondence: sato.takaomi@ah.mitsubishielectric.co.jp

Abstract: This study aims to analyze the process flow of skilled consultants who utilize production improvement know-how and digital technology to enhance production systems in external companies. The concept of a Digital Triplet (D3), which expands the authors' Digital Twin framework to include the intelligent activity world, is adopted as it aligns with this study's objective. Given the complexity of the problems faced by production system consulting and the resulting inadequacy of reusing decision-making processes of skilled engineers based on the Generalized Process Model (GPM) using D3, a production system consulting modeling method is proposed. This method incorporates the Generalized Production System Consulting Process Model (GCPM) to generalize the production system consulting process. Using the proposed method, a case study focusing on energy-saving improvements was conducted to describe and analyze the consulting process of skilled consultants. The results show that the proposed method effectively captures the process flow of skilled consultants while considering the iterative structure of the GCPM. Additionally, utilizing the GCPM enables a comprehensive view of the entire process, facilitating an understanding of how knowledge and tools are utilized in various contexts.

Keywords: industry4.0; cyber-physical production systems; digital twin; digital triplet; manufacturing system; production improvement; consulting service

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1. Introduction

In the manufacturing industry, the complexity of production systems is increasing due to digitalization and the shift from mass to variable-volume production [1].

As a response, some companies [2,3] have ventured into the field of "production systems consulting", i.e., offering consultancy services to enhance the production systems of other companies. These consulting firms leverage their accumulated know-how and digital technology to identify areas of improvement within the production systems [4].

Production system consultants apply their specialized knowledge and expertise to optimize production systems. Due to the growing complexity of these systems, clients are demanding increasingly greater quantity and quality of skills from consultants. Unfortunately, there is currently a scarcity of personnel who can meet these client requirements [5]. To address this shortage, skilled consultants have resorted to training unskilled individuals. However, due to the accumulation of experiential knowledge among the skilled workforce, knowledge transfer, and the training of unskilled individuals have proven unsuccessful.

The ultimate goal of this study is to translate consultancy on production systems into formal knowledge. The initial step, which is presented in this paper, involves identifying the process flows, knowledge, and tools utilized by skilled consultants, as well as the specific situations in which they are applied. Formalizing the knowledge of consultancy of skilled consultants may contribute to the evolution of production systems consulting in the future from the following perspectives:

- It facilitates the knowledge transfer from skilled to unskilled consultants.
- It will enable the sharing and exchange of knowledge among skilled personnel and promote continuous improvement of consultancy.
- It will serve as a basis for industry standards and accreditation, helping to maintain a certain level of competence and expertise among consultants. It will also enable the evaluation of consultants' qualifications.
- It enables the reuse of existing consultancies, allowing consultants more time to adapt to new technologies and address evolving industry issues.

The remainder of this paper is structured as follows. Section 2 describes the definition and scope of production systems consulting, along with the competencies demanded from production system consultants. Section 3 examines previous research on knowledge transfer, clarifies the Digital Triplet (D3) concept, and discusses the reusability of the decision-making processes of skilled consultants within the D3 framework. Sections 1–3 are a survey of prior research to aid in understanding this study, and Section 4 and beyond are the original proposal for this study. The approach employed in this study is outlined in Section 4. In Section 5, a method is proposed to support unskilled consultants in the use of the D3-based framework. Section 6 presents the results of a consulting case study conducted on energy-saving improvement production systems. Section 7 discusses the aspects solved by the proposed method, as well as areas that require further improvement concerning the training of unskilled workers. Finally, Section 8 concludes this study and provides insights into future avenues of research.

2. Production Systems Consulting

2.1. Definition and Target

Management consulting involves the empirical investigation and analysis of management problems by a management consultant, an expert with deep knowledge and experience in corporate management. At the request of a company, the consultant provides necessary recommendations to foster the company's development, along with guidance and advice on implementing those recommendations [6].

In line with the definitions of production systems and management consulting, we define production system consulting as the activity where consulting experts in business management and production control survey and analyze the client company's production system to identify areas of improvement and provide support for short- and long-term enhancements.

Although production system consultation encompasses improvements in production systems across various manufacturing industries, this study will focus on the machining and assembly manufacturing sectors, as the consultants from the production systems consulting team participating in the case study are professionals and well-versed in this area.

2.2. Competency Requirements for Production Systems Consultants

Similar to general management consultants, production systems consultants require problem-solving and communication skills [7]. In addition to these fundamental abilities, knowledge of production system improvement methodologies, such as Industrial Engineering (IE), Quality Control (QC), and Total Productive Maintenance (TPM), is essential [8]. Furthermore, in the context of digitalization and the increasing complexity of production systems in the Industry 4.0 era, proficiency in utilizing digital tools for data analysis has become necessary [9].

However, the shortage of competent production systems consultants remains a challenge in the field. To address this issue, skilled consultants are tasked with training unskilled individuals. Unfortunately, the accumulation of experiential knowledge among skilled consultants has hindered the transfer of knowledge to unskilled individuals and rendered their training unsuccessful.

Efforts to overcome the human resource shortage in production systems consulting include providing consultation support through digital transformation, although this aspect falls beyond the scope of this study.

When trained, unskilled consultants should accomplish the following goals:

Goal 1. Become familiar with specific cases of consulting efforts.
Goal 2. Understanding the general process flow employed by skilled consultants.
Goal 3. Applying generic process flows to diverse specific cases.
Goal 4. Learning various general improvement tools and methodologies.
Goal 5. Identifying the appropriate stage within the overall process flow where general improvement knowledge and tools can be applied.

3. Related Works

This section provides an overview of research conducted on methods and systems for transferring the knowledge of skilled engineers to unskilled engineers, addressing the goals outlined in Section 2.2. Additionally, we describe our proposed D3 concept and a framework designed to support unskilled engineers.

3.1. Knowledge Transfer

The term "manufacturing knowledge" (MK) encompasses various aspects, including knowing and understanding material properties, machine and process capabilities, and the implications of design decisions on manufacturing [10]. Alizon et al. [11] have found that MK is extensively reused in production management processes, with an average reuse rate of 28% for manufacturing applications [12]. These findings highlight the value of firms incorporating greater reuse of MK, as it leads to reduced production costs, increased production efficiency, and improved profitability by minimizing problem-solving time.

Industries characterized by knowledge-intensive activities, such as aerospace and construction, produce complex and long-lived products like aircraft, engines, and buildings. These products generate a substantial volume of information and knowledge throughout their "design-use-upgrade" life cycle [13].

Knowledge acquisition or elicitation from skilled employees is crucial, as knowledge loss often occurs when skilled workers document their experiences. When faced with a new problem, employees typically use similar past issues as a reference. However, documentation created for past solutions may not capture the extensive knowledge invoked during the decision-making processes [14].

Given the challenges associated with documenting and retaining the knowledge of skilled workers, direct training methods, such as on-the-job training (OJT), play a vital role in preserving expertise.

OJT stands as the most prevalent training approach adopted by companies [15]. Learning theory supports the notion that the further the learning environment is from the actual workplace, the greater the difficulty in transferring knowledge effectively [16]. Koike [17] conducted an in-depth study of in-company training in Japanese firms and concluded that OJT serves as the primary mechanism through which workers acquire knowledge. The importance of OJT has also been emphasized in previous studies [18,19]. OJT facilitates the development of skills related to a task in a specific workplace, as well as to other tasks closely associated with the relevant techniques.

Off-the-job training (off-JT) refers to training activities conducted outside the workplace, utilizing standard methods such as lectures, group discussions, role-plays, assigned reading, case studies, videotapes, and computer-based training. Since off-JT is often perceived as more expensive than OJT, many companies are reluctant to adopt this approach. A limitation of off-JT is that learning is detached from real-life scenarios unless the training material closely aligns with actual work activities, both physically and mentally [20]. Consequently, bridging the gap between the learning experience and tangible results can present challenges. However, off-JT offers a valuable opportunity to understand the "why" rather than the "how" behind certain concepts. Thus, the best practice for enhancing knowledge transfer involves employing a combination of both OJT and off-JT, as they serve complementary purposes: OJT enables the mastery of daily tasks and the grasp of fundamental concepts, whereas off-JT supplements the development of intellectual skills [21].

Digital technology also plays a significant role in facilitating knowledge transfer from skilled to unskilled workers. Watanuki and Kojima [22], drawing upon the SECI model [23], devised a technical handover system that stores technical documents and data, along with a virtual shared environment system utilizing VR space. This system creates a virtual OJT environment, enabling unskilled workers to learn repetitively without encountering real-world challenges, thereby facilitating the efficient acquisition of skilled workers' knowledge. Another study implemented the concept of the Learning Factory, allowing unskilled students to apply the engineering knowledge accumulated during their education to solve real industry problems and design products that address identified needs [24]. The Learning Factory approach aligns with the digitization and complexity of Industry 4.0 production systems. Additionally, Lugaresi et al. [25] developed the FactoryBricks project, which combines a lab-scale physical system kit comprising modular components and industrial IoT-compatible devices with a digital model. This integration presents a novel approach that combines a digital learning format with a lab-scale manufacturing system.

3.2. Summary of Related Works

In addressing the goals pertaining to the training of unskilled production system consultants listed in Section 2.2, it is evident that goals 1, 2, and 4 can be effectively resolved by providing unskilled individuals with textbooks and procedure manuals prepared by skilled personnel through off-JT or with direct training from skilled professionals through OJT.

However, goals 3 and 5 necessitate alternative solutions. One possible approach involves the creation of a virtual environment tailored specifically for OJT, focusing on a particular work process, as demonstrated by Watanuki and Kojima [22]. Another approach entails establishing a learning factory, as exemplified by Jorgensen et al. [24]. In contrast to the aforementioned approaches, our study adopts a more direct and explicit methodology to address goals 3 and 5: guiding unskilled consultants to comprehensively understand the processes employed by skilled consultants.

3.3. Digital Triplet

Umeda et al. [26] proposed the Digital Triplet (D3) as an extended framework of the Digital Twin (D2), integrating the "physical world" and the "cyber world" that are encompassed in D2 with the "intelligent activity world", the realm in which engineers engage in problem-solving activities based on D2, as depicted in Figure 1.

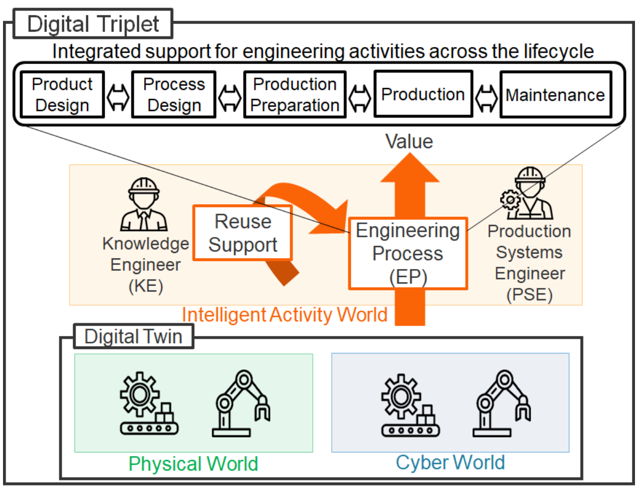

Figure 1. Schematic of the D3 concept Reprinted from Ref. [27]. 2022, the Japan Society of Mechanical Engineers.

The objective of D3 is to support the intelligent activities of production system engineers, assuming that a Cyber-physical Production System (CPPS) exists. Even with the advancement towards CPPS, not all decision-making processes will be fully automated, and the expertise of skilled engineers will remain indispensable. Through interviews, D3 strives to capture and express the cognitive processes of skilled engineers, providing information on the engineering processes (EP) involved in the design and performance of the production system, which is collected by the CPPS. The engineer responsible for these processes is referred to as a knowledge engineer (KE). Through leveraging digital tools in the information world, a more comprehensive and rational EP can be created by replacing certain aspects of a skilled engineer's cognitive process. Consequently, unskilled engineers can learn and emulate these thought processes by executing the digitally created EPs. Simultaneously, skilled engineers can gain insight into the significance of their own cognitive processes by studying the aforementioned more general and rational EPs.

In the D3 concept, the modeling of skilled engineers' EPs is achieved using the Process Modeling Language for Digital Triplet (PD3, Version 2) [28], which describes the implementation process flow, knowledge, and tools employed by skilled engineers throughout the process with the expectation that they will be reused.

PD3 represents an EP through a graph structure consisting of flows and actions, respectively, indicated by arrows and boxes (see Figure 2). Here, the term "flow" denotes the flow of information within the EP, whereas "action" refers to the processing of such information. Changes in input and output information are represented by arrows on the left and right sides of the box, respectively, with the content of the action being described within the box. The engineer's intention is depicted as an arrow originating from above, the knowledge and tools employed are represented by an arrow originating from below, and the rationale or reasoning behind deriving the output is indicated by an oblique arrow on the right side. Additionally, by utilizing container boxes, actions can be hierarchically and comprehensively represented.

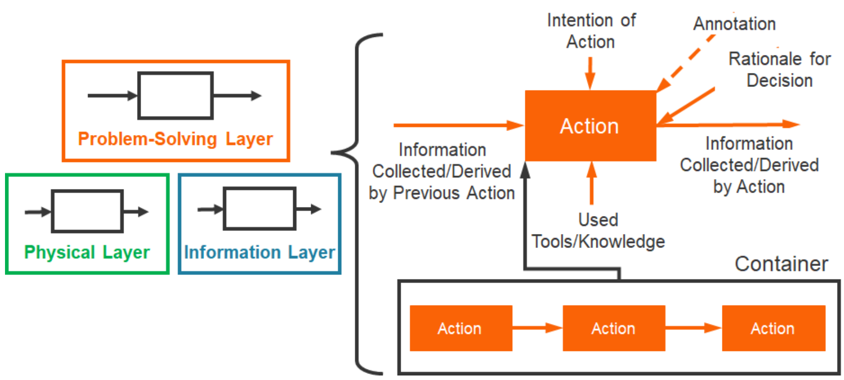

Figure 2. PD3 description Reprinted from Ref. [28]. 2021, the Japan Society of Mechanical Engineers.

As shown in Figure 3, Goto et al. [27] presented a framework utilizing PD3 to describe and reuse the cognitive processes of skilled engineers. Within this framework, two types of engineers are assumed: production systems engineers (PSE), responsible for executing problem-solving activities, and knowledge engineers (KE), tasked with describing and managing process knowledge. In Step A of Figure 3, the KE documents the decision-making process of skilled PSE, creating a "log-level description" by utilizing PD3. In Step B, the KE extracts the essential functions from the recorded description and generalizes them into a "generalized process model". Subsequently, in Step C, the generalized process model (GPM) described according to PD3 is stored in the Model Database. Finally, the GPM is updated in Step E by incorporating automation and software support for specific process parts. Through reference to the GPM, the learning of unskilled engineers can be facilitated (Step D in Figure 3).

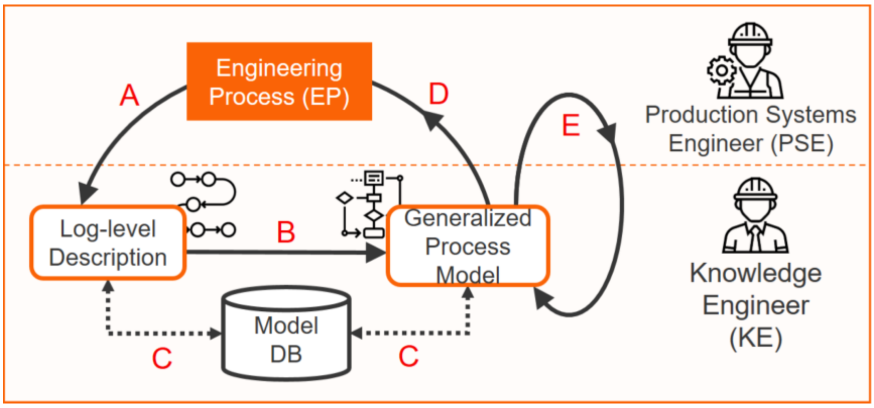

Figure 3. Framework for reusing the decision-making process of skilled production system engineers Reprinted from Ref. [27]. 2022, the Japan Society of Mechanical Engineers.

4. Approach

To accomplish this, we will establish and examine a process for production systems consulting utilizing the "A framework for reusing the decision-making process of skilled production systems engineers based on the D3 Concept" illustrated in Figure 3, which has demonstrated efficacy in engineering process analysis. Within this framework, a log-level description of a specific process executed by a skilled engineer in a particular problem is combined with a generalized GPM. Furthermore, the process-modeling language PD3, employed in this framework, delineates the comprehensive process flow, documenting the knowledge and tools employed in each process, as well as the underlying intent and rationale for these processes, which will be subject to review at a later stage. In essence, this approach effectively resolves the two aforementioned goals.

5. Production Systems Consulting Process Modeling Method

Due to the complexity of problem-solving in production system consulting within client factories, creating a GPM directly without guidance from inexperienced production systems consultants (KEs) poses a challenge. However, given that most consulting processes exhibit similar patterns [29], we hypothesize that by establishing a general consulting process (CP) pattern [30], it would facilitate the construction of a GPM by KEs and enable the analysis of skilled consultants' CP. This pattern is referred to as the Generalized Consulting Process Model (GCPM). The GCPM iteration generally ends when the client is satisfied with the consultant's proposed improvement plans. Strictly speaking, the iteration may be terminated even when the client is not convinced of the improvement plans since it depends on the contract with the client. Based on the author's previous experience and expert interviews, we have defined six types of GCPM actions, as depicted in Figure 4. A brief summary of each action is provided as follows:

1. Understanding the Client's needs
    - The consultant listens to the client's requests, gathers relevant information, and determines the improvement objectives. Examples of improvement objectives in production system consulting include enhancing productivity, energy efficiency, reducing breakdowns, and visualizing Key Performance Indicators (KPIs).
2. Problem setting
    - The consultant defines the problem based on the gathered information and past cases.
3. Current state analysis
    - To narrow down the problem scope, the consultant identifies and analyzes the current state of the target factory. This may involve assessing production facilities or specific product areas that require improvement.

4. Derivation of improvement plans
   - The consultant generates a list of potential improvement plans for the identified targets in Step 3. These plans may encompass work standardization and the introduction of high-efficiency facilities and equipment.
5. Evaluation of improvement plans
   - The consultant prioritizes the improvement measures by evaluating the return on investment associated with implementing the candidate improvement plans.
6. Verification/Validation
   - The consultant applies the prioritized improvement measures to the customer's production system and verifies their effects.

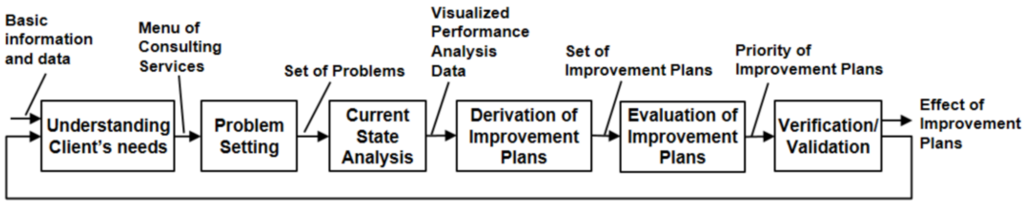

Figure 4. Generalized production systems consulting process model (GCPM) Reprinted from Ref. [30]. 2021, the Japan Society of Mechanical Engineers.

Incorporating the GCPM into the framework presented in Figure 3 can enhance production system consulting (Figure 5). As depicted in Figure 5, skilled consultants are initially tasked with executing the consulting process while referring to the GCPM (Process A in Figure 5). The KE assigns the processes performed by skilled consultants to each step in the GCPM based on the identified patterns and creates a log-level description (Process B in Figure 5). Given that skilled consultants typically focus on specific problem targets and areas during consultations, the log-level description is represented as an iterative structure of the GCPM (Process B in Figure 5). The KE then generalizes the log-level descriptions (Process C in Figure 5). These generalized descriptions become the domain-specific GCPM for each improvement objective, subsequently referred to as the domain-specific GCPM (Process C in Figure 5). The domain-specific GCPM is stored in the model DB for future reference during other consulting projects (Process D in Figure 5). Finally, the domain-specific GCPM is updated, certain processes are automated, and software support is implemented (Process E in Figure 5). Referring to the domain-specific GCPM aids in knowledge transfer to inexperienced consultants and facilitates the delivery of consulting services (Process F in Figure 5).

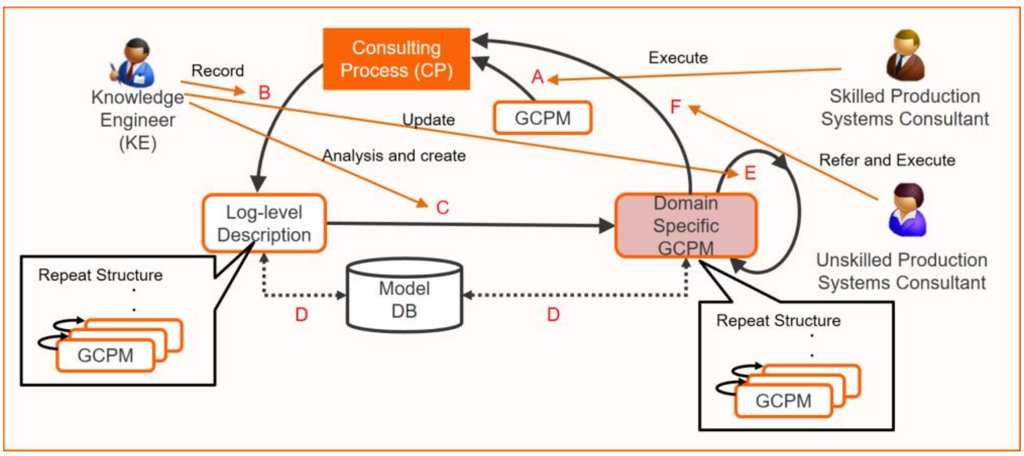

Figure 5. Production Systems Consulting Process Modeling Method.

6. Case Study

This section presents the analysis perspective and the results obtained from conducting a case study on energy-saving improvement consulting, utilizing the Production Systems Consulting Process Modeling Method introduced in Section 5.

6.1. Analysis Perspective

To address the goals identified in the unskilled training outlined in Section 2.2, we will follow the procedure proposed in Section 5, known as the "Production System Consulting Process Modeling Method", to document the consulting processes of skilled consultants and analyze them through case studies. In this study, the analysis will focus on processes A through C, as depicted in Figure 5. The following perspectives and considerations will guide our analysis:

- Can the flow of the production system consulting process be structured as a repetitive pattern of the Generalized Consulting Process Model (GCPM)?
- Where within the overall process can we identify the utilization of specific knowledge and tools?
- Is it feasible to comprehend the underlying reasons or intentions behind the application of knowledge and tools in each process?
- Can we construct a domain-specific GCPM based on the aforementioned three points?

6.2. Consulting Target

The target of our case study was a motor manufacturing factory operated by an electrical and electronic equipment manufacturer. The consulting activity was conducted by Team A between July and October 2021. Team A consisted of two skilled consultants, one unskilled consultant, and one data scientist, with the two skilled consultants assuming leadership roles. The client's objective was to "reduce energy consumption while maintaining productivity (energy-saving)". Energy, in this context, encompassed electricity, propane, mixed gas, and steam.

6.3. Results of Analysis

Consultant Team A embarked on energy-saving improvement consulting, referring to the GCPM (Process A in Figure 5) as their guide. Subsequently, the KE recorded the consulting process of the skilled consultants as a log-level description utilizing the GCPM (Process B in Figure 5). Finally, the KE generalized the log-level descriptions (Process C in Figure 5).

6.3.1. Process Flow

To verify the hypothesis put forward in Section 5, we conducted an experiment to determine whether the GCPM could be utilized to create a log-level description of the energy-saving improvement consulting process for skilled consultants. Through our investigation, we confirmed that the GCPM was applied iteratively five times to generate the final improvement plans. The subsequent section presents a summary of the energy-saving improvement consulting processes for each of the five rounds. The log-level description of the energy efficiency improvement consulting process, comprising the five rounds, is as follows:

Round 1:

Skilled consultants performed a Pareto analysis on the production facilities within the motor manufacturing factory, categorizing them by energy type (electricity, steam, propane gas, and mixed gas) over the past several years. This analysis aimed to identify the production facilities responsible for approximately 80% of the total energy consumption. For instance, in the case of electricity, the consultants identified seven production facilities, including iron core pressing, die casting, shaft machining, rotor assembly, varnishing, and stator assembly.

Round 2:

The skilled consultants estimated the expected energy loss, devised improvement plans, evaluated the potential improvement effects, and determined the scale of return on investment (large or small) for each production facility identified in the initial Pareto analysis. These estimations were based on past cases and their own experiences. Furthermore, the consultants determined the energy resources involved and prioritized the improvement order for the production facilities. This step aimed to acquire more detailed data along the time axis to facilitate the implementation of subsequent improvement processes. In this particular case, priority was given to energy resources such as electricity and production facilities like iron core press facilities.

Round 3:

Before delving into detailed data analysis, the skilled consultants obtained the client's time-series data, recorded at daily intervals, on power consumption and production volume specifically for the iron core press facilities over the past year. The objective was to determine whether any power consumption losses had occurred. They created scatter diagrams, with production volume on the x-axis and electricity consumption on the y-axis, for each product model produced. Subsequently, they identified variations in the scatter plots for the same product models, indicating potential power consumption losses.

Round 4:

The skilled consultants acquired more granular time-series data, recorded at hourly intervals, on power consumption and production volume for the iron core press facility over the past year, surpassing the level of detail obtained in Round 3. They then decided to extract data specifically from 12 October 2021, to calculate the number of losses incurred based on a rule of thumb. This approach allowed them to identify failures during periods of relatively stable production more easily. Additionally, they employed the Total Productive Maintenance (TPM) framework [Nakajima, 1988] [31] to manually calculate the amount of electricity consumed, even in the absence of production activities at the facility. The results revealed a loss of 15 kWh (equivalent to 7.3% of the total power consumption) on 12 October.

Round 5:

The skilled consultants opted to calculate the extent of power consumption loss by utilizing the complete dataset spanning one year. This approach aimed to provide the client with a more accurate prediction of the improvement effect. However, manually computing an entire year's worth of data would be excessively time-consuming. To address this challenge, the consultants enlisted the assistance of a data scientist to perform the calculations. At the request of the consultants, the data scientist developed a custom loss calculation program, which evaluated the amount of power consumption loss incurred by each facility throughout the year based on the principles outlined in the TPM framework. Subsequently, the consultants compared the results of this loss analysis with past improvement cases, identified improvement plans suitable for the current losses, and assessed the associated improvement effect and return on investment. In this specific case, the consultants presented the client with a proposed improvement measure that held the utmost priority: "standardization of equipment start-up timing before the commencement of production." This measure was expected to yield significant improvement effects within a short timeframe.

6.3.2. Utilization of Knowledge and Tools for Improvement and Their Associated Situations

The log-level descriptions provide valuable insights into the data, information, knowledge, and tools employed by skilled consultants throughout each process, as well as the specific situations in which they are applied. Table 1 presents a summary of the data, knowledge, and tools utilized in Rounds 1–5, as documented in the log-level descriptions.

Table 1. Data/information, knowledge, and tools used by the skilled consultants in each process, and the situations in which they are used.

Round No.	Data/Information, Knowledge, and Tools	Situation
Round 1	List of basic information required for energy-saving improvement	Confirm whether or not the basic information required for energy-saving improvement consulting, such as the configuration of production facilities and manufacturing BOM, can be collected, and determine whether or not the consulting can be implemented.
	Time-series data of various energy consumption for more than one year (about one-month intervals)	To analyze rough energy consumption trends for all production facilities in a factory, time-series data should be obtained for a relatively long period (one year or more), at intervals of about one month, which are easy to get.
	Pareto analysis (utilizing Microsoft Excel)	Identify production facilities that consume large amounts of energy to roughly narrow down the types of energy resources and production facilities that need to be improved before detailed and man-hour-intensive data analysis is conducted.
Round 2	Examples of past improvements	For the energy resource types and production facilities narrowed down as improvement targets in Round 1, past improvement examples are used to roughly estimate the improvement effect and return on investment with a small number of person-hours before starting the detailed analysis.
Round 3	Time-series data of various power consumption and production quantities (less than a one-day interval)	Since most production facilities have daily production plans, time-series data at intervals of about one day are used to check the variation in power consumption versus production volume for each product model.
	Scatter diagram (utilizing Microsoft Excel)	Before conducting a detailed, man-hour-intensive data analysis, determine whether there is potential for power consumption loss to occur with fewer person-hours by checking the variation in power consumption versus production volume for each product model being produced.
Round 4	Total Productive Maintenance(TPM)	The power consumption loss is calculated for each operating state of production facilities defined in the TPM framework to make it easier to find improvement plans that match past improvement cases later.
	Time-series data of power consumption and production quantities (less than 1 h intervals)	To calculate the amount of power consumption loss generated for each operating state of production facilities, time-series data at intervals of 1 h or less should be obtained so that the state transitions of the facilities can be grasped.
	Time-series graph of power consumption loss	Based on the TPM framework, a time-series graph is output manually using time-series data on production volume and electricity consumption as input to extract the time period of loss occurrence where electricity is consumed even though no products are being produced.

Table 1. *Cont.*

Round No.	Data/Information, Knowledge, and Tools	Situation
Round 5	Total Productive Maintenance (TPM)	Same as Round 4.
	Time-series data of power consumption and production quantities (less than 1 h intervals)	Same as Round 4.
	Power Consumption loss generation calculation program	Since it takes man-hours for skilled consultants to manually calculate the amount of electricity consumption loss from a year's worth of time-series data on electricity consumption and production volume, we request that a data scientist analyze the amount of electricity consumption loss and develop a program that can be reused the next time around. A data scientist develops the program using Python, an open-source programming language. The algorithm of the program is based on the TPM framework as described previously.
	Examples of past improvements	To propose highly accurate and appropriate improvement plans for the power consumption losses calculated for each operating state of production facilities, skilled consultants extract similar examples of past improvements that are likely to be reused.
	Return on Investment Formula	Since customers prefer to implement improvement plans with significant effects in the shortest possible time, the return on investment is calculated from the improvement effect amount, investment amount, and improvement implementation period.

To illustrate the linkage between data, enhanced knowledge, and tools, we can examine a specific instance from Round 4 of the log-level description. In this round, the consultants leveraged the TPM framework to enhance their knowledge, utilizing time-series data on power consumption and production volume as input, and a time-series graph as a tool to calculate the amount of power consumption loss incurred by the iron core press facility. As depicted in Figure 6, the production quantity and power consumption data were superimposed and visualized in the form of a time-series graph. By applying the TPM framework, the power consumed, despite no products being produced, was identified as power consumption loss.

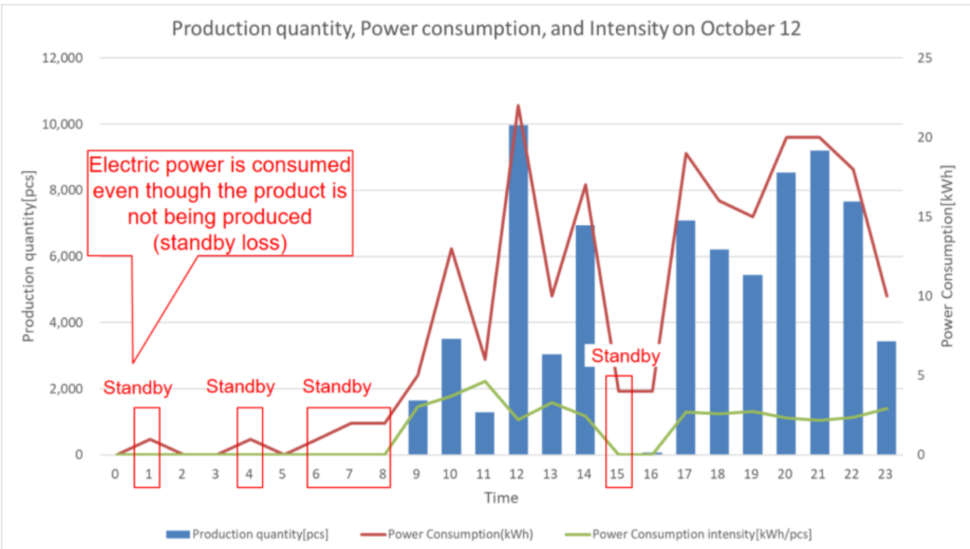

Figure 6. Time-series graphs for loss generation calculation based on the TPM framework.

This analysis also revealed that improvement knowledge is not only employed in isolation but also in conjunction with other improvement knowledge. For example, in Round 5 of the log-level description, when deriving the final improvement plans, the results of power loss generation served as input, and reference was made to past improvement examples. In order to establish a link between the generated loss results and the improvement examples, the loss type was documented as a data item in the spreadsheet of previous improvement cases, as illustrated in Table 2. By utilizing this information as a key, improvement plans corresponding to the identified losses were formulated.

Table 2. Past Improvement Examples.

Facility Type	Energy Resource Type	Loss Type	Problem	Improvement Plan
Press	Electricity	Start-up	Standby loss occurs due to start-up work before the required warm-up time.	Intermittent operation control (automation of facility power ON/OFF during standby).
		Shutdown	Standby losses occur when production is interrupted or left unattended without start-up after production is finished.	
		Short-time stop	Workpiece feeding timing is poor, resulting in standby losses.	Optimization of input quantity and timing (production control).
		Short-time stop	Poor timing of raw material exchange, resulting in standby losses.	
		Changeover (Set-up)	Variation in product-model setup time by the operator, resulting in standby losses.	Conversion of internal setup to external setup.
				Work standardization (positioning of jigs and tools).

6.3.3. Domain-Specific GCPM

Subsequently, the KE undertook the generalization of the process based on the aforementioned log-level description using a generalization method, encompassing cleansing, aggregation, and abstraction. This method, proposed in the authors' prior research [27], aimed to construct a domain-specific GCPM (a variant of GPM) tailored specifically for energy-saving improvement consulting. Here are some examples illustrating the application of abstraction and aggregation.

In the "Current Status Analysis 1" process depicted in Figure 7, which corresponds to Round 1 of the log-level description, the KE employed abstraction by eliminating specific nouns such as "iron core press". This abstraction allowed for the generalization of the process, enabling its application to other factory cases.

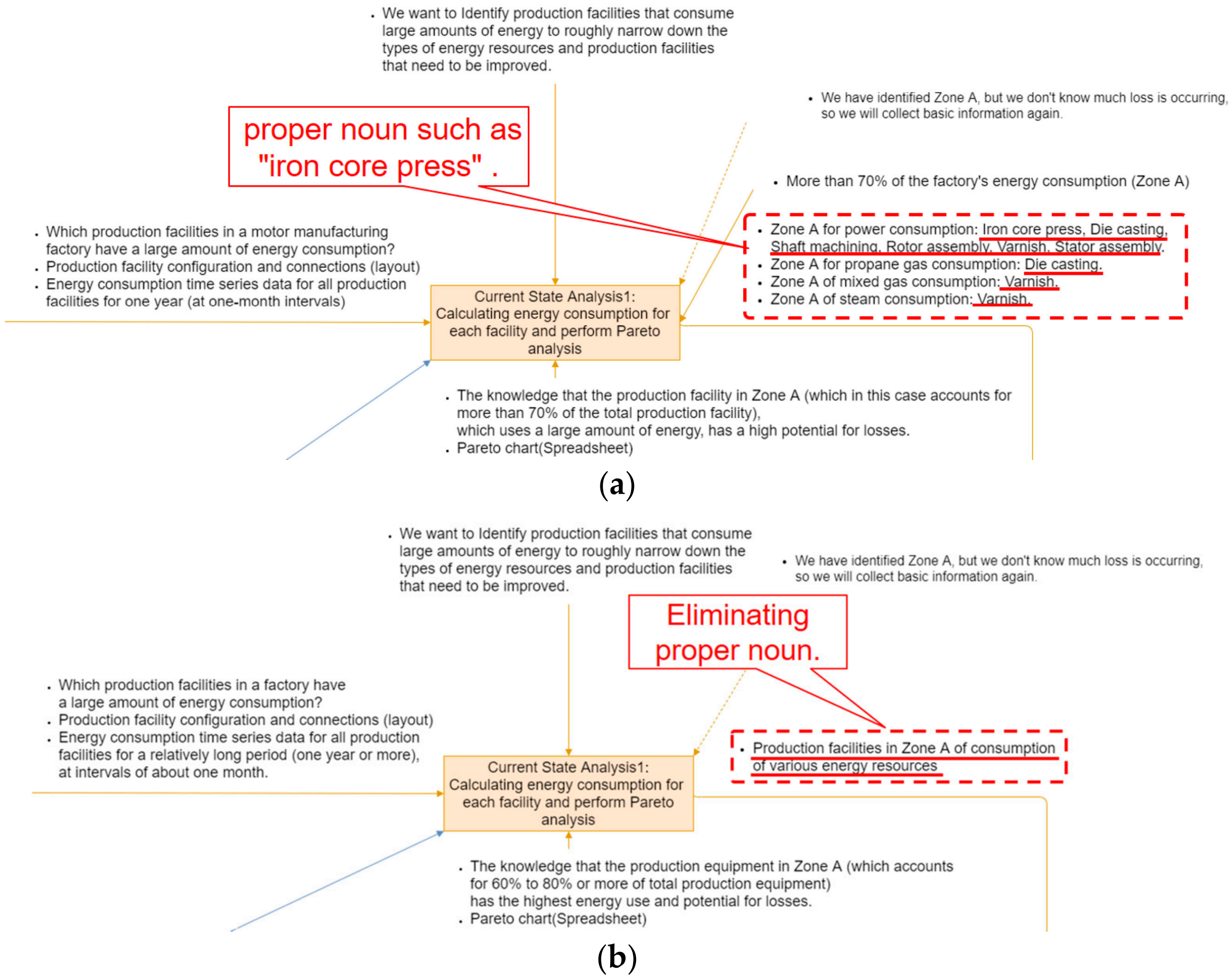

Figure 7. Generalization of Round 1 of log-level description: (**a**) Log-level description; (**b**) GPM for energy-saving improvement.

Next, we provide an example of aggregation. Figure 8a portrays Rounds 4 and 5 of the log-level description. In Round 4, skilled consultants refrained from manually calculating power consumption loss generation for the entire one-year period due to computational constraints. Instead, they enlisted the assistance of a data scientist to perform the calculations and develop a reusable program in Round 5. As the problem setting for calculating electricity consumption loss generation across the entire year remained the same in both rounds, the manual calculation conducted by the skilled consultants in Round 4 became redundant. Consequently, during the construction of the domain-specific GCPM, the KE was able to consolidate the processes of Round 4 and Round 5 into a single process, as demonstrated in Figure 8b.

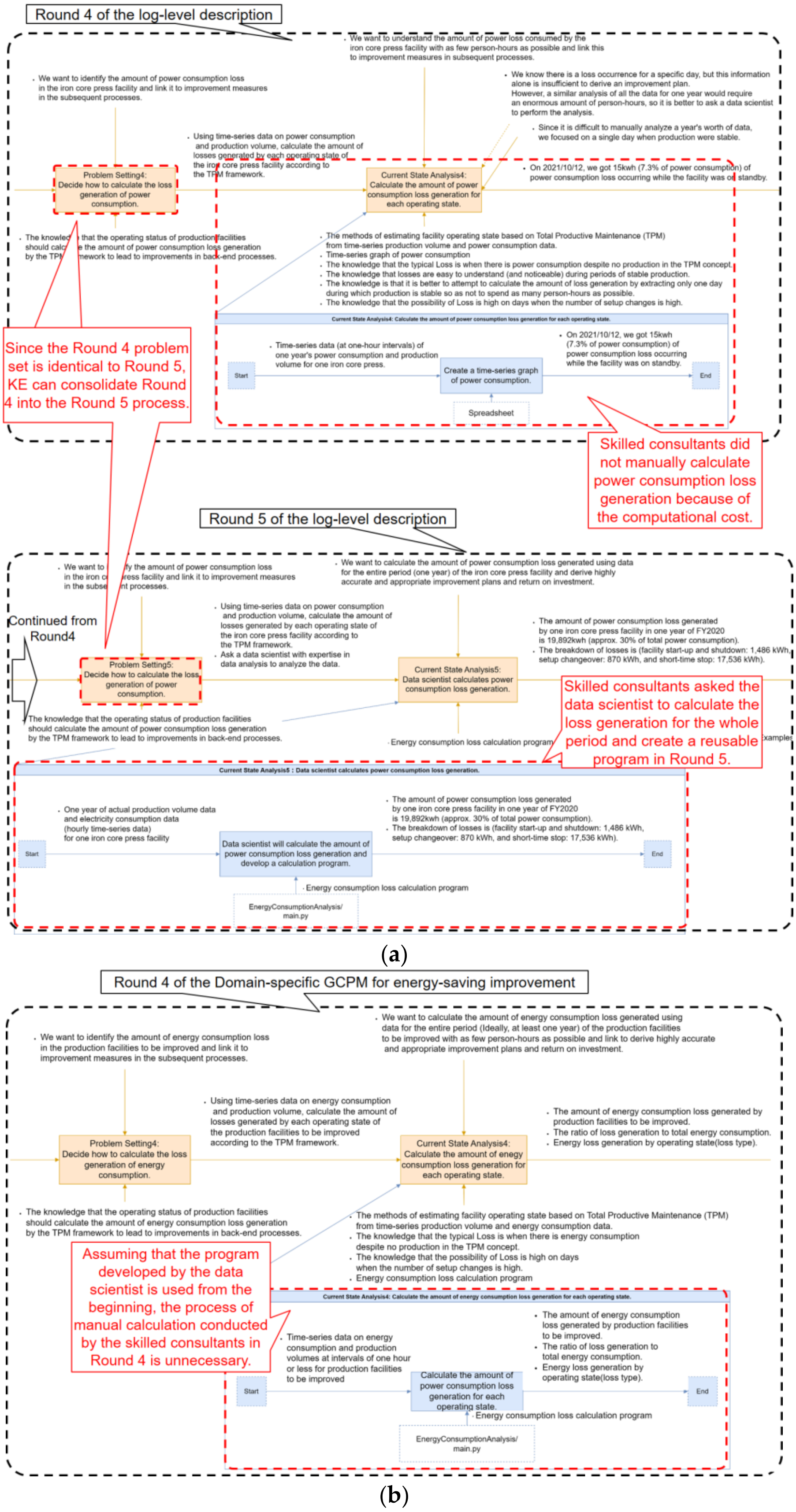

Figure 8. Generalization of log-level descriptions Round 4 and Round 5: (**a**) Log-level description; (**b**) GCPM for energy-saving improvement.

7. Discussions

The case study analysis results presented in Section 6 serve as the foundation for the discussions in this section. The primary focus is on evaluating whether the "production system consulting process modeling method" proposed in Section 5 effectively addresses goals 3 and 5 concerning the training of unskilled consultants, as outlined in Section 2.2. Additionally, areas that require improvement are identified.

7.1. Application of General Process Flows to Specific Cases

In the case study of energy-saving improvement consulting, we applied and organized the GCPM, observing that it followed a repetitive structure across five iterations. The skilled consultants progressively narrowed down the problem space, starting from a broad problem scope encompassing the entire factory and all energy resources in Round 1, and ultimately identifying high-priority areas for improvement in Round 5. This finding supports the hypothesis that the iterative structure of the GCPM effectively captures the production system consulting process. Furthermore, we developed a domain-specific GCPM for energy-saving improvement based on the log-level description. This achievement can be attributed to the inherent flexibility of the "problem setting" process within the GCPM, which facilitates a comprehensive understanding of how skilled consultants systematically narrow down the problem domain. Notably, the problem-setting process adapts to changes in the problem space.

By utilizing the domain-specific GCPM as an intermediary between the GCPM and log-level descriptions, we propose that unskilled consultants can gain a holistic overview of the actions performed by experienced consultants in a top-down manner. Simultaneously, they can acquire a detailed understanding of the specific actions taken by skilled consultants in individual cases in a bottom-up manner. This approach facilitates a more comprehensive understanding of the entire process, allowing for seamless navigation between the specifics of the cases addressed by skilled consultants. Essentially, the domain-specific GCPM enhances the understanding of the connection between general and specific processes, bridging the gap between the GCPM and log-level descriptions.

7.2. Application of Various General Improvement Knowledge and Tools to Specific Cases

By employing the proposed method, we can identify the specific locations and types of data, information, improvement knowledge, and tools utilized throughout the overall process flow of skilled consultants, as demonstrated in the case study of energy-saving improvement consulting.

Through this case study, we observed that skilled consultants progressively narrowed down the problem space while collecting data and information in a staged manner. Instead of gathering all the necessary information and data at the outset, they acquired detailed information incrementally based on the evolving circumstances and applied relevant improvement knowledge and tools accordingly. This approach aligns with the repetitive structures found in the GCPM, which exhibit similar patterns. In contrast to a simple sequential depiction of the process flow, the GCPM offers unskilled consultants a comprehensive perspective on the required data and information for different problem settings (problem space). This holistic view can be beneficial for unskilled consultants in understanding the process

However, it is important to note that the authors greatly benefited from the PD3 process modeling method proposed in a previous study. This is because the PD3 description represents the intention of a single action through the arrow accordingly, while the arrows accordingly signify the knowledge and tools employed. The PD3 method enables the linkage between the intention and the utilized knowledge and tools, which proved valuable in this study.

7.3. Overview of the Production Systems Consulting Modeling Method

In this study, we aimed to provide an overview of our work and analyze the consulting process employed by skilled consultants. To achieve this, we utilized the GCPM, known for its high level of abstraction and broad applicability in general consulting, to generate a log-level description of the energy-saving improvement consulting process. This log-level description captured the specific details of the consulting process in skilled consultants' cases. Subsequently, using this log-level description, the KE derived a domain-specific GCPM tailored for energy-saving improvement consulting, which could be applied to other factory cases.

The domain-specific GCPM represents a compromise between the top-down approach of the GCPM and the bottom-up approach of log-level descriptions. This unique proposition combines the bottom-up approach of the GPM proposed in our previous study with the top-down approach derived from the GCPM.

With the domain-specific GCPM, unskilled consultants can navigate between the GCPM, which offers a comprehensive bird's-eye view, and the log-level description, which provides a detailed understanding of the process. This allows unskilled consultants to grasp the flow of skilled consultants' processes, comprehend the knowledge and tools utilized, and identify the contexts in which they are applied. Additionally, as future examples are accumulated, they can serve as valuable resources to support unskilled consultants in their consulting endeavors.

8. Conclusions

This paper presents the initial step of an ongoing study whose ultimate goal is to translate production system consulting activities into formal knowledge. This first stage involved understanding the process flow of skilled consultants, their utilization of improvement knowledge and tools, and the specific contexts in which they are applied. To achieve this, we adopted the D3 concept, which extends our D2 framework by incorporating the intelligent activity world of skilled engineers, because it aligned well with the objectives of our study. Given the complex nature of the problems and the diversity of clients involved in production system consulting, it is challenging to handle them solely by reusing the decision-making process of skilled engineers through GPM, as proposed in previous research. Thus, we proposed a production system consulting modeling method that integrates the GCPM into the framework of reusing skilled engineers' decision-making processes. By applying the proposed method, we conducted a case study on energy-saving improvements to describe and analyze the consulting process of skilled consultants. The results demonstrated that our approach effectively captured the process flow of skilled consultants while acknowledging the iterative nature of the GCPM. Moreover, the structured approach provided a holistic view of the entire process, facilitating the comprehension of how knowledge and tools are utilized in specific contexts. Consequently, by combining the bottom-up approach from our previous work with a top-down approach, which constitutes the enhancement of the method proposed in this study, we successfully developed a domain-specific GCPM that strikes the right level of abstraction needed to assist unskilled consultants in bridging the gap between the GCPM and log-level descriptions, facilitating their understanding of the consulting process.

However, during our research, we identified several areas that require further investigation. Therefore, the following studies should be conducted in the future to formalize production system consulting activities:

- Verification of the applicability of the domain-specific GCPM developed in this study for energy conservation improvements to different scenarios.
- Assessment of the support provided to inexperienced consultants using the domain-specific GCPM.
- Accumulation of log-level descriptions encompassing objectives beyond energy-saving improvements and creation of multiple types of domain-specific GCPMs.

- Verification of the ability to maintain performance after implementing domain-specific GCPM for a client company.

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