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CONCEPTUAL MODELING FOR SUPPLY CHAIN DIGITAL TWIN

Chang Seong Ko, HaeKyung Lee and Taioun Kim*

Department of Industrial and Management Engineering
Kyungsung University
309, Suyeong-ro, Nam-gu, Busan 48434, Korea
{ csko; hshklee72 }@ks.ac.kr; *Corresponding author: twkim@ks.ac.kr

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Abstract. *Since the inception of digital twin idea, it has been applied to wide areas which encompass product lifecycle management, product development, manufacturing, logistics and process control, to name a few. With the development of IT, physical and cyber things are combined and interconnected in real-life environment. Regarding production and delivery of any product to the customer, the whole physical process is highly intertwined with cyber process from product design to the delivery. The purpose of this paper is to model supply chain process based on digital twin concept. Important requirements of supply chain are seamless connection, real time, reliability, quality of service, visibility and efficiency. Supply chain digital twin model would satisfy most of the requirements in supply chain.*
Keywords: Digital twin, Supply chain, Cyber physical system, Big data analytics, Supply chain digital twin

1. **Introduction.** Digital Twin (DT) refers to a digital replica of physical assets, processes and systems that can be used for various purposes. The digital twin concept model contains three main parts: a) physical entities in real space, b) virtual entities in virtual space, and c) the connections via data and information that links the virtual and real space together. In the Industry 4.0 context, similar aspects may be referred to through adjacent concepts such as Cyber-Physical Systems (CPS). In the supply chain or smart factory domain, CPS can be implemented via the concept of a digital twin.

Based on SCOR (Supply Chain Operation Reference), Supply Chain (SC) is defined as the integrated processes of plan, source, making, delivery, return, and enabling from suppliers' supplier to customers' customer. With organizational perspective, SC covers both internal and external entities in yourself, supplier's and customer's side. Digital twin promises the best physical response via real-time digital awareness for our SC tasks. Through the realization of the Internet of Things (IoT), connectivity is becoming ubiquitous. Thus, almost anything in the SC can be tracked in real time – not just finished goods but also the raw material, tasks and supply chain process, etc.

A Supply Chain Digital Twin (SCDT) is a detailed simulation model of an actual supply chain which uses real-time data/snapshots to forecast supply chain dynamics. From this, analysts can understand a supply chain's behavior (understanding), predict abnormal situations (learning) and work out an action plan (reasoning) [1].

The major contributions and significance of this study are proposing a conceptual model composed of actors, physical entity, cyber entity, network, data and service for SC decision making. This model extends the previous 3D or 5D model to be adaptable to SC environments. This may contribute to the realization of digital replica for the physical processes in the SC problems.

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This paper sets out to explore the state of the art of digital twin modeling prevalent in the factory unit operations environment, to a wider supply chain context. Following a literature review, broad view of three-layer architecture is proposed. They are automation pyramid, computing pyramid, supply chain focus and supply chain digital twin focus. Conceptual model of digital twin for supply chain is proposed for future application potentials. The paper closes providing directions for future research.

2. **Previous Research.** Digital twin model and its implementation have been tried in various perspectives. Opportunities and challenges of supply chain digital twin are presented with cases in pharmaceutical, organic food and precision agriculture areas [2]. Possible attributes of a supply chain digital twin are defined and conceptually evaluated.

Among many papers about DT, a few important papers related with SC and DT have been adopted and reviewed below.

In the seminal paper of Grieves [3], 3D model is proposed. DT contains three main parts: a) physical products in real space, b) virtual products in virtual space, and c) the connections of data and information that ties the virtual and real products together.

A Life-Cycle Assessment (LCA) and Life-Cycle Cost (LCC) are adopted to quantitatively analyze the environmental and economic impact of the steelmaking system in Liu et al. [4]. Through analysis, it is found that the main categories of environmental impact are freshwater eutrophication, human toxicity, freshwater ecotoxicity, marine ecotoxicity, and natural land transformation.

An analytical description of a digital twin architecture reference model for the Cloud-based Cyber Physical Systems (C2PS) has been proposed in [5]. In the model, every physical thing accompanies a hosted cyber thing in the cloud. Two things can establish mutual connections either through direct physical communications or through indirect cloud-based digital twin connections.

The C2PS modeling is composed of physical system (P), cyber system (C), and hybrid system (H). Each model is described as the following. Physical system is composed of physical things.

Physical things $p \in P$ are composed of seven components.

$$p = (S_p, A_p, F_p, E_p, N_p, P_p, D_p) \tag{1}$$

where S_p: sensor, A_p: actuator, F_p: functional unit, E_p: events, N_p: interfaces, P_p: power supply, D_p: data storage.

Also, cyber system (C) and hybrid system (H) have a similar structure.

The key properties of C2PS are computation, communication, and control. The proposed C2PS architecture can be modeled based on Finite State Machine (FSM). The FSM is composed of input, transition function, functional states, output function, and event (output). The cyber world is connected with physical world through FSM and vice versa.

The traditional three-dimension DT defined by Grieves is extended to a five-dimension model, as shown in the following expression [6].

$$\mathrm{MDT} = (\mathrm{PE}, \mathrm{VE}, \mathrm{Ss}, \mathrm{DD}, \mathrm{CN}) \tag{2}$$

where PE refers to the physical entity, VE represents the virtual entity, Ss stands for the services for both PE and VE, DD is the involved data, and CN is the connection that ties different parts of the DT together. From the reviews about DT and LCA modeling, each model deals with the problem which is suitable for the model applications. Regarding supply chain process, an adequate model can be found which can be easily applicable. Thus, we try to build a conceptual model which is applicable to supply chain process in general.

Shevtshenko et al. [7] presented a multitier DT approach with four tiers of details to make a supply chain agile. The approach is validated by modelling of SC as multitier DT, which includes business processes, operations workflow, work cells activities and SC management dashboard tiers. The model has been validated of the DT approach for agile supply chain management in the fields of manufacturing.

Most of the existing works provide DT applications in the design or production stage, and several other researchers have investigated the DT application on the specific domains. Indeed, most works focus on the DT application on a single scope level, and only a few focused on conceptual modeling for SC processes.

3. **Digital Twin Modeling for Supply Chain Process.** Connected system is typically characterized by a hierarchical structure. It is composed of three layers, data acquisition layer, local control layer, and service layer with respect to automation pyramid. Three-layer DT concept, in the view of automation pyramid, computing pyramid, SC focus and SCDT perspectives, is presented in Figure 1.

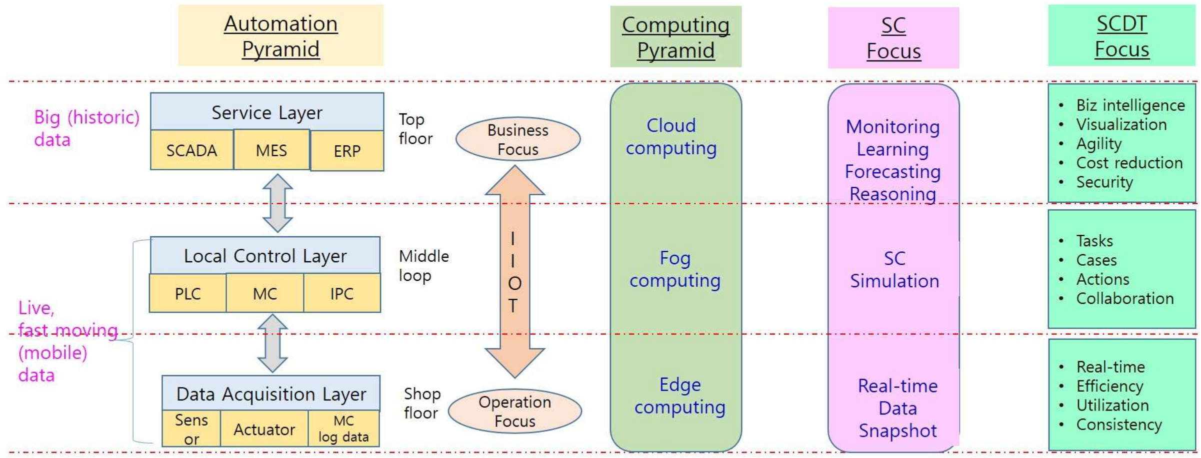


FIGURE 1. Three-layer DT concept for automation, computing, SC and SCDT perspectives

Sensor, actuator data and machine log data in the shop floor are inputs to local control layer. In the middle loop, Programmable Logic Controller (PLC), Micro-Controller (MC), and Industrial PC (IPC) are names of mediator [8]. In the service layer, there are Supervisory Control and Data Acquisition (SCADA) networks, Manufacturing Execution System (MES), and Enterprise Resource Planning (ERP) [9]. SCADA is a control system architecture that uses computers, networked data communications and graphical user interfaces for high-level process supervisory management.

With computing viewpoint, it is edge computing, fog computing and cloud computing. In the SC, it is real-time data snapshot, SC simulation and learning/reasoning intelligence. In the SCDT perspective, it is real-time data, efficiency, task and cases, and business intelligence and visualization.

Transferring those comprehensive data from the Operational Technology (OT) systems in the shop floor to the Information Technology (IT) systems at the top floor would require special methodologies and techniques for big data analytics. The above mentioned concept of automation, computing, SC and SCDT pyramid perspective is conceptualized as Figure 1.

Eight rules for DT modeling are suggested in Tao et al. [6] as the following. They are data and knowledge based, modularization, light weight, hierarchy, standardization, servitization, openness and scalability and robustness. The eight rules seem to be appropriate principles for DT modeling when we consider various aspects of DT.

3.1. **Digital twin architecture for smart system.** Key features of smart systems are connectivity, optimization, transparency, proactive and agility [10]. Smart systems require the underlying processes and materials to be connected to generate the data necessary to make real-time decisions. The optimized smart system can increase yield, uptime, quality, as well as reduce costs and waste. A transparent network can enable greater visibility across the facility and ensure that the organization can make more accurate decisions by real-time alerts and notifications, and real-time tracking and monitoring. The proactive features enable advance identifying and warning of anomalies, quality issues, safety and maintenance concerns. Self-adaptation to schedule and product changes is available by agile features.

The scheme of smart system control and monitoring system based on digital twin works as the following. All the features of smart system with sensors, network, and legacy system are mirrored in the tablet or PC which is integrated with big data analytics in the cloud or main server. All the actions and tasks in the production and manufacturing cell are monitored transparently in the tablet or PC with real time. Based on big data analytics, quality issues or facility problem is forecasted or prevented proactively. The results of big data analytics are fed back to the industrial field to monitor and control the process.

Figure 2 shows the digital twin architecture composed of physical and digital world. It is composed of six entities. They are supply chain actors, physical entity, cyber entity, network (connection), data and service. In the SC actors, six parties are defined as product, supplier, manufacturing, warehouse, distribution and customer.

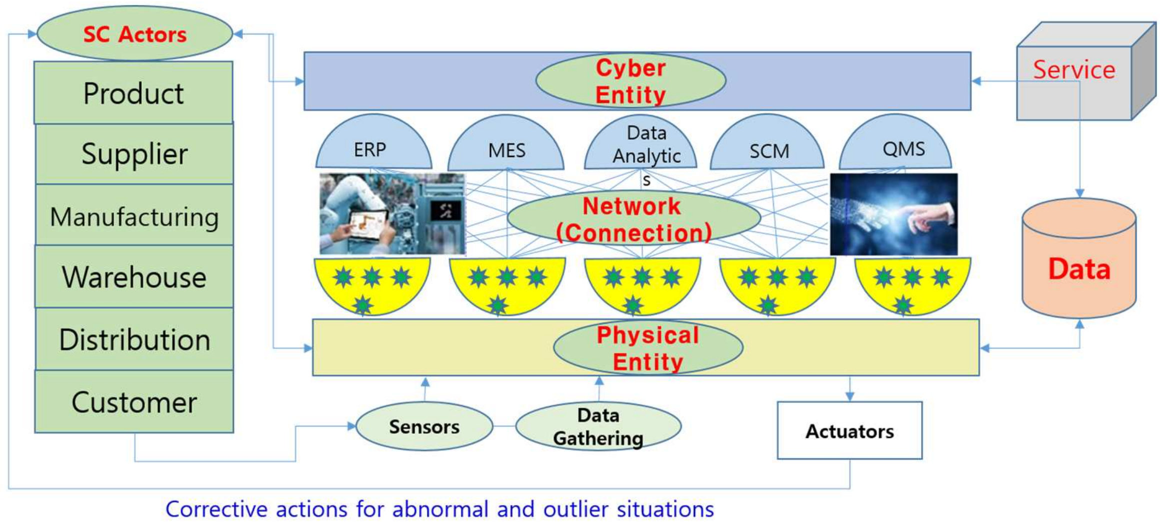


FIGURE 2. Conceptual model architecture of SCDT

In the physical world, various data are acquired via wireless and wired sensor network. It is a hardware-dependent process with embedded system, multi sensors and IIoT (Industrial Internet of Things). In the cyber world, ERP (Enterprise Resource Planning), MES (Manufacturing Execution System), SCM (Supply Chain Management), QMS (Quality Management System) and data analytics work to implement IoS (Internet of Service) [11]. These correspond to legacy system in the manufacturing industry.

3.2. **Supply chain digital twin modeling.** What makes an SC into a DT? The following section describes the relationship between SC and DT.

- A digital twin is a detailed simulation model of SC: A DT should be able to predict the behavior of SC.
- Real/time data snapshot: A DT uses real-time data to make forecast.
- Notifications/alarms/alerts about abnormal situations and outlier data: A DT should allow you to define what abnormal behavior is and send notifications about critical/ abnormal situations.
- Triggers and action plan: A DT should allow the definition of automatic actions for some events.

- Integration with IT infrastructure: A DT should be able to integrate with its surrounding IT environment, e.g., IT control tower.

Real-time visibility provided by DTs enables participants to implement new SC fulfillment models like door-to-door pick-up or micro-fulfillment. The DT also creates an umbrella across siloed data enabling critical information to be available throughout the SC.

Following the concept described above, the proposed SCDT architecture was transformed into conceptual model in order to catch physical properties, behaviors and rules of the physical entity and reproduce them in the cyber world. A conceptual scheme of SCDT can be modeled as (3)∼(9). The SCDT model has six tuples.

$$\mathrm{SCDT} = f(\mathrm{A}, \mathrm{P}, \mathrm{C}, \mathrm{N}, \mathrm{D}, \mathrm{S}) \tag{3}$$

where A is an actuator, P is a physical entity, C is a cyber entity, N is network (e.g., connection), D is data and S is service for decision making.

$$\text{Actuator, } \mathrm{A} = f(\mathrm{Pr}, \mathrm{Su}, \mathrm{Ma}, \mathrm{Wa}, \mathrm{Di}, \mathrm{Cu}) \tag{4}$$

where Pr is product, Su is supplier, Ma is manufacturer, Wa is warehouse, Di is distribution, and Cu is customers.

$$\text{Physical entity, } \mathrm{P} = f(\mathrm{Se}, \mathrm{Ac}, \mathrm{Co}) \tag{5}$$

where Se is sensors, Ac is actuator and Co is controller.

$$\text{Cyber entity, } \mathrm{C} = f(\mathrm{Ph}, \mathrm{Be}, \mathrm{Ru}) \tag{6}$$

where Ph is physical properties, Be is behavior of the entity and Ru is rules extracted from the historical data.

$$\text{Network (connection), } \mathrm{N} = f(\mathrm{Ds}, \mathrm{Dt}, \mathrm{Va}, \mathrm{Sa}) \tag{7}$$

where Ds is data source, Dt is data destination, Va is value and Sa is sampling interval.

$$\text{Data, } \mathrm{D} = f(\mathrm{Dp}, \mathrm{Dc}, \mathrm{Ds}, \mathrm{Dd}, \mathrm{Df}) \tag{8}$$

where Dp is the data from physical entity, Dc is the data from cyber entity, Ds is the data with service, Dd represents the domain data and Df represents the data fusion.

$$\text{Service, } \mathrm{S} = f(\mathrm{Fu}, \mathrm{In}, \mathrm{Ou}, \mathrm{Qu}, \mathrm{St}) \tag{9}$$

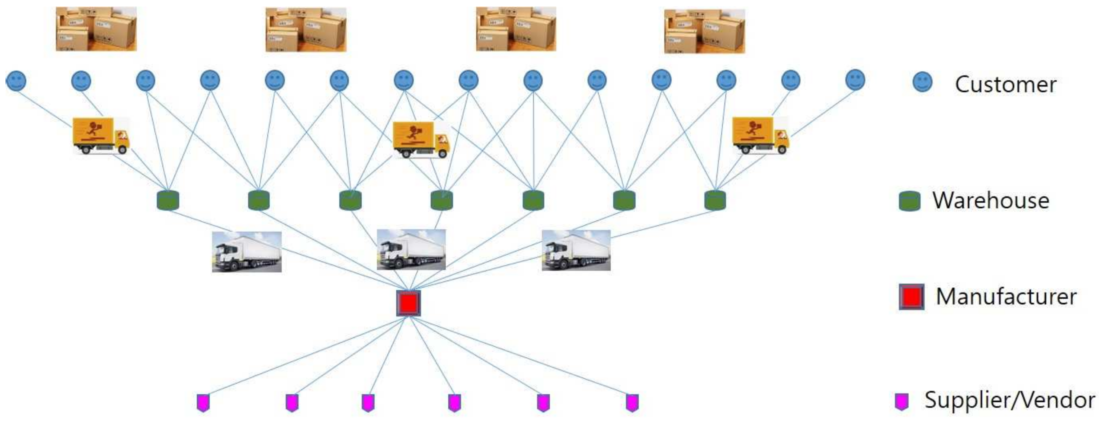
where Fu represents function, In is input, Ou is output, Qu is quality and St is state.

SCDT model enables us to create a digital realization of real-world things, places, business processes, and people. It gives us insights that help produce better products, optimize costs and operations, and create similar customer experiences.

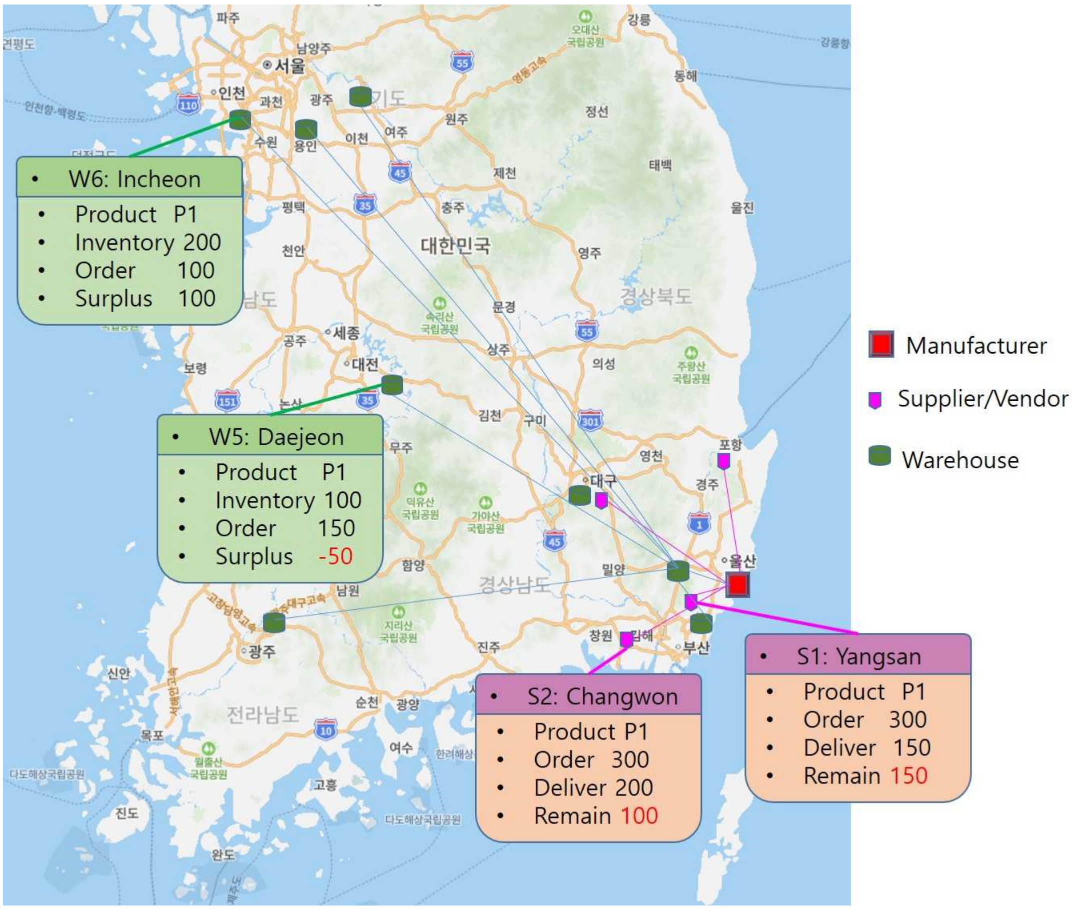
Based on the above conceptual model, a demonstration scenario is presented assuming producing a product according to a BOM (Bill of Material) and distribution system. The SC network architecture is assumed as Figure 3(a). The SCDT will operate as real-time simulation model in the physical map as shown in Figure 3(b).

4. **Conclusions.** A conceptual digital twin model for supply chain process is proposed. The model includes most stakeholders encompassing production plan, manufacturer, transportation, warehouse, retailer and data. The SCDT can model the state of production, warehouses, logistics and material flows, inventory positions, processes, people and assets for each stakeholder. Real-time sensor and equipment data, as well as ERP and other business system data, feed the model to create a live DT system. Central database gathers on-line data and performs big data analytics for business intelligence, visibility and optimization.

The proposed system can be implemented in the production and delivery process in the real world. The IoT and sensor network are essential for the realization of smart system and Industry 4.0.



(a) SC network architecture



(b) SCDT demo scenario in the physical map

FIGURE 3. Demonstration scenario for conceptual SCDT model

Further research is required in the modeling and implementation area. At present, the digital twin model is at its infancy stage. Through simulation and trial, the model needs to be upgraded for robust result. Also, for the SC process, the DT model can be implemented with real data access and visualization tool.

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