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Development of a cloud-based factory simulation system for enabling ubiquitous factory simulation

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ABSTRACT

This study investigated several problems related to the implementation of cloud-based factory simulation. First, the differences between cloud-based factory simulation and parallel and distributed factory simulation were discussed. Individually managed, resource heterogeneity, uneven load partitioning, and potential business opportunities were found to be the novel characteristics that discriminate cloud-based factory simulation from parallel and distributed factory simulation. The problems in existing cloud-based factory simulation systems are discussed. An experimental cloud-based factory simulation system was developed and used for simulating a mobile lift table factory.

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1. Introduction

Cloud computing is a model for enabling on-demand network access to a shared pool of resources [1]. Three services are provided depending on the type of resources available: Software as a Service, Platform as a Service, and Infrastructure as a Service. Cloud manufacturing refers to the application of cloud computing in the manufacturing sector. This study investigated a practical problem in cloud manufacturing, namely cloud-based factory simulation, which simulates a factory by using cloud resources and services. Simulation has been applied to improve the performance of factories by, for example, determining an internal due date that is both appealing and achievable for each order [5], comparing the performance of various scheduling methods [6], enhancing product and production engineering process [7], and translating the six-sigma philosophy into competitive solutions [8]. However, simulating a factory is a long-term task entailing considerable expertize, time, and effort. In addition, factories require a scalable simulation solution, which can be supported by cloud computing systems, when they are expanding their capacity. Thus, factories are seeking alternatives, such as a simulation consultant or a cloud-based simulation service. Therefore, we developed a cloud-based simulation service, which has rarely been investigated previously. The establishment of a cloud-based factory simulation system is expected to help factories acquire ubiquitous simulation capability.

Chi et al. [9] established a web-based automotive factory simulation system. The simulation model and system database were placed on the server side, and the running process was shown on the client's screen. However, the client could not upload another model for simulation. Lindskog et al. [10] used three-dimensional (3D) lasers to scan a factory. They used this method to generate an efficient 3D factory simulation model, which was a crucial step toward rapid factory visualization. However, whether factory visualization was crucial for cloud-based factory simulation was unclear [4]. According to Chen [4], cloud-based factory simulation includes five stages: preparing and analyzing the data, defining the equipment, building the layout, defining and converting the recipes, and running the simulation.

In addition, some techniques in parallel and distributed simulation, such as those for migrating simulation components and adding nodes to the distributed architecture at runtime, could not be directly applied to cloud-based simulation [17].

Most studies on cloud-based simulation have simulated communication networks [17]. A factory can be small (e.g., a company with only an independently operating computer numeric control machine) or complex (e.g., a wafer fabrication factory comprising hundreds of machines to process thousands of jobs). The resources required for simulating factories of various sizes vary considerably; hence, the simulation requires a highly-scalable cloud-based system. In addition, the existing factory simulation systems differ in their input formats, processing logic, data structures, and other aspects. When different factory simulation systems are utilized on clouds, interoperability hampers the smooth operation on a cloud-

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based simulation system [20].

Therefore, this paper discusses several problems related to the realization of cloud-based factory simulation. The following section presents a literature review. The methodology is proposed in Section 3. In Section 4, an experimental cloud-based factory simulation system is presented and used for simulating a factory mobile lift table. Section 5 concludes this paper.

2. Literature review

2.1. Cloud manufacturing

According to Zhang et al. [26], resources, cloud systems, and cloud services constitute the three core components of a cloud manufacturing system. Virtualization, interoperability, and scalability are three attributes of and targets for a cloud manufacturing system [4]. In a recent study on machine virtualization, Barnt and Sundaram [25] linked an additive manufacturing machine to a cloud, enabling users to subsequently upload instruction codes to the cloud for operating the additive manufacturing machine. Chen and Lin [23] assigned a unique digital equipment identifier (DEI) to each machine to ensure that machines with identical DEIs could be virtually aggregated online; this process was considered a vital step toward realizing the interoperability of the available capacities of these machines, which in turn contributed to the scalability of each factory. A certain type of intelligence is also required for seamlessly connecting the three core components of cloud manufacturing systems. For example, Xiang et al. [27] solved a multiobjective decision-making problem to map user requests to cloud manufacturing services, thereby maximizing the quality of service (QoS) while minimizing energy consumption. They also proposed a the group leader algorithm to facilitate finding a global optimal solution to the multiobjective decision-making problem.

Most extant studies on cloud manufacturing have been conducted from an information viewpoint (not from a manufacturing perspective). Therefore, service mapping (or selection) and composition are frequently examined topics. Although studying these topics from an information perspective may be appealing, they have not been evaluated from the perspective of addressing the major concerns of manufacturers. Few previous studies have examined critical concerns such as cloud-based factory simulations. Nevertheless, manufacturers still require a scalable solution to problems encountered in factory simulation systems when they are expanding their capacity.

In recent years, increasingly more researchers in this field have focused on the Industry 4.0 concept rather than cloud manufacturing. Although these two concepts actually foster the growth of each other, Industry 4.0 involves greater emphasis on cyber-physical systems (CPSs) [28]. A cloud-based factory simulation system must capable of reading real-time factory data, and such a system can be considered a large CPS.

2.2. Differences between cloud-based factory simulation and parallel and distributed factory simulation

Parallel and distributed simulation is the foundation for cloud-based simulation [11–13]. The advantages of parallel and distributed simulation include faster simulation, integration of simulators that are geographically distributed, integration of a set of commercial off-the-shelf simulation software, and composition of different simulation models in a single simulator [14].

The differences between cloud-based simulation and parallel and distributed simulation are as follows [15]. Conventionally, in parallel simulation, the parts of a simulation task, or logical processes, are completed simultaneously on a parallel computer. If these parts advance asynchronously in the simulation time, an effective synchronization scheme is required. Parallel simulation techniques include functional decomposition, time-stepped simulation, and asynchronous parallel simulation [16] (Table 1).

Table 1
Parallel simulation techniques.

Technique	Definition
Functional decomposition	The steps of a simulation task are processed using different processors.
Time-stepped simulation	The simulation time is divided into fixed-size intervals. Each processor simulates its parts at these time points.
Asynchronous parallel simulation	Each processor maintains its own clock. The events on the processors may advance asynchronously.

In distributed simulation, the parts of a simulation task are distributed over multiple computers, each working concurrently and sending its results to a central control unit to be aggregated. However, the processing sequence is no longer ensured. Cloud computing establishes a distributed architecture involving several remote or virtual servers. In addition, some techniques in parallel and distributed simulation, such as high-level architecture, migrating simulation components, and adding nodes to the distributed architecture at runtime, cannot be directly applied to cloud-based simulation [17,22]. D'Angelo and Marzolla [17] proposed an adaptive simulation mechanism and a multiagent system paradigm to solve these problems.

Cloud-based factory simulation divides the task of simulating a factory into separate subtasks that can be simultaneously and collaboratively processed on multiple simulation clouds (or core architectures). Chen [4] mentioned four types of collaborations among simulation clouds: partitioning a factory simulation model, evaluating the performance of various scheduling methods, considering different possible values of uncertain/stochastic parameters, and replicating the same simulation on multiple clouds. Based on the type of collaboration, simulation clouds are typically accessed by using a cloud service provider (CSP) on a pay-per-use basis. Both during and after simulation, the results of multiple simulation clouds must be aggregated to repartition the simulation task [16], determine whether to stop the simulation earlier or request an extension [4], and summarize the simulation results [4]. After aggregation, the casual consistency [19] among the simulation clouds must be ensured [17].

Simulation resources in cloud-based factory simulation are more heterogeneous than those in parallel or distributed factory simulation. In addition, compared with parallel or distributed simulation, in which the simulation resources, whether distributed or not, are managed in a centralized manner, cloud-based simulation aggregates simulation resources (including simulation clouds) that are individually managed for supporting various business policies. Therefore, the partitioning policy adopted by a parallel or distributed factory simulation system is different from that adopted by a cloud-based factory simulation system. In parallel or distributed simulation, a common partitioning policy is to evenly distribute the tasks among simulation units and reduce the communication among the simulation units [17]. For cloud-based factory simulation, Chen and Lin [20] proposed three possible partitioning policies: an equal division policy, a proportional-to-efficiency policy, and a simultaneous stopping policy.

Moreover, synchronization is crucial to distributed simulation. For example, D'Angelo et al. [17] compared three synchronization approaches for distributed simulation: a time-stepped synchronization approach, conservative synchronization approach, and optimistic synchronization approach (Table 2). By contrast, in cloud-

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