Process Capability Modeling for Manufacturing-as-a-Service (MaaS)

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Abstract: Disruptions from geopolitical tensions, natural disasters, or regulations threaten the stability of production networks, necessitating greater resilience. Manufacturing-as-a-service (MaaS) offers a promising solution to remediate these challenges. A significant challenge in developing and implementing MaaS at scale is enabling the automated translation of product properties to process properties, i.e., allowing service consumers to identify appropriate service providers. Describing process capabilities underlying the services is an essential foundation to achieve this. This paper first conceptualizes process capability before proposing a model for describing process capabilities in a MaaS context. A case study of a utility sensor manufacturing company demonstrates the model's practical application, showing its effectiveness in efficiently describing relevant process capabilities to support MaaS adoption.

Keywords: Manufacturing-as-a-service; process capability; modeling; resilience; production networks.

1 INTRODUCTION

The stability of production networks is increasingly threatened by disruptions to operation caused by geopolitical tension, natural disasters, regulatory barriers, etc. (Romero, et al., 2024) These challenges require companies to increase the resilience of their production networks to ensure continued operation in the face of disruptions. The focus on climate action also challenges many manufacturing companies operating in a linear economy, where needs for lower resource consumption and emissions are pressing matters. A promising solution to these challenges is Manufacturing-as-a-service (MaaS) (Hasan and Starly, 2020). Originating from the concepts of Software-as-a-Service (SaaS), MaaS aims to servitize production processes and facilitate the connection between companies with excess capacity (i.e., service providers) and those in need of production resources (i.e., service consumers) (Ren et al., 2017). However, an essential element of MaaS is that service providers can define their manufacturing services. Doing so requires knowledge of the service provider's manufacturing processes and what outputs these can provide, i.e., their capabilities. However, the novelty of MaaS means that many manufacturers do not have the sufficient data foundation to engage in these ecosystems as service providers. Based on the challenges described the research question for this study is:

"How can manufacturing process capabilities be effectively described by practitioners to enable participation in Manufacturing-as-a-Service?"

The remainder of this paper is structured as follows. Section 2 reviews related research. Section 3 presents the conceptual foundations for process capability modeling. Section 4 then introduces the proposed model for analyzing process capabilities. Section 5 presents the findings from a case study demonstrating the proposed model. Hereafter, Section 6 discuss the findings from this paper, and lastly, Section 7 conclude this study.

2 RELATED RESEARCH

This section reviews research related to process capability modeling, particularly in the context of MaaS, including process classification, capability definition, description, and analysis.

2.1 Process type classification

Describing services composed of individual manufacturing processes starts with identifying available processes in a manufacturing system. Feng and Song (2003) classify processes into part making, inspection, and assembly, each with multiple subclasses, but their scheme is limited in the scope of process types considered, omitting, for example, material handling. Giess et al. (2009) use faceted classification, enabling filtering by multiple parameters but likewise demonstrate only a limited process scope. Sørensen et al. (2018) propose a comprehensive scheme covering over 200 process types across manufacturing, material handling, and inspection. While this ontology provides an overview of a company's processes, it lacks attributes to describe process capabilities.

2.2 Process capability definition

For manufacturers seeking to servitize their production processes, understanding process capabilities for *producing products within and beyond their current portfolio is essential*. While process capability is well-established in quality management – focusing on consistent conformance to specifications (Juran and Godfrey, 1999) – it often overlooks the attributes needed to produce diverse products. Notably, no universal definition exists, as reflected by its absence from the *CIRP Encyclopaedia of Production Engineering*. Studies describe process capability by various aspects, e.g., geometric precision (Case, 1994; Zhao et al., 2020), process technology or performance (Case, 1994), or transformation potential relative to desired outputs (Hoang and Fay, 2019). Zhao et al. (Zhao et al., 2020) argue that multiple perspectives are indeed necessary to fully describe the capabilities of a process. Such a comprehensive understanding requires considering inputs (materials, labor, energy, information), transformations (handling, additive/subtractive, assembly), and outputs (products, waste, information), each characterized by measurable attributes (e.g., material hardness, workpiece dimensions, energy use). This study, therefore, defines process capability as *"the state of having measurable attributes required for tasks to transform inputs into specified outputs."* This definition emphasizes that (i) process capabilities consist of measurable attributes and (ii) these attributes determine which products a process can produce. Describing process capabilities clarifies available services and enables service consumers to match product specifications with suitable providers, making capability modeling essential for manufacturers.

2.3 Process capability modeling

Case (1994) proposes a system enabling translation between product features and process capabilities. However, the proposed system considers only geometric form features of individual components. This implies that processes that do not alter geometric features, such as heat treatment, are impossible to model. Component assemblies are likewise impossible to model with the proposed system, limiting its broad applicability for MaaS. Michaelis et al. (2015) present an integrated product-process model. Their modelling effort is directed towards modelling between product and process domains in the development phase by integrating function-Means trees and elements of the configurable component method. This allows linkages between functions, design solutions, and architectures of both products and processes. However, being focused on design solutions and functions, their capability description does not include process attributes nor ranges to support MaaS scenarios. Brunoe et al. (2020, 2018) propose frameworks for company-specific ontologies linking product properties with process capabilities. However, the context-specificity of these ontologies potentially challenges their application in a MaaS context as MaaS systems rely on the ability to translate product parameters and process capabilities in a standardized manner across organizations. Zhao et al. (2020) demonstrate a system for the automated classification of process capabilities from CAD models of manufactured components. However, the system is only demonstrated for three manufacturing processes and does not consider assembly operations, limiting the applicability for general MaaS scenarios. Focusing specifically on process capability description, Brunoe et al. (2024) proposes a method for identifying process capabilities through ERP data mining techniques. This method allows companies to adopt a more automated approach to process capability definition. A fundamental prerequisite of this method is the availability of the relevant data. This also means that small and medium-sized enterprises pursuing MaaS may find applying this method challenging.

3 PROCESS CAPABILITY MODELING FOR MANUFACTURING-AS-A-SERVICE

This section begins by defining process capability in the context of MaaS, after which different approaches to, and levels of, process capability description are presented.

3.1 Process capability attributes

Attributes provide information about what a process is capable of, and the valid value combinations across process attributes define the process capability envelope. An attribute may have one of several value types used to describe the process capabilities, including binary (true, false), numerical (integer, decimal), list (text, numerical), or text. Recording values for some attribute types may be easier than for others. For example, while lists of certifications that a company has obtained for a given process may be manageable to record, the same may not be valid if listing all the materials and their specific variants that a milling center can process, as there may be hundreds of relevant alloys. Two potential solutions may accommodate this challenge. First, adopting an object-oriented modeling approach may, for example, simplify the notation of which material types a process is capable of handling. The second approach allows attribute values to list excluded rather than included values.

While not all processes share the same set of attributes, it is possible to define specific generic attributes that would be relevant to all manufacturing processes. Simultaneously, not all process attributes may be equally relevant across industries or even across companies within the same industry. Table 1 lists examples of process attributes from generic to case-specific process attributes.

Table 1: Process attribute relevance hierarchy and associated attribute examples for a printed circuit board assembly (PCBA) line.

Relevance	Example attributes
General	• Min/max workpiece dimensions • min/max workpiece weight • material types
Industry	• Panel dimensions • Number of component reels • min/max component size
Case	• Number of SMT component reels • Number of THT component reels • Full Electrical Test • Component glueing

Operating with several classes of attribute specificity may assist in describing these more efficiently, as the analysts can be presented with only relevant subsets of process attributes. Furthermore, attributes relevant to a company may be added or act as variations of more generic attributes.

3.2 Process capability description approaches

Process capability, as described in Section 2.2, relates to a process's input, transformation, and output. It is, therefore, argued that in addition to the capability description methods described in the reviewed literature, which rely on the outputs generated by a process (Brunoe et al., 2024, 2020) or based on the process inputs (Zhao et al., 2020), a third specification-based method may be identified. These three different approaches to capability description are illustrated in Figure 1.

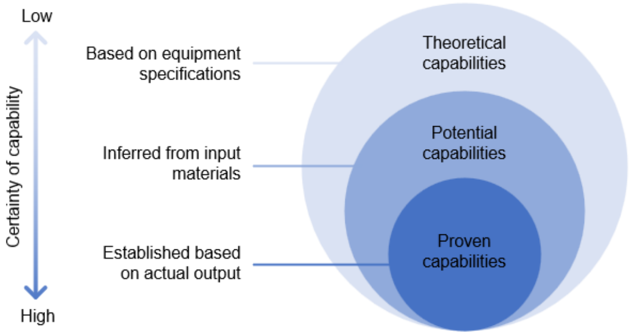

Figure 1: Three different approaches to describing process capabilities with associated degrees of uncertainty. (Andersen, 2024)

What a process produces is typically only a fraction of what the process can produce. For example, a milling process may produce gears with 100-, 150-, and 200-mm diameters, resulting in a 100 – 200 mm capability envelope. We refer to these as *proven capabilities*. The work area of the milling center may, however, be 300 x 300 mm, meaning that gear sizes outside the output-defined envelope could be milled. This information may, however, not reside in a company's ERP system (Brunoe et al., 2020) and may only be available within the control systems of production equipment or as technical documentation for the equipment, making it more cumbersome to collect. Furthermore, establishing the actual limits on manufacturable gear sizes may not only be a factor of the work area. For this reason, we refer to this capability envelope as *theoretical capabilities*. Lastly, capabilities may be inferred from process inputs (Zhao et al., 2020). For example, the gear material may suggest that materials with similar properties could be milled on the same equipment. In most discrete manufacturing scenarios, however, input materials are not transformed per se but reconfigured (Andersen et al., 2021). The input-based method may be more relevant in the process industry, where outputs are typically distinctively different from their inputs. For example, an industrial bakery may produce bread in different sizes. However, since bread shares ingredients with numerous other baked goods, the actual capabilities of the bakery may depend more on which process inputs it can handle. While capabilities inferred from this approach are not validated, they are based on actual inputs to a process and are, therefore, referred to as *potential capabilities*. Confidence in a process's capabilities varies across the methods, with the output-based approach offering the highest confidence and the specification-based method offering the lowest. Even so, interpolation in the output-based method requires validating identified capabilities before offering them to service consumers.

3.3 Process capability description levels

A MaaS service provider may offer services related to different aggregation levels of manufacturing processes, ranging from individual processes to process chains. If a MaaS service provider decides to offer several different manufacturing processes as individual services, each must have their capabilities described (see left side of Figure 2).

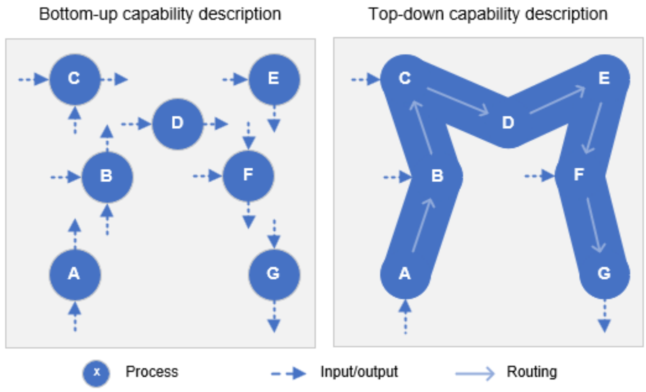

Figure 2: Two fundamental approaches to manually describing process capabilities based on the type of service offered. (Andersen, 2024)

On the other hand, if a business decision has been made to offer services related to a specific chain of processes, such as a production line, a different level of detail is required to describe the capabilities of that specific chain of processes. In this case, not all capabilities of all processes that comprise the production line need to be described, as some capabilities will be redundant. For example, the process with the most restrictive set of dimensions will limit the physical dimensions of the product that can be produced on a production line. Furthermore, only external inputs to a production line are relevant to describe as within-line inputs, i.e., inputs received from previous processes in the production line are implicit. This aggregated approach to describing process capabilities are visualized on the right side of Figure 2. In the aggregated scenario shown in Figure 2, the chain of processes can be described similarly to each of the individual processes, thereby reducing the complexity of the analysis. The same simplification holds for subsets of a process chain or production line.

4 PROCESS CAPABILITY DESCRIPTION METHOD FOR MANUFACTURING-AS-A-SERVICE

This section first describes prerequisite decisions and considerations before applying the proposed process method for the capability description of manufacturing processes.

4.1 Prerequisites for applying the process capability description method

Describing all process capabilities for all manufacturing processes in a company can be very resource intensive. Several decisions must be made before embarking on such a task, as illustrated in Figure 3. These decisions define the scope of the analysis, the appropriate level of detail, and the sequence of activities. The first prerequisite is a business decision regarding which services a prospective MaaS service provider wants to offer. This decision defines the scope of the subsequent analysis, specifying whether individual processes or process chains will be offered. This knowledge, in turn, allows the analyst to choose whether to apply a "top-down" or

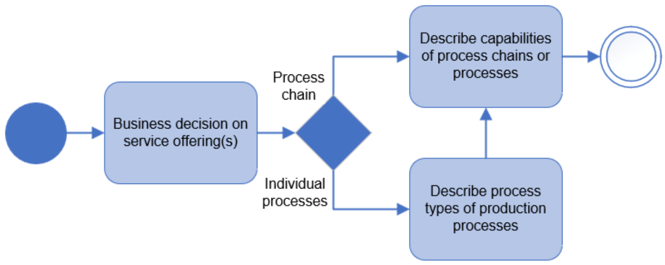

Figure 3: Prerequisite steps and decisions to applying process capability modeling process. (Andersen, 2024)

"bottom-up" approach to process capability description, as described in Section 3.3. Regardless of which approach is chosen, identifying relevant process attributes and their values is augmented by including a domain expert in the process. If individual processes are offered as services, their process type must first be determined using the classification scheme by Sorensen et al. (2018), thereby providing an overview of which processes are available. Next, process attributes can then be described for each process, providing an overview of what is possible to make with the available processes.

4.2 Process model for process capability description

This section outlines the process model for describing manual process capabilities with digital assistance, as illustrated in Figure 4. Due to space limitations, the model description takes the outset in a "bottom-up" process capability description scenario, whereas the "top-down" scenario is described through the case study in Section 5. Describing process capabilities is a recursive process and starts from the first process in scope. Since the process type has been defined previously, the next step is to select the process's first generic attribute and determine its relevance. If relevant, the appropriate descriptive value(s) are recorded. If the attribute is irrelevant, the following generic attribute is selected. This is repeated for all generic attributes. If the generic attributes do not sufficiently describe the process's capabilities, the analyst can create a custom attribute and assign appropriate values. This is repeated until the process' capabilities are sufficiently described.

Determining the relevance of a process attribute is a sub-process that warrants a more detailed description. This sub-process is illustrated in Figure 5. For each generic or industry-specific attribute considered, if a product in the company's portfolio requires a specific attribute value, the specific attribute is included in the analysis, and the corresponding value(s) are noted. If no current product utilizes a given attribute, i.e., no values for it are recorded, the process capability envelope can be expanded by considering also discontinued products. If any previously manufactured products require a specific attribute value, these additional values are considered for inclusion. However, this is only the case if no modifications to the specific process have been made since the particular product was discontinued as the capability of the process may no longer reflect the past capability.

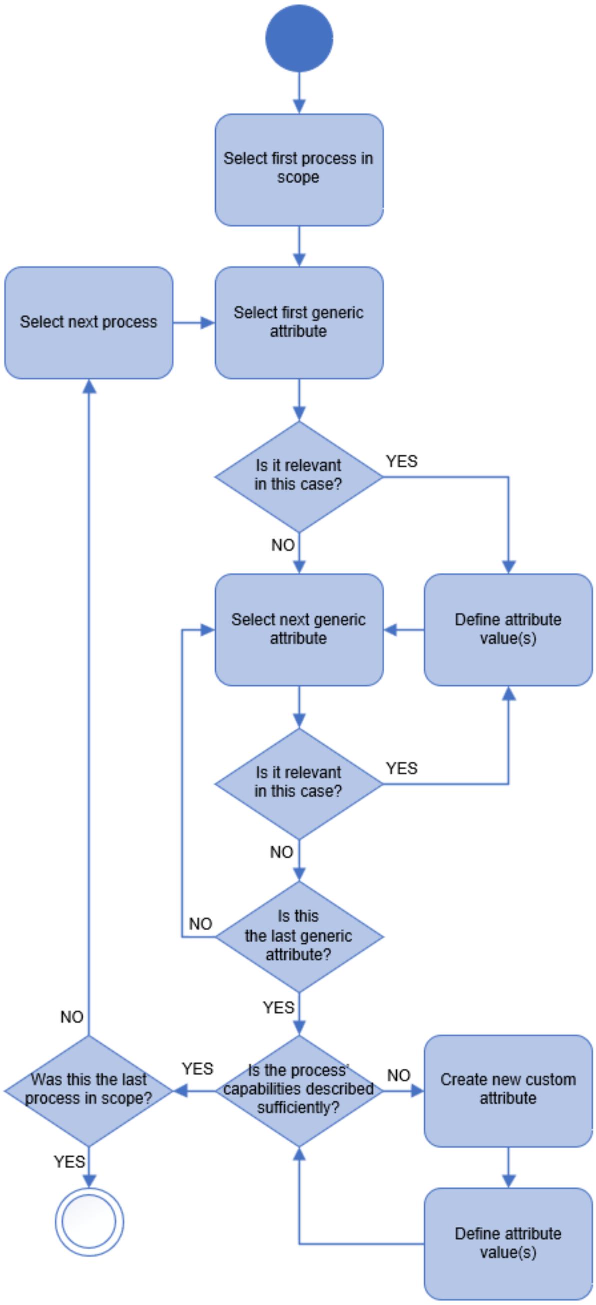

Figure 4: Process capability description model. (Andersen, 2024)

4.3 Practical considerations on process capability description

Process capability can be determined based only on what has been produced or extended to include more uncertain capabilities, as described in Section 3.2. Each perspective brings its own set of challenges for a MaaS service provider. Aiming for the broadest capability envelope comes at potentially very high costs associated with analyzing and validating these capabilities. Therefore, a pragmatic approach for companies pursuing the role of MaaS provider is initially taking the outset in the output-based method. This will reduce resource use for determining process capabilities, lowering the entry barrier to offer services. It should, however, be noted that this would come at the expense of more potential customers

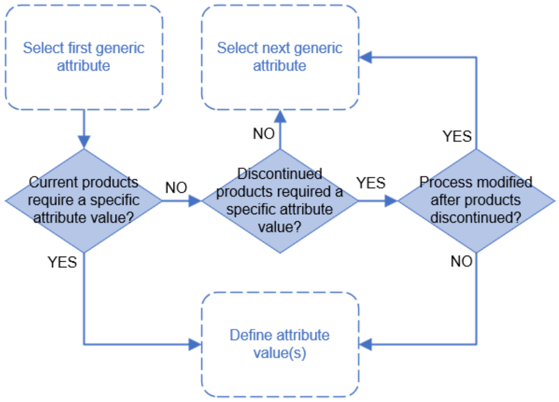

Figure 5: Logical flow of the sub-process for determining process attribute relevance. (Andersen, 2024)

due to a smaller capability envelope and, consequently, a narrower manufacturing service offering.

The description model illustrated in Figure 4 is a primarily manual process. Whether to apply this or the data mining-based method by Brunoe et al. (2024) depends on the context. The first consideration concerns the prerequisites of the two process capability determination models, where the method proposed in this paper may be suitable for smaller companies that lack the required data or employee competencies to utilize the data mining-based approach. Another consideration concerns the scope of the analysis. If many production lines with many processes must have their capabilities determined, applying the data mining-based method may be more resource-efficient. However, large companies seeking to determine process capabilities only for a single production line or just a few processes may also find the manual process relevant.

5 CASE STUDY

The case study focuses on a large European utility sensor manufacturer. Central to these sensors are PCBs that process and communicate data. The company operates multiple PCBA lines with varied equipment and capabilities and is interested in the potential for increasing production network resilience by offering internal PCBA services. A key step is describing the capabilities of these lines. This section demonstrates the application of the proposed capability description model (see Section 4) to one PCBA line, using a top-down approach aligned with their goal of offering complete PCBA services (i.e., the whole process chain depicted in Figure 6). Domain experts ensured the inclusion of relevant process attributes.

5.1 Investigated PCBA line and its comprising processes

The processes of the PCBA line in scope are illustrated in Figure 6 and briefly described in the following. The process begins with a panel loader machine holding a magazine of PCB panels for component mounting. Panels proceed to a stencil printing machine, applying solder paste in product-specific patterns. A solder paste inspection follows to prevent quality issues, discarding faulty panels. Passed panels move to pick-and-place machines for SMT (surface mount technology) components, followed by another inspection to ensure correct placement. SMT components are secured via reflow soldering,

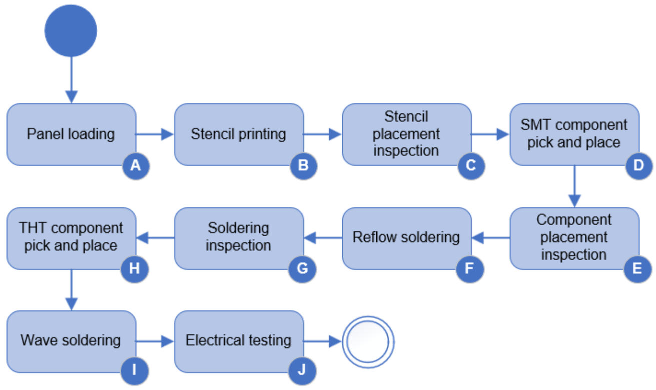

Figure 6: A process flow chart of the PCBA line in the case company. (Andersen, 2024)

with an inspection verifying the solder quality. Additional pick-and-place machines install THT (through-hole technology) components adhered through wave soldering. Finally, the completed PCBs undergo full electrical testing to ensure functionality.

5.2 Top-down process capability description of PCBA line

Describing the process capabilities of the selected PCBA line started with a visit to the production facilities, where the involved researchers and domain experts started from the first process (A) and walked along the production line, getting an introduction to each subsequent process. Since the objective was to describe the PCBA line's process capabilities with the minimal information required, the domain expert identified process attributes only for each process considered critical to describe, focusing on how the inputs to the processes related to the product outputs. Table 2 describes the relevant process attributes for the essential processes and their relation to the products produced on the PCBA line.

Table 2: Identified relevant process attributes for each essential process and their relation to product properties.

PCBA process	Relevant attribute	Product properties
A	Panel dimensions (length, width, height)	Dimensional boundaries on PCB sizes
D	Reel capacity	No. of different SMT components on PCBs
D	Component sizes (min, max)	Smallest and largest SMT components for PCBs
F	Temperature range (min, max)	Soldering of components, SMT component types
H	Reel capacity	No. of different THT components on PCBs
H	Component sizes (min, max)	Smallest and largest THT components for PCBs
J	Fixtures and software	Item numbers

Evident from the highlighted processes in Table 2 is that enabling internal MaaS service offerings of PCBA at the case company required only a description of a subset of production processes, thereby reducing resource needs required to offer services. Furthermore, as Table 2 shows, only a limited number of process attributes are considered essential for each process, thereby further reducing capability description efforts.

6 DISCUSSION

This section discusses the findings of this study, emphasizing the academic and practical implications of the findings and the potential limitations of the present study.

Specifications-based process capability methods offer a broader capability envelope, but the validation effort associated with these extended capabilities makes validation increasingly relevant toward the outer layers of the capability circle. Therefore, exploring optimal validation methods is a promising avenue for future research.

Process routings may define services through their production processes, as shown in the case study (see Section 5). Dynamic process chains could also offer additional services but would require defining all potential chains and their capabilities, a potentially extensive effort. Even in the limited case study, the lack of standardized methods for recording process attributes poses challenges for MaaS integration. Developing digital assistance systems to support practitioners in describing process capabilities is relevant for future research.

Lastly, as the industrial demonstration in Section 5 was limited to a single case study of a particular type of production system, there is a need for further validation in other manufacturing contexts to explore the bottom-up approach and potential application of the sub-division of process chains.

7 CONCLUSIONS

This study proposes an approach to effectively describing manufacturing process capabilities for companies intending to participate in Manufacturing-as-a-Service (MaaS) ecosystems. By proposing a model that considers multiple levels of process description, from individual processes to entire production lines, it enables manufacturers to describe their intended service offerings in a structured and standardized way. The case study demonstrated the practical application of the proposed method, highlighting the feasibility of adopting a top-down approach for describing process capabilities in a practitioner-oriented way. The findings of this study show that while detailed process capability descriptions offer the greatest confidence, a pragmatic approach, starting with output-based capabilities, may lower entry barriers for companies, particularly small and medium-sized enterprises. The contributions of this paper have been three-fold: (i) presented a conceptual foundation of process capability in a MaaS context, (ii) proposed a practitioner-oriented method for structured process capability description, and (iii) demonstrated the proposed model's application in an industrial context.

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