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A simulation approach for optimal design of RFID sensor tag-based cold chain systems

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ABSTRACT

This study introduced a systematic approach for assessing alternative operational models and to determine optimal values for some of the core design parameters in an RFID sensor tag-based cold chain system. First of all, we defined an RFID and sensor data collection and storage model. Next, we developed an RFID sensor tag-based cold chain simulation model and a simulator based on Discrete Event System Specification (DEVS) formalism. Finally, based on a case study, we demonstrated a procedure for determining the optimal sensing interval value with the proposed simulator. The results from the case study have shown that the proposed approach presents important advantages to analyze the Key Performance Indicator (KPI) of cold chain systems according to changes of RFID sensor tag-based cold chain system's operation models and parameter values.

1. Introduction

Most foods are perishable and temperature is the most critical factor affecting the safety and quality of perishable foods. Therefore, keeping foods at safe temperature throughout entire supply chain is one of the core functionalities of food supply chain systems, or cold chain systems (CCS). A CCS consists of processes, facilities, and information management, which collaboratively act to keep temperature-sensitive products at sufficiently low temperature while they are produced, stocked, transported, sold, and consumed. An effective CCS can minimize products' value losses (Wang et al., 2006), enable responsive decision making, and achieve operational efficiency in logistics. In addition, companies can take full competitive advantage via strategic marketing based on a well-implemented CCS, and effectively respond to legal matters such as product liability issues (Mitsugi et al., 2007, Montanari et al., 2008).

The application of a radio frequency identification (*RFID*) *sensor tag* or smart active label, which is a typical sensor-enabled semi-passive RFID tag, in CCSs has recently received a great deal of attention. RFID sensor tags are, in general, the integration of various sensors designed to collect environmental information, including temperature, pressure, humidity, inclination, and acceleration, into ordinary RFID tags, which are originally used only to identify products, with a film battery supplying power for internal information processing (Jung et al., 2007; Ruhanen et al., 2008). The use of RFID sensor tags in CCSs enables the monitoring not only of time and location information but also of environmental information about the food or product of interest (Cho et al., 2007; Ruhanen et al., 2008).

However, as the implementation of RFID sensor tag-based cold chain monitoring systems requires a large investment, it is very important to design a system that minimizes the initial investment and operational costs while fulfilling the functional and operational requirements of the CCS. Some of the CCS requirements include energy efficiency, timeliness, reliability, and correctness regarding sensing, identification, and data sharing (Zhang and Wang, 2006; Cho et al., 2007; Li et al., 2008; Abad et al., 2009). Unfortunately it is very hard to find a serious research on optimal design of RFID sensor tag-based cold chain's *operational models*, even though recently there have been a few studies focusing on information systems architectures, traceability performance evaluations, and economic analysis of proposed systems.

The purpose of our research is to provide a simulation approach for assessing alternative operational models and to determine optimal values for some of the core design parameters in an RFID sensor tag-based CCS (hereafter *Smart Cold Chain System* (SCCS)), which can maintain high traceability performance such as timeliness and reliability of product ID and sensor information. For this purpose, we developed an *SCCS simulator* for designers to model a CCS easily, and carried out a simulation study to evaluate the expected key performance metrics of the CCS. The developed SCCS simulator adopts Discrete Event System Specification (DEVS)

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formalism, which can well describe the logistics processes, because SCCSs are easily modeled as a discrete event-driven system.

The rest of this paper is organized as follows. Section 2 reviews the benefits of RFID-sensor integration and some of the earlier research in this area, and then presents a brief introduction to DEVS formalism. Section 3 explains a set of alternative operational models, namely possible options for collecting, transferring, and storing ID and sensor data in an SCCS. Section 4 describes how to model the components of an SCCS based on DEVS formalism, and how we have implemented the SCCS simulator. Section 5 validates and discusses the use of the suggested approach and software using the results of a case study. Finally, Section 6 presents the conclusions and directions for future research.

2. Related work

2.1. Integration of RFID and sensor technologies

The benefits of integrating two complementary technologies – RFID and sensor – are substantial, as pointed out by many researchers. First of all, from the information acquisition perspective, the richer information available from the addition of 'environment traceability' to 'object traceability' facilitates better decision support and responsive localized management, thereby achieving higher safety level in cold chain management, for example. Secondly, from the view point of technical performance improvement, if the RFID technology is embedded in a wireless sensor network (WSN), RFID tags and readers can build more intelligent networks by sharing the sensing, logic, and transmission capabilities of the sensor networks. For example, longer-distance transmission can be achieved with lower power consumption and less interference by utilizing multi-hop transmission and clustered reading capabilities provided by sensor network technologies. Therefore, the number of expensive RFID readers can be minimized and the system implementation cost reduced (Cho et al., 2007; Li et al., 2008; Liu et al., 2008; Mitsugi et al., 2007).

The two technologies can be integrated in two different ways: sensor-enabled RFID tags (or RFID sensor tags) and RFID-embedded WSN. The latter offers the second and third benefits explained above. However, if the WSN capabilities are not essential requirements as in cold chain management, individual sensor nodes are simply too expensive with excessive capabilities, meaning that RFID sensor tags are more economic approach in such a case.

2.2. Applications of RFID and sensor for cold chain management

An integrated system of RFID and sensor technologies can be applied to various areas such as health care, supply chain management, military operations, wild habitant monitoring, and cold chain management. For the latter, Fu et al. (2008) proposed a cold chain monitoring system using both RFID and WSN. They implemented a cold chain traceability system using Nano-Qplus WSNs and LabVIEW. They emphasized the importance of historical traceability data as well as real-time monitoring data for facilitating the decision making process. Yan and Lee (2009) monitored the flow and requirements of all phases in cold-chain logistics. In addition, they designed a monitoring and tracking solution consisting of RFID tags, temperature sensors, program modules and especially GPS systems for cold-chain logistics. Abad et al. (2009) dealt with the problems in monitoring packaged foods using conventional technologies. They developed a real-time cold-chain monitoring systems based on a flexible tag, which was developed by integrating temperature and humidity sensors with RFID communication capability. Through a series of lab and field tests, the developed flexible tags were validated in terms of accuracy and temperature resistance. Similarly, Carullo et al. (2009) pointed out the difficulties of item-level temperature monitoring in cold-chain logistics due to the packing of the items in small containers and the high expense of item-level tagging. Therefore, they proposed a monitoring system architecture for temperature-sensitive products contained in a refrigerated vehicle using WSN.

Unlike most studies that focused on monitoring for cold chain management, Wang et al. (2010) suggested a system model to predict the status of food at its destination and to provide appropriate actions in any abnormal situation based on historical data and real-time monitoring data. They developed an online decision support system based on RFID systems, a sensor network and a decision rule base. Their research results demonstrated that the historical and real-time cold-chain traceability data can effectively support the decision making processes.

2.3. DEVS formalism

We developed an SCCS simulator based on DEVS (Zeigler et al., 2000) – a formalism for modeling and analysis of discrete event systems. DEVS formalism is appropriate to model and simulate SCCSs for the following reasons. In the discrete event modeling and simulation, the inner workings of operational processes are modeled and simulated based on the occurrence of events that move the process forward (North and Macal, 2007). An SCCS has an operational logistics process and their states are changed by performing logistical activities such as receiving, packaging and shipping. Since logistical activities can be regarded as events, SCCSs belong to discrete event systems. Besides the logistics processes, DEVS formalism has been also applied to various areas including computer/network systems and process control in a factory (Farooq et al., 2006; Pujo et al., 2006; Zacharewicz et al., 2011).

DEVS formalism describes discrete events in a hierarchical and modular form. DEVS formalism represents each component of a system as an *atomic model*, and describes the relationships and hierarchical structure among them using a *coupled model*. An atomic model can be defined as follows. Fig. 1 explains the state-transition mechanism in an atomic DEVS model.

$$M = \langle X, Y, S, ta, \delta_{\text{ext}}, \delta_{\text{int}}, \lambda \rangle,$$

where X is the set of input events; Y is the set of output events; S is the set of sequential states (also called the set of partial states); $ta : S \rightarrow R^{+}_{0,\infty}$ is the time advance function that is used to determine the lifespan of a state; $\delta_{\text{ext}} : Q \times X \rightarrow S$ is the external transition function that defines how an input event changes a state of the system, where $Q = \{(s,e)|s \epsilon S, 0 \leqslant e \leqslant ta(s)\}$ is the set of total states, and e is the elapsed time since the last event' $\delta_{\text{int}} : S \rightarrow S$ is the internal transition function that defines how a state of the system changes internally (when the elapsed time reaches to the lifetime of the state); $\lambda : bS \rightarrow Y$ is the output function.

A coupled model constitutes a large system by linking multiple atomic models, and also allows the system to be a part of a bigger system. Therefore, DEVS formalism can well support hierarchical system modeling and the behavioral dynamics of discrete event systems. A coupled model can be defined as follows.

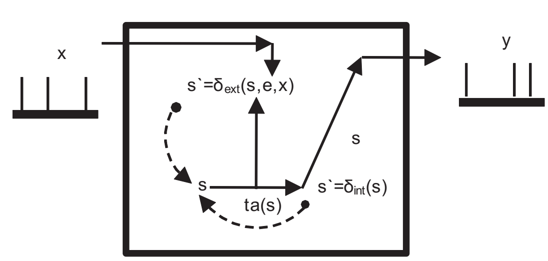

Fig. 1. DEVS in action.

$N = \langle X, Y, D, \{M_i\}, C_{xx}, C_{yx}, C_{yy}, \text{Select} \rangle,$

where X is the set of input events; Y is the set of output events; D is the name set of sub-components; $\{M_i\}$ is the set of sub-components where for each $i \epsilon D, M_i$; $C_{xx} \subseteq X \times \bigcup_{i \epsilon D} X_i$ is the set of internal couplings; $C_{yx} \subseteq \bigcup_{i \epsilon D} Y_i \times \bigcup_{i \epsilon D} X_i$ is the set of internal couplings; $C_{yy} : \bigcup_{i \epsilon D} Y_i \rightarrow Y^{\phi}$ is the external output coupling function; Select $: 2^D \rightarrow D$ is the tie-breaking function which defines how to select the event from the set of simultaneous events.

3. Data collection and storage model in SCCS

This section describes the SCCS data collection and storage model to acquire sensor data and transmit them to information systems by using RFID tags, RFID readers and wired/wireless communication devices. As shown in Fig. 2, a sensor measures very small changes in an environment and then stores the measured data to a user memory space of an RFID sensor tag. Reader and Middleware reads the ID such as Electronic Product Code (EPC) (Traub et al., 2005) and the sensor data stored in an RFID sensor tag, and sends them to the information systems. In this paper, we assume that an RFID reader and a middleware (Reader and Middleware) constitute one combined component to collect RFID/sensor data from an RFID sensor tag and to send RFID/sensor data to information systems. We also assume that if wireless communication devices such as Code Division Multiple Access (CDMA) are installed in trucks, RFID/sensor data can be submitted to information systems during the transportation phase.

3.1. RFID sensor tag

(1) Sensing types

Most commercial RFID sensor tags fall into two sensing-type categories.

- *Interval sensing:* the sensors of this kind wake up periodically and sense the environment. This sensing mode can be used for long-distance transportation and/or long-term storage in general.
- *Immediate sensing:* the sensors of this kind are waken up and sense the environment temporarily according to a user's request. This sensing mode can be used to sense the environment at essential and/or obligatory logistic points in order not to miss those points using interval sensing.

Fig. 3 shows the differences between these two approaches. We expressed that the RFID sensor tags sense environments when they passes main logistics points such as receiving and shipping.

(2) Storing conditions

For the CCSs that cannot transmit sensor data to a server in real time, it would be unavoidable to lose the data due to the limited memory size. Hence, it is essential to judiciously filter out unnecessary sensor data in order to save the tag memory storage. The conditions for storing sensor data in a tag memory can be divided into three approaches.

- *None:* this storing condition means that all the sensor data are to be stored in a tag memory without any filtering.
- *Range:* this storing condition means that only the out-of-range sensor data values are to be stored as shown in Fig. 4(a).
- *Gap-out:* this storing condition means that only the sensor data value which deviates from the previous one greater than a given criterion are to be stored as shown in Fig. 4(b).

(3) Overflow handling modes

When a sensor stores some sensor data in a user memory when the user memory is full, memory overflow occurs. Some intelligent sensors can handle memory overflow in various ways as follows.

- *None:* this mode allows memory overflow, meaning the overflown sensor data are simply discarded. This mode can be applied to the CCS which uses tags with a sufficiently large memory and/or with periodical memory backup functionality.
- *Last update:* this mode replaces the last data in a tag memory with the new one when the memory is full. This mode can be used when the recent data is important and/or when tags have tiny memory and sensor data can be easily transmitted to information systems in a real-time manner.
- *Queue:* this mode deletes the oldest data in a tag memory and store the new one in the memory. This mode can be used to

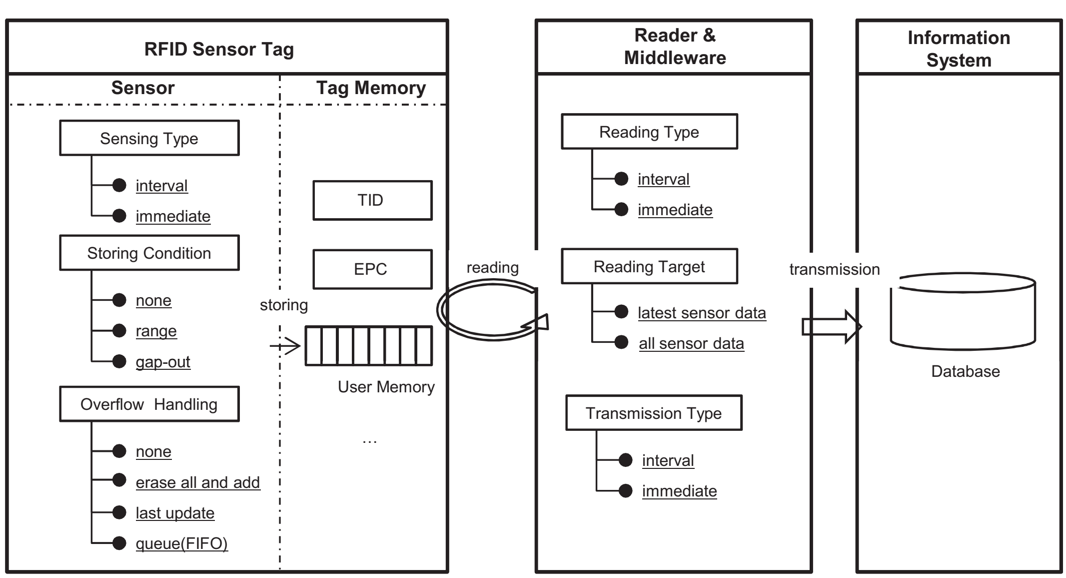

Fig. 2. SCCM data collection and storage model.

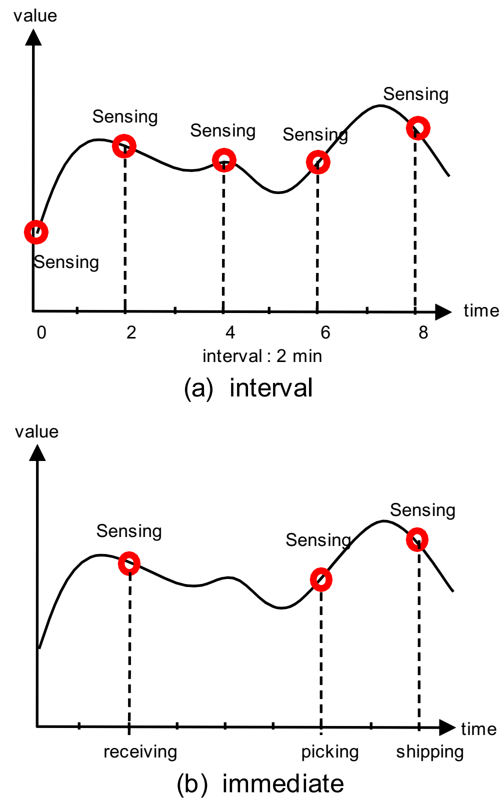

Fig. 3. Sensing types.

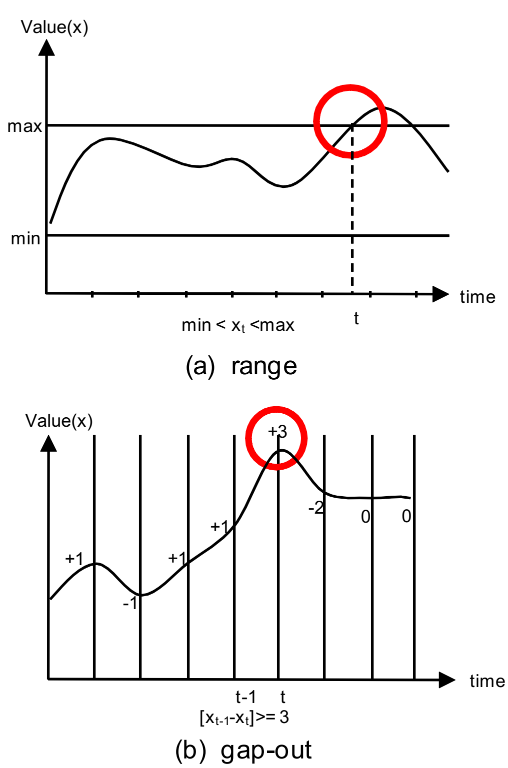

Fig. 4. Storing conditions.

keep a fixed amount of latest data, thereby minimizing data lose when the data transmission to information systems are not very stable.

- *Erase all and add:* this mode deletes all the data in a tag memory and puts the new one into the memory.

Fig. 5 demonstrates these overflow handling modes.

3.2. Reader and Middleware

(1) Reading type

A Reader and Middleware's data collecting methods from an RFID sensor tag are composed of interval mode and immediate mode. The former measures an environment periodically while the latter detects temporarily according to a user's request at a main logistics point such as shipping/receiving.

(2) Reading target

Basically, a Reader and Middleware identifies the ID of an RFID tag. In addition, a Reader and Middleware reads some sensor data stored in the user memory of an RFID Sensor tag. At that time, a Reader and Middleware optionally can read (1) only the latest sensor data or (2) all sensor data in a tag user memory. The first approach can be applied to high-tech cold-chain systems that can send sensor data to information systems anywhere and in real-time. The second approach can be used in the situation using trucks without any wireless communication device. After transportation, a Reader and Middleware reads all sensor data at once that is stored during transportation. In addition, despite high-tech CCSs, the second approach is useful to compensate for data transmission failure if wireless communication device's faults occur during transportation (i.e., data logging).

(3) Transmission type

The transmission types of a Reader and Middleware are divided into the following two methods: (1) interval mode and (2) immediate mode. Furthermore, they can be mixed together. For instance, a Reader and Middleware transmits the sensor data to an information system in interval mode if the sensed value is allowable temperature. However, if the sensed value is not permissible, the Reader and Middleware sends the data to an information system immediately and decreased the interval time elastically.

4. Implementation of the SCCS simulator

In order to implement a SCCS simulator, we defined the models for each of the SCCS components explained in Section 3, such as RFID-sensor tags, readers, middleware, and information systems, along with other essential components such as trucks and warehouses.

4.1. DEVS modeling for SCCS core components

In SCCS, an RFID sensor tag acts as an object of transportation and storage moves along a supply-chain and sends measured information like timestamps and temperature to the external information system through an RFID reader or middleware according the predetermined manner. In terms of an RFID sensor tag, measuring temperature at each stage of the SCCS and interacting with the trespassing Reader and Middleware are the main concerns. In this perspective (SCCS is composed of a sensor tag and its interacting devices and facilities), basic components that are sufficient to model any SCCS should be abstracted as DEVS atomic models. Just five DEVS atomic models seem sufficient for the SCCS modeling and Simulation for the proposed simulator. Table 1 describes the five atomic DEVS models for SCCS.

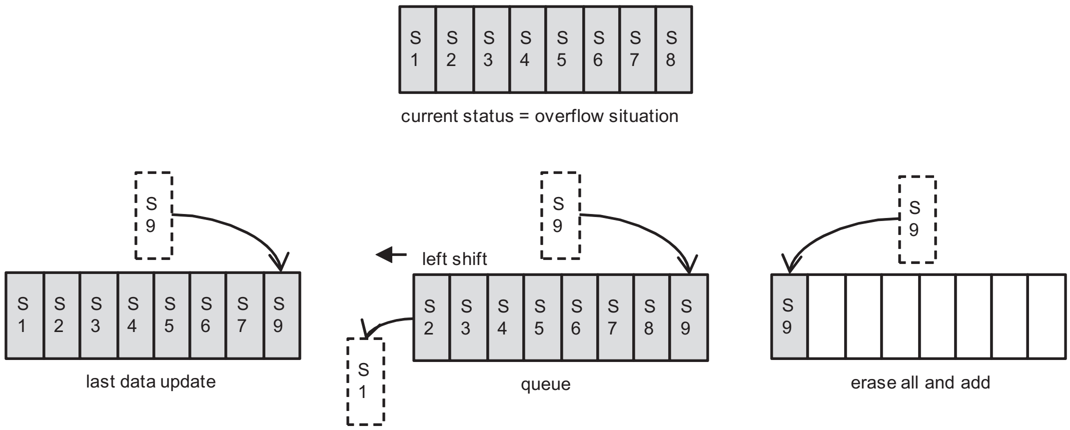

Fig. 5. Overflow handling modes.

Describing the dynamic features of Sensor_Tag_Node, which is the most critical one among the five atomic models in terms of researchers' concerns and the complexity of connecting to other atomic models, basically it holds the environmental data delivered from Carrier_node and sends them (temperature and timestamp) to the connected active Reader_Node. This atomic model has two input ports (in, t_in) and one output port (t_out). Through the "in" input port, start and end orders (signal) from Start_End_Node and information requesting signal from Reader_Node are delivered and processed. The "t_in" input port is mainly used to receive the time–temperature paired data from Carrier_Node. Through the "t_out" output port, the data held inside Sensor_Tag_Node are sent to Reader _Node.

Sensor_Tag_Node can have various states, and may have various internal and external transitions. Under the condition of interval temperature sensing, Fig. 6 depicts Sensor_Tag_Node's state transitions by various events which are delivered from outer atomic models or are autonomously generated inside. From the programming perspective, each atomic model in the SCCS simulation is developed by inheriting (extending) the Atomic Java class provided in DEVSJAVA™(ACIMS, 2009).

Table 1
Five SCCS atomic models.

Atomic model	Descriptions
Sensor_Tag_Node	An atomic model corresponding to the RFID Sensor Tag. Environmental information like temperature that is delivered from any Carrier_Node is stored and maintained inside. In addition, the information stored is passed to Reader_Node by request
Carrier_Node	An atomic model for any storage or transportation facility where the sensor tag is stationed temporarily. Once the temperature changes, it passes the changed temperature data to Sensor_Tag_Node
Reader_Node	An atomic model corresponding to RFID Readers and Middleware. This model requests and receives data such as temperature and temperature recorded time (timestamp) from Sensor_Tag_Node. It also delivers the received data to Database_Node
Database_Node	An atomic model for the external information system or data storage for temperature–timestamp information transferred from Reader_Node
Start_End_Node	An atomic model to start and end a simulation run. This model generates a signal for simulation start and activates the connected atomic models such as Sensor_Tag_Node, Carrier_Node and Reader _Node. When it is used as the last component in the SCCM simulation model, it sends a "deactivating" signal to Database_Node, and Sensor_Tag_Node

In a general simulation for logistics and production systems, a sensor tag may be treated as a traveling entity walking through the relevant facilities. In the general case, the main purpose of simulation modeling is determining the status and time concerning changes of the facilities (so called resources) and not the traveling entities. However, in the SCCS simulation, sensor tag should be deliberately checked and studied as time passes more than the resources and facilities used in constructing SCCS. Therefore, the simulation model is constructed so that the sensor tag is surrounded by other facilities or operations and each surrounding facility is alternately activated and interacts with the sensor tag.

It is simple to construct any simulation model in the SCCS study with the proposed method. According to the sequence of the surrounding facilities, corresponding atomic models can be arranged and connected to each other. After that, Sensor_Tag_Node only needs to be connected to each surrounding atomic model in order to start the simulation. In this way, the simulation model is we constructed and executed relatively easily.

4.2. Implementation

The suggested simulator is composed of an SCCS modeler, model translator, simulation engine of DEVSJAVA and model repository. Fig. 7 shows the hierarchical structure of the proposed simulator.

- *SCCS modeler:* a graphical modeler for the SCCS components and their connections. The SCCS components, which are provided in the window pane as an iconic node, can be dragged onto the working area and connected to next one. By double-clicking the node, attribute values can be assigned in the conventional manner of the general window's applications. It is difficult and error-prone to write Java language source codes for constructing atomic DEVS models and to set internal attribute values. This modeler helps construct and modify SCCS models easily.
- *Model translator: cold* chain components and their connection created with GMF are translated into java program codes of SCCS DEVSJAVA atomic or coupled models.
- *Repository:* this is the repository for the SCCS simulation models and the simulation results.
- *Simulation engine:* run the SCCS simulation model in Java language with the DEVSJAVA library and is responsible for performing the simulation test.

The SCCS simulator proposed in this research has been developed with Eclipse Rich Client Platform (RCP) based on the Java programming language, and Eclipse Graphical Modeling Framework

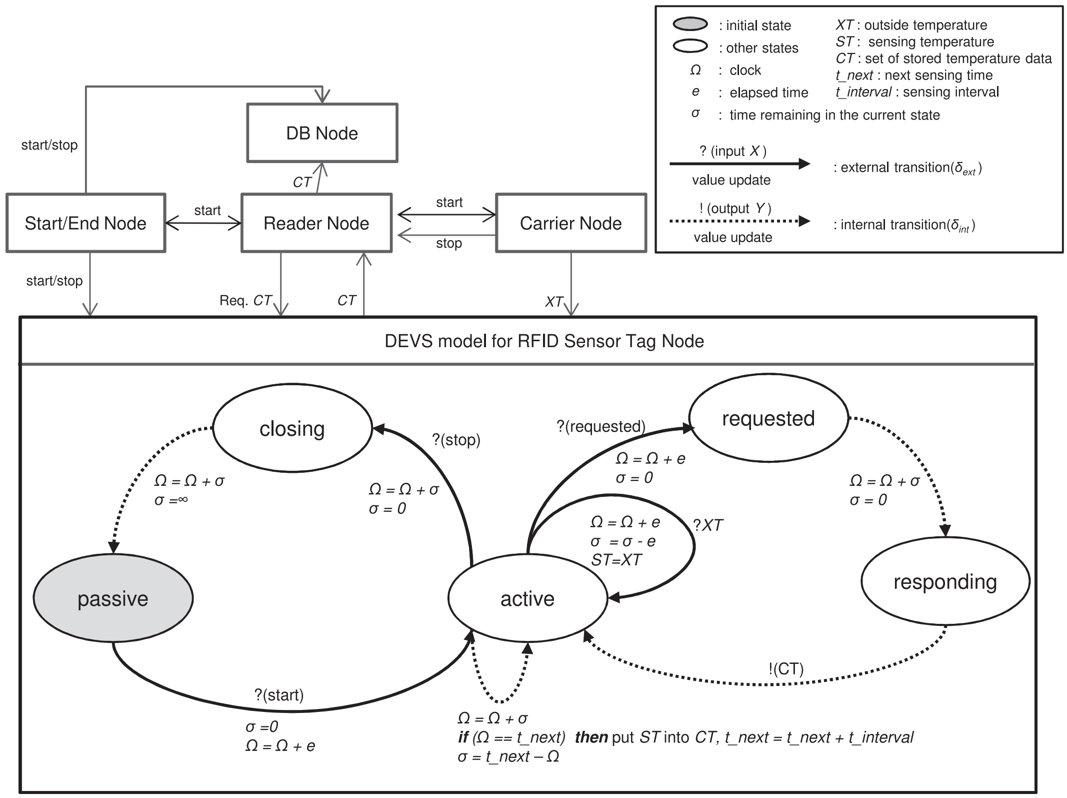

Fig. 6. Abstract SCCS DEVS model.

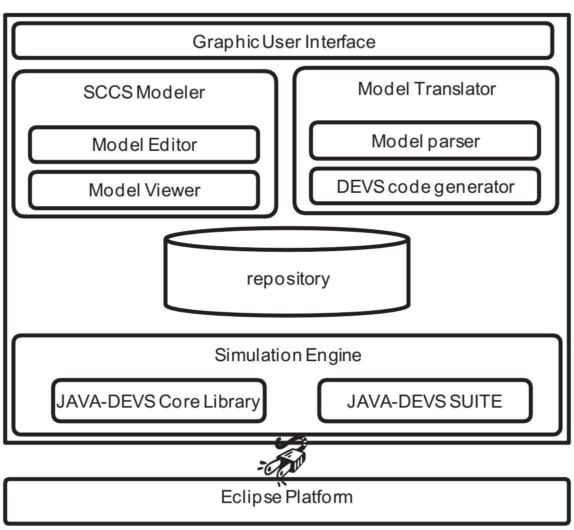

Fig. 7. Architecture of the SCCS simulator.

(GMF) plug-ins are mainly used for graphical modeling of the cold chain components and their connections. A screenshot of the SCCS Modeler is shown in Fig. 8. SCCS network models can be created in the large middle window and attribute values for each node can be set in the Node attribute setting window.

5. Case study

RFID sensor tags in a cold chain act as a traveling entities in various sections, including production lines, transportation, and distribution centers. The functional requirements of RFID sensor tags are different from each other depending on the types of section. However, once programmed, it is not easy to change the setting parameters of the RFID sensor tags in the middle of a travel. Accordingly, it is very important to determine the optimal setting values by taking into account the overall cold chain environment. In this section, we evaluate the proposed SCCS simulator by applying it to a real SCCM implementation project carried out by C logistic company in Korea. The purpose of the simulation in this case study is to evaluate the current setting parameters from the viewpoint of reliability and timeliness of SCCS information, and to determine the optimal *sensing interval*, in which RFID sensor tags sense the temperature, based on repetitive simulations.

5.1. Scenario

The target SCCM system was a temperature monitoring system for frozen foods such as sausages passing through three distribution sites, as shown in Fig. 9. RFID sensor tags were attached to pallets, while ordinary passive RFID tags were attached to individual food boxes. Then the IDs of both tags were aggregated and stored in the SCCM information repository. Accordingly, the boxes on a specific pallet could share the temperature information sensed by the RFID sensor tag attached to the pallet in the information system. In the stocking and transportation sections, pallet ID and temperature data were collected periodically, while in the other sections the data were read only when the RFID sensor tags passed by RFID readers. The transportation trucks were equipped with CDMA-based mobile transmission devices, and periodically sent pallet ID and temperature data to the information system.

5.2. Simulation model and experimental design

The details of the company C's current operational model can be specified using a state-transition diagram as shown in Fig. 10. Because, in a discrete event system, states are changed according to

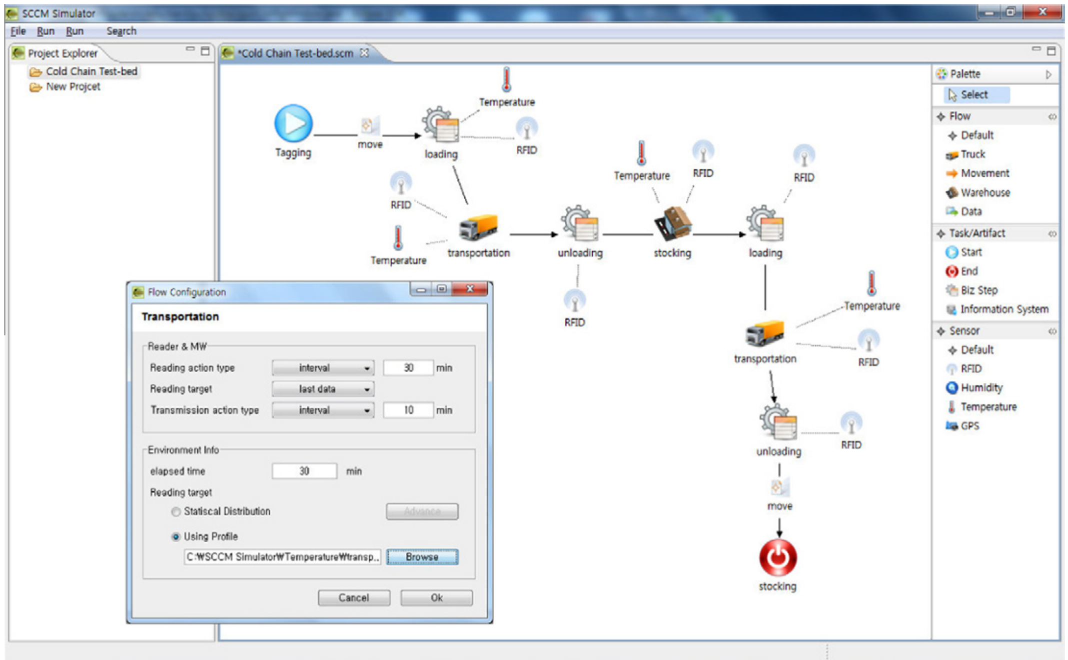

Fig. 8. Execution environment of the SCCS simulator.

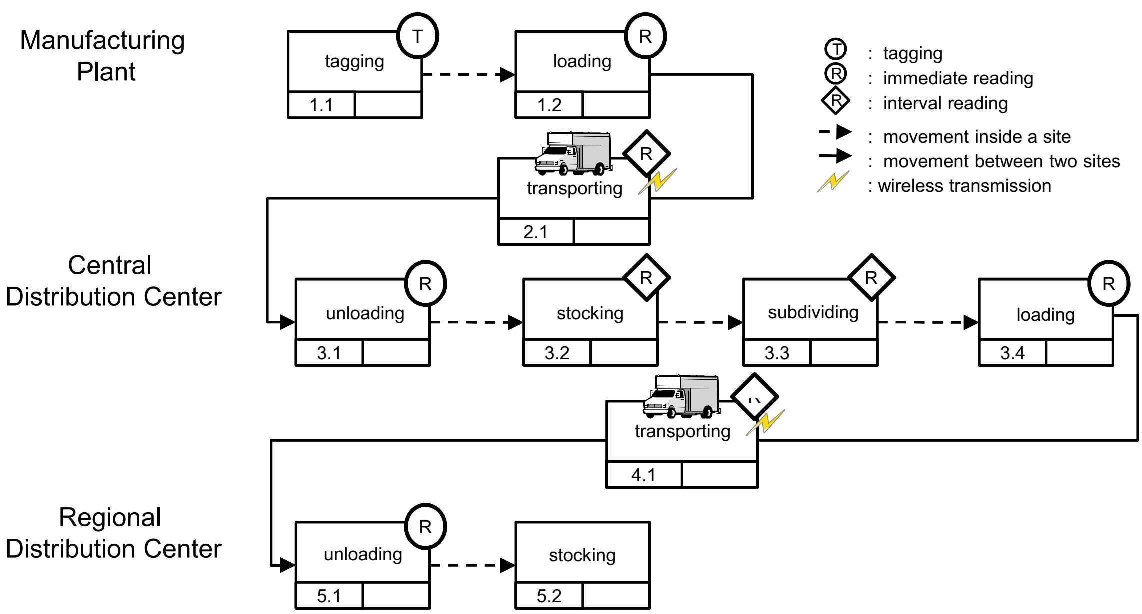

Fig. 9. Detailed process of a cold-chain system scenario.

events, the state-transition diagram can effectively describe the SCCS data collection and storage model on the top of logistic processes. In this diagram, as a state-transition diagram, the transitions (denoted by bars) represent RFID-read events, while the states (denoted by circles) represent the current locations (such as warehouse, truck, and forklift) of the RFID sensor tags. The cold chain model itself and the detailed operational parameters, including sensing interval and duration times, were all drawn based on a series of field interviews and measured data from the field.

The settings on the RFID sensor tags were not changed throughout the whole cold chain. In addition, in the stocking and transportation sections, the ID and temperature data were collected via a hybrid transmission method, which combines periodical (10-min interval) transmission and additional immediate transmission when an out-of-bound (or abnormal) temperature is detected. The user-memory capacity of the RFID sensor tag was 16 Kbyte, and two bytes were used for storing a single sensor datum. Accordingly, one RFID sensor tag could hold 64 temperature data.

5.2.1. Key performance indicator of cold-chain system

In a CCS, a crucial functionality is to identify the time when the foods are exposed to an out-of-bound temperature, and to quickly respond to the undesirable situation. In this research, we assessed the reliability of the SCCM system using three key performance indices: *Abnormal Section Detectability* (ASD), *Abnormal Period*

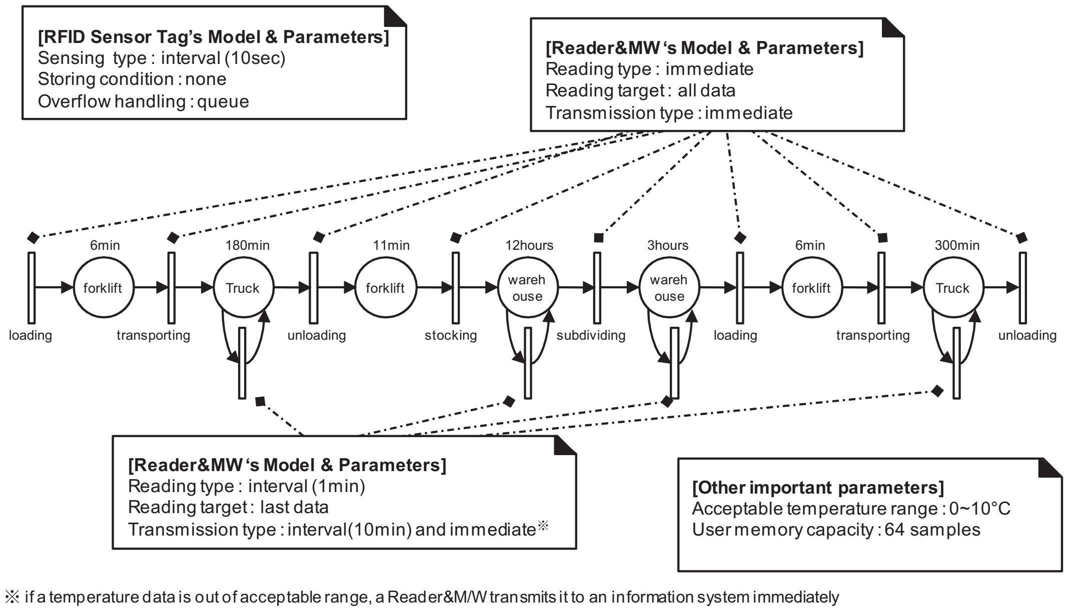

Fig. 10. SCCS data collection and storage model and its parameters for the case study.

Estimation (*APE*), and *timeliness*. ASD is the capability of the system to detect abnormal-temperature events, and APE is the estimation accuracy of the duration time that the foods were exposed to an abnormal temperature. Timeliness represents the time lag between the abnormal temperature sensing-event occurrence and the ultimate arrival at the database server. ASD, APE, and timeliness are defined by following expressions.

$$\text{ASD} = \frac{(c(R_t, D_t))}{nR_t} \times 100,$$

where R_t is the set of actual temperature sensing data; D_t, the set of temperature data which is ultimately saved in SCCM system; $n(X)$, the number of abnormal-temperature data in a sensing data set X; $c(X, Y)$, the number of detected out-of-bound sections in set Y with set X.

$$\text{APE} = 1 - \frac{|AT_{\text{actual}} - AT_{\text{stored}}|}{AT_{\text{actual}}},$$

where AT_{actual} is the actual duration time while residing at out-of-bound temperatures; AT_{stored}, the estimated out-of-bound duration time based on the temperature data stored in the information system.

$$\text{timeliness} = \frac{\sum_{i=1}^{n}(Td_i - Ts_i)}{n},$$

where Ts_i is the time at which the i-th out-of-bound temperature was sensed; Td_i, the time at which the i-th out-of-bound temperature data was saved in the information system

5.2.2. Experimental temperature profiles

For the simulation purpose, we needed temperature profiles, which are basically a serious of temperature data changing over time throughout the whole cold chain. As a result of interviews with subject matter experts, we concluded that the average temperature values were 7.5 and 8.5 °C in the warehouses and transportation trucks, respectively. We also recognized that there are various situations where foods are exposed to out-of-bound temperatures in a cold chain, such as during the loading/unloading operations, when the environmental temperature is too high, when the refrigerators are out of order, and in the presence of a localized heat source in a truck. Truck drivers even sometimes intentionally turn off the refrigerator or set the temperature higher than expected in the middle of transportation in order to save gas.

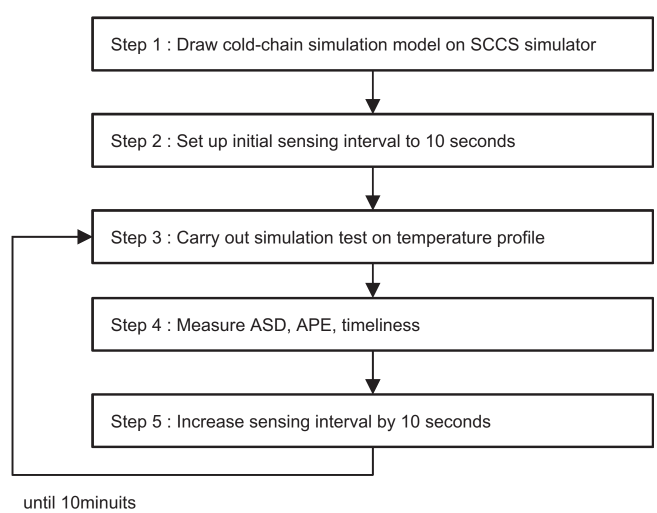

Fig. 11. Simulation procedure.

Table 2
Inter-arrival time and duration time of abnormal sections.

	Loading	Transporting	Unloading	Stocking	Subdividing	Loading	Transporting
Working time (*WT*)	6	30	11	720	180	6	50
Inter-arrival time (*AT*)	~Exp(3)	~Exp(30)	~Exp(3)	~Exp(60)	~Exp(60)	~Exp(3)	~Exp(30)
Duration time (*DT*)	*WT*–*DT* (if *WT*<*DT* then 0)	~Exp(30)	*WT*–*DT* (if *WT*<*DT* then 0)	~Exp(60)	~Exp(60)	*WT*–*DT* (if *WT*<*DT* then 0)	~Exp(30)

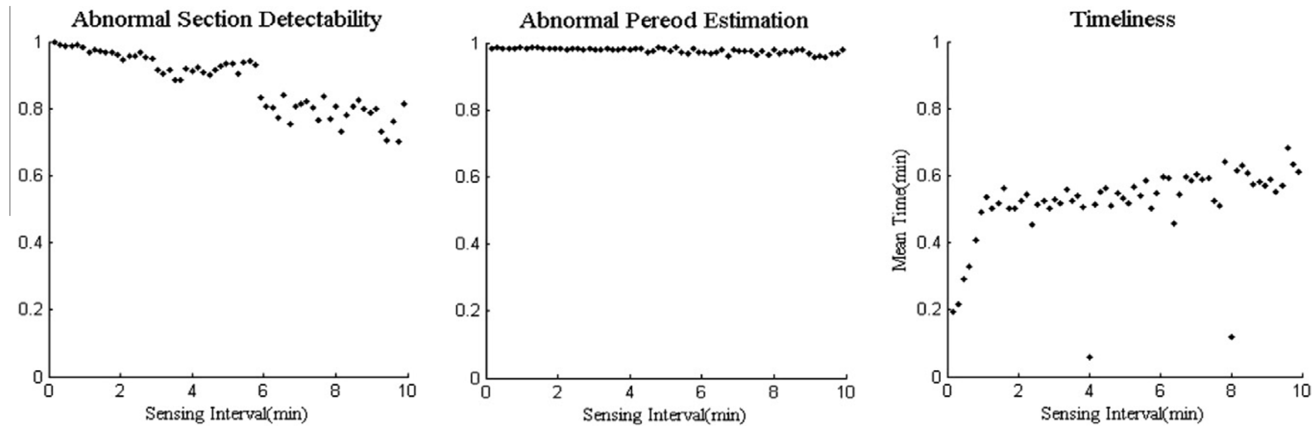

Fig. 12. Simulation results – ASD, APE, and timeliness with respect to sensing interval.

Table 2 summarizes the statistical distribution functions with parameters for generating temperature profiles that include abnormal temperatures. Unlike other distribution sections, during the loading and unloading steps, once an out-of-bound temperature occurs it lasts until the end of the step, because there is no refrigeration facility during these steps.

5.2.3. Simulation test

Fig. 11 describes the simulation procedure based on the simulation model explained above. Twenty temperature profiles were generated per individual sensing interval (Step 3), and the average ASD, APE, and timeliness data were recorded (Step 4). The initial sensing interval was set to 10 s (Step 2), which is the current setting in company C's current operation. The value was increased from ten seconds up to 10 min because the Korean government regulates that companies must be able to provide the temperature history for their foods with a maximum interval of 10 min.

5.3. Simulation results

Fig. 12 shows the simulation results. The ASD values decreased almost linearly with increasing sensing interval. This decreasing tendency was an obvious result because the longer sensing interval hindered the SCCM system's ability to detect out-of-bound period with the relatively shorter duration time. The APE values also decreased with increasing sensing interval, but not to the extent that ASD had decreased because the shorter out-of-bound sections were not detected, which meant that the influence on APE values could be ignored. The timeliness values increased slightly, but only to a maximum of a minute, indicating that the increased sensing interval did not affect the timeliness significantly.

In conclusion, with the current SCCM operational setup, it is desirable to set the sensing interval to approximately 5 min in order to achieve 90% ASD. This indicates that the current sensing interval of ten seconds is too short and reduces the battery life due to unnecessarily frequent sensing activities. The simulation results demonstrate that the sensing interval and hence the battery life of the RFID sensor tags can easily be increased without significantly decreasing the system's reliability.

If the simulation results are different from Fig. 12, we may be able to draw different explanations. For example, if the ASD values do not decrease with increasing sensing interval, a decision maker is able to choose the maximum sensing interval for saving the battery life. If the ASD values dramatically decrease in a short sensing interval, the simulation result gives enlightenment that the decision maker should set up short sensing interval and care about milestones replacing the battery.

6. Conclusion

The functional requirements of an RFID sensor tag-based cold chain system (CCS) differ in each section of a target cold chain process. Accordingly, a methodology must be optimized for the operation model and parameter values in order to maximize the performance in all sections of the cold chain and to operate the CCS for a long time.

With these considerations, we first defined an RFID and sensor data collection and storage model by considering the current and impending technology, which we termed the Smart CCS (SCCS) data storage and collection model. The defined model may be used as a reference model when an RFID sensor tag-based cold system is implemented. Next, we developed an SCCS simulation model based on DEVS formalism and implemented an SCCS simulator with an open source JAVA-DEVS library. The proposed SCCS simulation model and simulator may be regarded as a guideline basic model for further development in this research field. With the SCCS simulator, a CCS can easily be drawn by a user in a graphic user interface environment. Furthermore, through repetitive simulation testing, the user can compare and analyze the Key Performance Indicator (KPI) of CCS according to changes of the SCCS's parameter values. The SCCS simulator can be used as a decision making tool for the optimal design and set up of an RFID sensor tag-based CCS. Finally, based on a case study of the CCS of a South Korean logistics company, we demonstrated and discussed a procedure for determining the optimal sensing interval with the proposed SCCS simulator.

Although in the case study we tried to find only the optimal sensing interval, the developed simulator also can be used to optimize various operational models of SCCSs in an exploratory manner. Therefore, in future research, we plan to measure the KPI changes of an SCCS with variations of other adjustable parameters such as the size of the RFID sensor tag's user memory, and the reading and transmission intervals of the reader and middleware. It will thus be possible to analyze the correlation among the parameters and results. In addition, other KPIs of CCSs need to be comprehensively defined in order to determine the field's requirements with the goal of preserving food quality.

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