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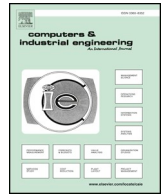
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New modeling formalism for the energy simulation of conveyor systems

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ABSTRACT

Presented in this paper is a modeling formalism for the energy simulation of conveyor systems. Reducing the energy consumption of a conveyor system can decrease a significant portion of the operation cost, contribute to the sustainable operation, and prepare for future energy cost increases related to regulations for green industry. Therefore, the energy consumption is becoming one of the key performance indicators in conveyor systems design. To construct a simulation model considering the energy consumption of conveyor systems, the modeling formalism is necessary to represent the multiple material transportations and conveyor operation switching (on and off) depending on material load states. This paper proposes a new modeling formalism satisfying the requirements by extending the conventional discrete event system specification (DEVS) formalism. In the proposed formalism, each simulation entity has an energy model, which is derived from the reverse engineering of real conveyor operations, to determine energy consumption states and rates. The simulation results of this research have been applied to the revision of a warehouse conveyor system in Korea.

1. Introduction

A conveyor system is a material handling equipment that addresses the movement, storage, and management of all related materials including raw materials, parts, goods, and products for processes (e.g., cleaning, preparation, manufacturing, packaging, distribution, consumption, and disposal). A conveyor system provides durable and reliable automated logistics services to the facilities for warehouse, mining, and production systems (Pang & Lodewijks, 2005). To succeed in those logistic operations, a conveyor system must be capable to react appropriately to various demands (Hsieh, Chang, & Chang, 2007). Therefore, in the logistics-planning phase, a conveyor system must be designed flexibly and efficiently to prevent loss by reconfiguration after installation (Chin, Wheeler, Quah, & Low, 2011; Zhao & Lin, 2011).

For the construction of a conveyor system, engineers design the layout of the conveyor network (Müller-Boyaci and Wenzel, 2016) and determine the type, size, power, and speed of the conveyor units based on their physical features (e.g., weight and size) of the target materials and the performance goals (e.g., lead time) (Luo, Huang, & Zhang, 2015). After installation, a conveyor system has an energy cost, which is a considerable portion of its operation cost. Thus, reducing the energy consumption of a conveyor system can save operation cost (Dong & Luo, 2011). Furthermore, reduced energy consumption contributes to the sustainable operation of a target system by preparing for future

energy cost increases by regulations, such as carbon dioxide reduction for green industry (Paul, Bhole, & Chaudhari, 2014; Rohrmus, Dörich, & Weinert, 2015).

Although the energy consumption of a conveyor system must be considered as one of the KPIs (Key performance indicators) during the design phase (Sáenz, Celik, Asfour, & Son, 2012), existing research has focused mainly on smooth material flow controls. Proposed approaches in the existing research use simulation and linear programming-based numerical methods to estimate and optimize KPIs, such as average travel time, time-delay, bottlenecks (Johnstone, Creighton, & Nahavandi, 2015), flow/feed rate capacities (Göttlich, Hoher, Schindler, Schleper, & Verl, 2014), work-in-process levels (Matsui, 2005), and the expected waiting time and buffer size of each station (Bozer & Hsieh, 2004). However, various plans using the advanced operation control techniques of conveyor systems by information technologies can be developed in the design phase (Lev, Mayer, Wohlmuthová, & Prošek, 2013), and numerical methods are limitedly usable to describe unit entity performance and simple material flows and difficult to represent the systematic performance of complex plans (Herazo-Padilla, Montoya-Torres, Nieto Isaza, & Alvarado-Valencia, 2015; Ho & Lin, 2017). Simulation methods can describe rapidly the consequence of various KPIs of a system plan in many operation scenarios by the construction and modification of a virtual conveyor system (Ham & Park, 2014; Klaas, Laroque, Renken, & Dangelmaier,

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Fig. 1. Conventional conveyors.

2016; Wang, Lee, Hsu, & Nguyen, 2016). Therefore, the energy efficiency of a conveyor system can be predicted using simulations similar to other KPIs (Alyamani, Damgacioglu, Celik, Asfour, & Feiock, 2016).

Previous research on modeling conveyor systems pertains to the improvement of mechanical systems for driving, such as rollers, belts, chains, or motors (Alspaugh, 2003), and to obtain optimal parameters for electric power, speed, and feed rate under the target operational conditions (Zhang & Xia, 2011). This research focuses on conveyor systems for enhancing the energy efficiency for material handling systems with continuous operations and constant speed. In terms of time-of-use, conveyor systems for the irregular transportation of relatively small and light materials can be modeled as discrete operation systems that control each conveyor zone by entering an idle state, if it is irrelevant with material transportation (Zhang & Xia, 2010). These technology-based conveyors can reduce energy consumption (Poon et al., 2011) in conditions where a conveyor unit has sufficient time for a turn on/off operation and requires less energy to shut down and restart than the total idle energy consumption. Conveyor systems in many warehouses and assembly lines have adopted the discrete conveyors for energy efficiency, and the energy consumption of those conveyor systems relies more on the system operation control than on each conveyor performance. Thus, the simulation method is useful to predict the performance of complex conveyor systems including energy efficiency (Ko & Park, 2014), and must represent material flows in conveyor streams to achieve the objective of simulations.

However, existing modeling approaches for conveyor simulation are devised to describe system states without considering material handling (Castro, Kofman, & Wainer, 2010). The objective of this research is to model a conveyor system to simulate material-flows in the model to predict operation performance including energy consumption. For conveyor system simulation, the multiple material transportation and conveyor operation switching (on and off) by material load states must be modeled. To meet the requirements, we propose a new modeling formalism by extending the discrete event system specification (DEVS) formalism (Zeigler, Praehofer, & Kim, 2000), which is called 'E-DEVS' (abbreviation of the extended DEVS) in this paper. This paper constructs simulation entities by modeling the operations of each component in a conveyor system using the proposed E-DEVS formalism. Each simulation entity has an energy model that determines energy consumption states in the operation states of a simulation entity. In this research, the energy consumption states and rates are defined for discrete-material flows by the reverse engineering that is the abstraction of energy consumption data acquired from real conveyor operations (Choi & Xirouchakis, 2014). The main objective of the research is to propose modeling methodology to represent components in conveyor systems by E-DEVS-based simulation entities and to construct a conveyor system model using the simulation entities. The conveyor system model can describe energy consumption results by simulations in various network designs and logistic scenarios, and this paper describes the construction and simulation process of a conveyor system model as an example

implementation.

The remainder of this paper is organized as follows. Section 2 provides the technical approach used in this research and explains E-DEVS formalism in detail. Section 3 describes the E-DEVS-based modeling methodology for conveyor systems. The implemented models and simulation results are illustrated as an example in Section 4. Finally, the conclusions are provided in Section 5.

2. Technical approach

2.1. Description of candidate conveyors

This research categorizes candidate conveyors as two operation types, continuous and discrete conveyors. The continuous operation type is used in conventional conveyors in many existing facilities, and it provides stable transportation for a wide range of materials in size and weight. However, energy can be wasted by operating regardless of whether materials are loaded. This conveyor type has been implemented with various device types including belt, roller, and chain conveyors. Fig. 1 depicts commercial conveyors as examples.

The discrete operation conveyor type is a recently introduced device to operate only the relevant conveyor zones with material transportation. A conveyor zone in the discrete conveyor system is structured with one power roller and several linked non-power rollers. Each conveyor zone has a control board to administer the power roller of the zone to operate or stop, and a control board connected to a sensor to recognize the material load state and communicate the operation state with other control boards. A control board can receive the operation state change of a prior conveyor zone and send the operation state change of the current conveyor zone to a subsequent conveyor zone. Thus, a conveyor zone can prepare operations for an upcoming material loading with this communication. The structure of this power roller-based zone control conveyor is represented in Fig. 2.

Compared to a conventional conveyor type, to implement a power roller-based zone control conveyor requires a more sophisticated control system structure (e.g., control board, sensor, embedded software system, and communication link); however, it has a simpler structure in the drive system (Chin & Wheeler, 2013). Therefore, the discrete operation conveyor type has advantages in both energy consumption and mechanical maintenance, and it is expected to replace the conventional conveyor for sustainable material handling systems (Bowoo System, 2016). Fig. 3 presents a real application example of power roller-based zone control conveyors for a discrete operation.

2.2. E-DEVS formalism

Discrete-event systems describe the operation of a system as a sequence of discrete events along a time lapse (Choi & Kang, 2013). A model in a discrete-event system is composed of input events, output events, and state variables. In simulation, it changes the state variables

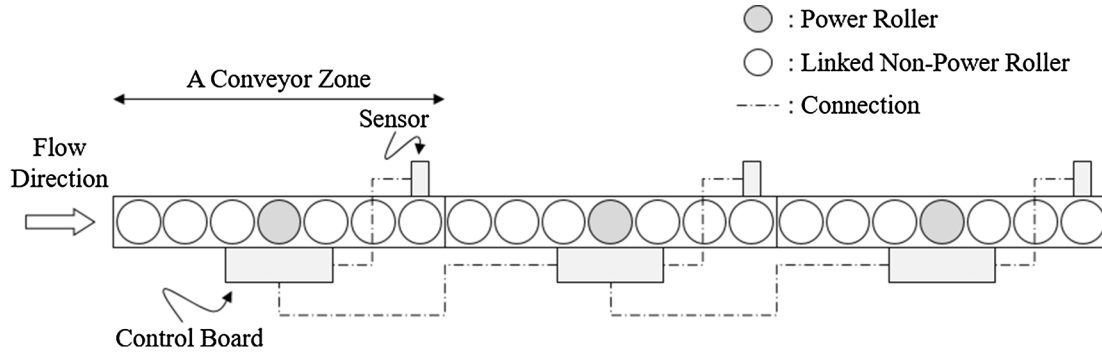


Fig. 2. Power roller-based zone control conveyor.

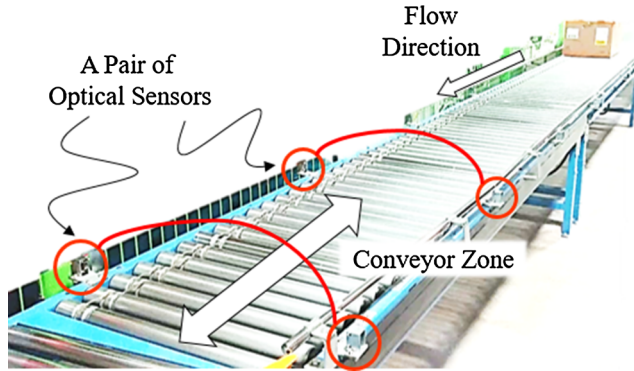


Fig. 3. Example conveyor system for discrete operation.

as an action fired by an input event and outputs the result of the state variables as an event (Robinson, 2015). Modeling formalisms, such as DEVS formalism, event graphs, activity cycle diagrams, and Petri-net, have been used to describe various autonomous control systems, and are interchangeable in many cases. Among these types of formalisms, DEVS formalism that combines Timed-FSA (finite state automata) with hierarchical and modular concepts has been very popular in both academia and industry owing to its two main advantages: (1) its rigorous formal definition and (2) its support of the specifications of discrete event models in a hierarchical and modular manner. For these reasons, this research proposes E-DEVS formalism to describe the entities of a conveyor system by extending the DEVS formalism. The semantics of the formalism are compatible with object-oriented specifications for simulation models. The E-DEVS formalism is composed of two types of models: an atomic model, the modular models from which larger models are built; and a coupled model, how atomic models are connected in a hierarchical manner. E-DEVS formalism extends the atomic model of the original DEVS formalism to contain variables and to define functions for variable modification and transition-disable conditions (DEVS, 2018). In the previous research, transformed DEVS formalisms for individual domain have been introduced without specific modeling parameters and design methodologies (Zeigler et al., 2000). Thus, they are ambiguous when applied to conveyor system model development, and the functions proposed by E-DEVS are not considered. The following 13-tuple specifies the atomic model M of E-DEVS: $M = \langle X, Y, S, V, \delta_{int}, \delta_{ext}, \omega_{in}, \omega_{out}, \psi_{int}, \psi_{ext}, \lambda, \mu, t_a \rangle$, and each symbol is explained in Table 1.

The nine elements, δ_{int} , δ_{ext} , ω_{in} , ω_{out} , ψ_{int} , ψ_{ext} , λ , μ , and t_a are the characteristic functions of an atomic model. A coupled model represents the methodology to couple several modular models together to build a new model. E-DEVS formalism extends the coupled model of the original DEVS formalism to represent dynamic model construction and conditional coupling relations. The coupled model N of E-DEVS has 11-tuple defined as: $N = \langle X, Y, M, EIC, EOC, IC, DI, IE, TE, WC, SELECT \rangle$, and each

Table 1
Atomic model description of E-DEVS.

Symbol	Description	Function
X	Input event set	
Y	Output event set	
S	Sequential state set	
V	Model variable set	
δ_{int}	Internal transition function	$S \rightarrow S$
δ_{ext}	External transition function	$Q * X \rightarrow S$
ω_{in}	Data import function from input events	$X * (data) \rightarrow V$
ω_{out}	Data export function with output events	$Y \rightarrow V$
ψ_{int}	Internal transition-disable condition function	$\delta_{int} * E \rightarrow S$
ψ_{ext}	External transition-disable condition function	$\delta_{ext} * E \rightarrow S$
λ	Output function	$S \rightarrow Y$
μ	Variable modification function	$S * \{v \mid v \in V, \text{total variables of } M\} \rightarrow V$
t_a	Time advance function	$S \rightarrow \text{Real}$
Q	Total state of M	$Q = \{(s, e) \mid s \in S, 0 \leq e \leq t_a(s)\}$
E	Cancelling a transition by a false result	$E = \{(v, condition) \mid v \in V\}$

Table 2
Coupled model description of E-DEVS.

Symbol	Description	Function
X	Input event set	
Y	Output event set	
M	Model set, which is composed of m_i (static model) and $[m_j]$ (dynamic model)	
$\emptyset, \{m_0, \dots, m_i\}, \{[m_0], \dots, [m_j]\}, \{m_0, \dots, m_i, [m_0], \dots, [m_j]\} \subseteq M$		$0 \leq i, j$
EIC	External input coupling relation	$EIC \subseteq N.IN * M.IN$
EOC	External output coupling relation	$EOC \subseteq M.OUT * N.OUT$
IC	Internal coupling relation	$IC \subseteq M.OUT * M.IN$
DI	Data interchange function	$\{C \mid C \in EIC, EOC, IC\} \rightarrow (data)$
IE	Instantiation function of a dynamic model $[m]$	$EVT \rightarrow [m]$
TE	Instance termination function of a dynamic model $[m]$	$EVT \rightarrow [m]$
WC	Weak coupling relation that is valid by condition	$WC \subseteq (M \parallel N).OUT * Condition$
$SELECT$	Tie-breaking selector	$2^M - \emptyset \rightarrow M$
EVT	$EVT = \{evt \mid evt \in [m].IN \& .OUT\}$: total input and output events of a model $[m]$	

symbol is explained in Table 2. The extensions .IN and .OUT represent the input port set and output port set of the respective E-DEVS models.

To summarize this section, the proposed formalism E-DEVS constructs an atomic model with thirteen tuples that are four sets and nine functions and a coupled model with eleven tuples that are three sets, four coupling relations and four functions. Comparing to the original

DEVS, the atomic model of the E-DEVS has additional one set (V) and five functions (ω_{in} , ω_{out} , ψ_{int} , ψ_{ext} and μ) and the original tuples, and the coupled model also has the tuples of the original model and additional three functions (DI , IE and TE) and one coupling relation (WC). Basically, coupling relations have the identical concept to the original DEVS, and data interchange function DI which is a new tuple of a coupled model specifies the data interchange between atomic models in a coupled model as the output of coupling relations. Moreover, for a coupled model, we adopt the dynamic model concept ($[m]$) and new two tuples (IE and TE) to describe multiple operations that dynamically generated and terminated by events. The detail modeling and application process using E-DEVS is explained in Chapter 3.

2.3. Reverse engineering for energy models

This research constructed the energy model of a conveyor using a reverse-engineering process to represent energy consuming trends in real operation environment. The reverse-engineering process identified the corresponding energy consumption states of the operation states of a conveyor by employing energy consumption data measured from operation experiments on the conveyor. The practical alternatives of operational conditions regarding the material weight, feed rate, and transportation speed were defined in an experiment-planning phase to obtain valid data. During an experiment of each operational condition, the drive system of a conveyor was measured for recording instantaneous electric power usage using an oscilloscope. The recorded energy consumption data in each experiment were formalized to construct an energy model for a conveyor.

This research categorized two energy model types according to the electric power sources of the conveyors: DC (direct current) and AC (alternating current). Because the AC power type is a stable power source, motors in an AC conveyor type are robust and low-cost. The DC power type is an easily controllable power source, and motors in a DC conveyor type are able to operate a power drive system with a swift response time. Therefore, the AC conveyor type has been commonly used for conventional conveyors that operate continuously and the DC conveyor type has been adopted in conveyors for discrete operations. The instantaneous energy consumption rate (Wh/s, watt-hour per second) of a conveyor represents different trends by each power source type, and the energy consumption trends can be modeled as two states ('Idle' and 'Work') for the AC conveyor, and three states ('Idle', 'Start', and 'Work') for the DC conveyor. In a condition that operation state is not changed, the instantaneous energy consumption rate is kept in a linear form by time as modeled in Fig. 4. In a common measurement unit, the amount of cumulative energy consumption is represented by Wh (watt-hour). Energy measured by the instantaneous energy consumption rate was converted to the cumulative energy amount using the following equation.

$$CE = (IE \times T) \div 3600$$

where CE is the cumulative energy amount (Wh), IE is the instantaneous energy consumption rate (Wh/second), and T is the time (second) for IE .

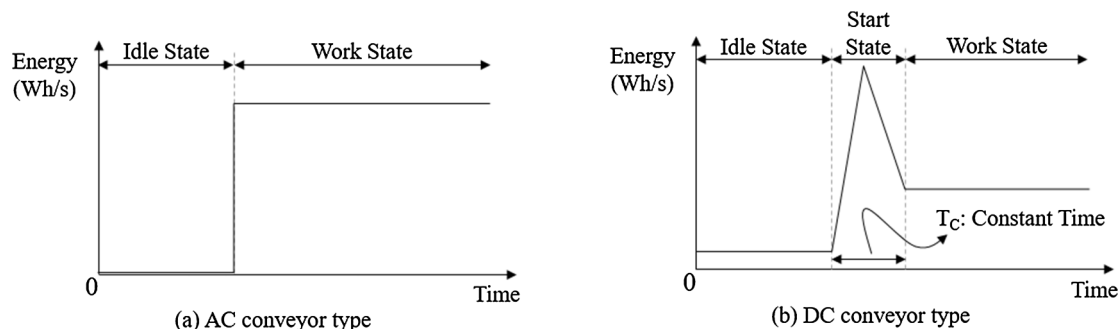


Fig. 4. Instantaneous energy consumption rate.

The reverse engineering identified energy consumption rates along the operational conditions from operation experiments, and an energy model configured a corresponding energy consumption rate with current energy consumption state and conditions. Therefore, an energy model was structured with three components: (1) an E-DEVS-based atomic model that controls operation states by material load states; (2) a relation that defines corresponding energy consumption states to the operation states and conditions; (3) an energy consumption table that describes the energy consumption rates (in various operational conditions) of each energy consumption state.

3. E-DEVS-based conveyor system modeling

To construct a conveyor simulation system, this research defines the following simulation entities: source, sink, junction, continuous conveyor (conveyor_C), and discrete conveyor (conveyor_D); and a material entity: part. Each simulation entity has input and output ports and a process. The output port of a simulation entity is connected to the input ports of other entities. A material entity that describes the material characteristics by their attributes is generated in a source entity and flow simulation entities. Simulation entities possess and interchange material entities 'Part' to represent material load states. The description of each defined entity is explained as follows. The source entity represents the material input station of a conveyor system, and it has an output port to send materials to a connected conveyor at a designed feed rate. The sink entity represents the material output station of a conveyor system, and it has an input port to receive materials from a connected conveyor. The junction entity represents the stations of intermediate buffer and material distribution on a conveyor stream, and it can have multiple input ports to receive materials from connected conveyors and multiple output ports to send the materials to connected conveyors by designed rules. The conveyor_C entity represents a continuous conveyor, and it has a pair of input and output ports to transport materials from the input to the output. The conveyor_D entity represents a discrete conveyor that has a pair of input and output ports to transport materials from the input to the output, and it operates during a specific work time after receiving a sensor signal from a connected entity with an input port, and transmits a signal to a connected entity with an output port when its own sensor recognizes the material. The part entity represents a material unit that flows on a conveyor system by attributes: ID, weight, and size.

For the representation of conveyor design specification, a conveyor was modeled by the following attributes: an electric power source type, power in an HP (horsepower) unit, and speed in an m/min (meter per minute) unit, regular energy consumption in a Wh (watt-hour), operation time, and a designed target zone length. This research selected candidate conveyors as two continuous operation conveyors and one discrete conveyor. The design specification attributes of the candidate conveyors are presented in Table 3. Regarding work time, the continuous conveyors operate infinitely from the start of an operation, and the discrete conveyor operates two seconds after receiving a sensor signal. This study assumes that a sensor is located 0.2 m before the terminal of a conveyor.

Table 3
Design specification attributes of candidate conveyors.

Conveyor ID	Operation Type	Power source type	Power	Speed (/Min)	Regular energy consumption	Operation time	Zone length
Conv1	Continuous	AC	1 HP	20 m	750 Wh	∞	6 m
Conv2	Continuous	AC	0.5 HP	20 m	400 Wh	∞	6 m
Conv3	Discrete	DC	0.15 HP	20 m	40 Wh	2 s	1 m

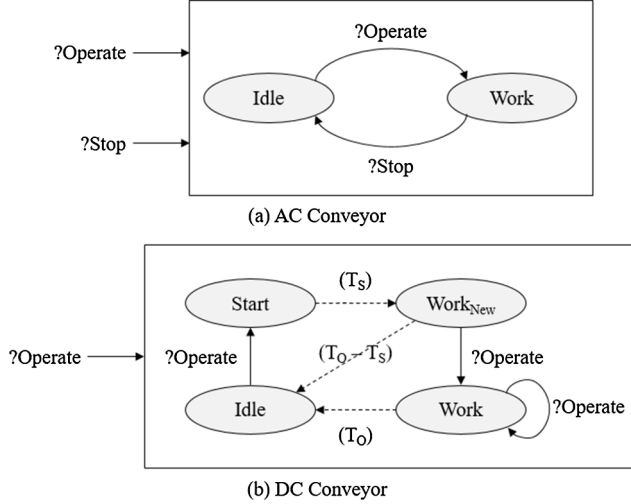


Fig. 5. Diagram for conveyor operation control models.

The electric power type of a conveyor, AC or DC, determines the atomic model design of the energy model for the conveyor. The following two atomic models describe the controlling operation states of AC and DC conveyors. The state diagrams of the two models are depicted in Fig. 5. For the time variables in the atomic models, T_O is the operation time, defined as 2 s in Table 3, and T_S is 0.15 s, identified by the reverse-engineering process.

Atomic models for the conveyor operation control:

< AC conveyor >
 $X = \{?Stop, ?Operate\}$
 $Y = \emptyset$
 $S = \{Idle, Work\}$
 $V = \emptyset$
 $s_0 = (Idle, \infty)$
 $\delta_{ext}(Idle, ?Operate) = Work$
 $\delta_{ext}(Work, ?Stop) = Idle$

< DC conveyor >
 $X = \{?Operate\}$
 $Y = \emptyset$
 $S = \{Idle, Start, Work_{New}, Work\}$
 $V = \emptyset$
 $s_0 = (Idle, \infty)$
 $\delta_{int}(Start) = Work_{New}$
 $\delta_{int}(Work_{New}) = Idle$
 $\delta_{int}(Work) = Idle$
 $\delta_{ext}(Idle, ?Operate) = Work_{New}$
 $\delta_{ext}(Work_{New}, ?Operate) = Work$
 $\delta_{ext}(Work, ?Operate) = Work$
 $t_a(Start) = T_S$
 $t_a(Work_{New}) = (T_O - T_S)$
 $t_a(Work) = (T_O)$

The energy consumption table for each candidate conveyor was constructed from the reverse-engineering process. The relation between operation states and energy consumption states is described by (Operation State \rightarrow Energy Consumption State), and the results were (Work, $Work_{New} \rightarrow Work$), (Idle \rightarrow Idle), and (Start \rightarrow Start). ‘Conv3’ was designed for 40 kg as the maximum load, and the maximum weight per unit of the target system was 30 kg. Therefore, experiments for

Conv3 were executed with a 50 kg maximum weight. The other candidate conveyors were tested up to 180 kg, which is the maximum possible weight in the operational condition of a target system. From the reverse-engineering process, the energy consumption tables of the candidate conveyors are presented in Table 4.

The operations of a simulation entity were represented as an atomic model or a coupled model using the E-DEVS formalism. Each single function of a simulation entity was constructed as an atomic model and a simulation entity, which had several functions, and was constructed as a coupled model that was a combination of atomic models. To prevent the redundant development of similar functions, we identified the required functions of each simulation entity. For example, to support a mixed system with continuous and discrete conveyors, the sensor function was included in junction, conveyor_C, and conveyor_D entities. The identified functions of simulation entities are listed as follows: Source (*Generation*), Sink (*Disposal*), Junction (*Buffer, Export, Sensor*), Conveyor_C (*AC Conveyor Operation Control, Transportation, Sensor*), Conveyor_D (*DC Conveyor Operation Control, Transportation, Sensor*).

The following atomic models were constructed for the listed functions. In the atomic models, ‘Part’ as imported and exported data, is the part entity, and the model variables were designed to contain single or multiple part entities, expressed by the ‘[]’ mark that represents an array of entities. Variables formed in an array have operators and methods that comply with rules in common computer knowledge, such as pop, push, and indexing. The atomic model for the *Generation* function has the time variable T_{NG} that describes the duration time for the next input-material generation. Atomic models for the generation (see Fig. 6) and disposal (see Fig. 7) models were constructed as follows, with the state diagrams.

< Atomic model for the Generation function >
 $X = \emptyset$
 $Y = \{!Unload\}$
 $S = \{Idle, Generation\}$
 $V = \{Part_Out, Parts[]\}$
 $s_0 = (Idle, T_{NG})$
 $v_0 = (Part_Out, Empty)$
 $\delta_{int}(Generation) = Idle$
 $\delta_{int}(Idle) = Generation$
 $\omega_{out}(!Unload) = Part_Out$
 $\lambda(Generation) = !Unload$
 $\mu(Generation, Part_Out) = Parts.Pop()$
 $t_a(Generation) = T_{NG}$

< Atomic model for the Disposal function >
 $X = \{?Load\}$
 $Y = \emptyset$
 $S = \{Idle, Disposal\}$
 $V = \{Part_In, Parts[]\}$
 $s_0 = (Idle, \infty)$
 $v_0 = \{(Parts[], Empty), (Part_In, Empty)\}$
 $\delta_{int}(Disposal) = Idle$
 $\delta_{ext}(Idle, ?Load) = Disposal$
 $\omega_{in}(?Load, Part) = Part_In$
 $\mu(Disposal, Parts[]) = Parts.Push(Part_In)$

The construction of the atomic models for the *Buffer* and *Export* functions is described below. The state diagrams of the atomic models are depicted in Fig. 8, for the buffer model, and Fig. 9, for the export model. For the time variable in the export model, T_{XP} is the duration time for sorting or regularizing the material flow rate.

Table 4
Energy consumption tables of candidate conveyors.

State	Material weight	Conveyor ID		
		Conv1	Conv2	Conv3
Idle	–	0 Wh/s	0 Wh/s	1.96 Wh/s
Start	–	–	–	29 Wh/s
Work	10 kg	676 Wh/s	304 Wh/s	20 Wh/s
	20 kg	676 Wh/s	305 Wh/s	20.5 Wh/s
	30 kg	676 Wh/s	305 Wh/s	21 Wh/s
	40 kg	676 Wh/s	305 Wh/s	23 Wh/s
	50 kg	676 Wh/s	305 Wh/s	25 Wh/s
	60 kg	677 Wh/s	306 Wh/s	–
	90 kg	677 Wh/s	308 Wh/s	–
	120 kg	677 Wh/s	311 Wh/s	–
	150 kg	677 Wh/s	313 Wh/s	–
180 kg	677 Wh/s	314 Wh/s	–	

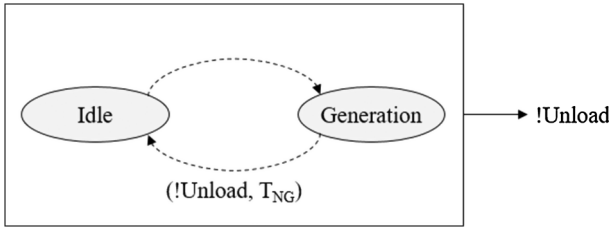


Fig. 6. Diagram for the generation model.

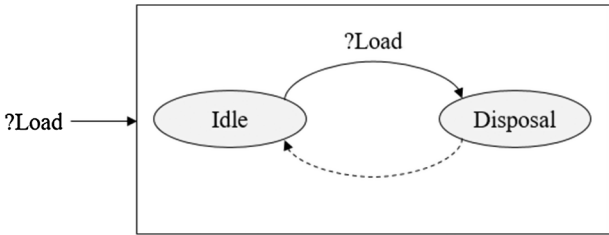


Fig. 7. Diagram for the disposal model.

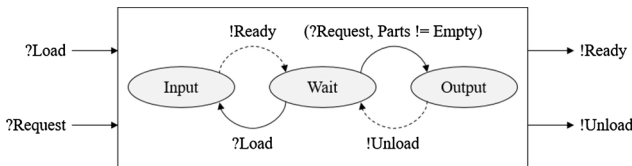


Fig. 8. Diagram for the buffer model.

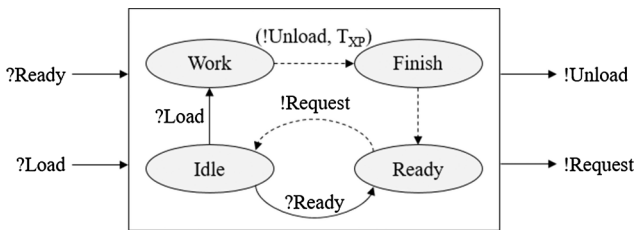


Fig. 9. Diagram for the export model.

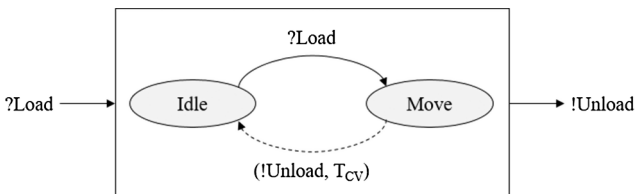


Fig. 10. Diagram for the transportation model.

```

< Atomic model for the Buffer function >
X = {?Load, ?Request}
Y = {!Ready, !Unload}
S = {Wait, Input, Output}
V = {Part_In, Part_Out, Parts[]}
s0 = (Idle, ∞)
v0 = {(Parts[], Empty), (Part_In, Empty), (Part_Out, Empty)}
δ_int(Input) = Wait
δ_int(Output) = Wait
δ_ext(Wait, ?Load) = Input
δ_ext(Wait, ?Request) = Output
ω_in(?Load, Part) = Part_In
ω_out(!Unload) = Part_Out
ψ_ext(δ_ext(Wait, ?Request), Parts[] != Empty) = Output
λ(Input) = !Ready
λ(Output) = !Unload
μ(Input, Parts[]) = Parts.Push(Part_In)
μ(Output, Part_Out) = Parts.Pop()

```

```

< Atomic model for the Export function >
X = {?Ready, ?Load}
Y = {!Unload, !Request}
S = {Idle, Ready, Work, Finish}
V = {Part}
s0 = (Idle, ∞)
v0 = (Part, Empty)
δ_int(Work) = Finish
δ_int(Finish) = Ready
δ_int(Ready) = Idle
δ_ext(Idle, ?Ready) = Ready
δ_ext(Idle, ?Load) = Work
ω_in(?Load, Part) = Part
ω_out(!Unload) = Part
λ(Ready) = !Request
λ(Work) = !Unload
t_d(Work) = T_XP

```

The atomic model for the *Transportation* function has the time variable T_{CV} that describes the transportation time from input to output and is calculated by the following equation: $T_{CV} = \text{Conveyor Length (m) / Speed (m/s)}$. The atomic model for the *Sensor* function has the time variable T_{SN} that describes the sensing time after a material input was calculated by the following equation: $T_{SN} = \text{Sensor Length (m) / Speed (m/s)}$. The two models were constructed as below, and the state diagrams are depicted in Fig. 10, for the transportation model, and Fig. 11, for the sensor model.

```

< Atomic model for the Transportation function >
X = {?Load}
Y = {!Unload}
S = {Idle, Move}
V = {Part}
s0 = (Idle, ∞)
v0 = (Part, Empty)
δ_int(Move) = Idle
δ_ext(Idle, ?Load) = Move
ω_in(?Load, Part) = Part
ω_out(!Unload) = Part
λ(Move) = !Unload
t_d(Move) = T_CV

```

```

< Atomic model for the Sensor function >
X = {?Load}
Y = {!Recognize}
S = {Idle, Sensing}
V = ∅
s0 = (Idle, ∞)
δ_int(Sensing) = Idle
δ_ext(Idle, ?Load) = Sensing
λ(Sensing) = !Recognize
t_d(Sensing) = T_SN

```

Simulation entities structured as composite functions were constructed as coupled models. The following coupled models were used for the

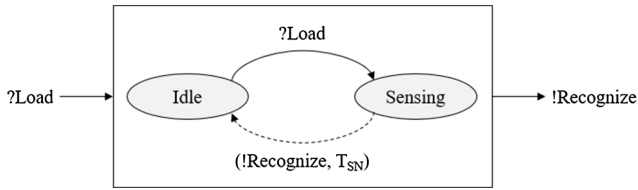


Fig. 11. Diagram for the sensor model.

simulation entities: junction, conveyor_C, and conveyor_D. In the coupled models, ‘Part’ for interchanging data in coupling relations represented the part entity. Coupled models for junction, conveyor_C, and conveyor_D entities were constructed as follows. The network diagrams are depicted for junction (Fig. 12), conveyor_C (Fig. 13), and conveyor_D (Fig. 14) entities.

```

< Coupled model for the junction entity >
X = {?Load}
Y = {!Unload, !Recognize}
M = {Buffer, Export, Sensor}
EIC = {?Load * Buffer.?Load}
EOC = {(Export.!Unload * !Unload), (Sensor.!Recognize * !Recognize)}
IC = {(Buffer.!Ready * Export.?Ready), (Buffer.!Unload * Export.?Load), (Buffer.!Unload * Sensor.?Load), (Export.!Request * Buffer.?Request)}
DI(?Load * Buffer.?Load) = Part
DI(Export.!Unload * !Unload) = Part
DI(Buffer.!Unload * Export.?Load) = Part
WC = {(!Unload * Sequential-Switch)}
Sequential-Switch: indicates one coupling relation and switches the indicated coupling relation sequentially

< Coupled model for the conveyor_C entity >
X = {?Load}
Y = {!Unload, !Recognize}
M = {AC Conveyor Operation Control as AOC, [Transportation], [Sensor]}
EIC = {?Load * AOC.?Operate}, (?Load * [Transportation].?Load), (?Load * [Sensor].?Load)}
EOC = {( [Transportation].!Unload * !Unload), ([Sensor].!Recognize * !Recognize)}
DI(?Load * [Transportation].?Load) = Part
DI([Transportation].!Unload * !Unload) = Part
IE([Transportation].?Load) = [Transportation]
IE([Sensor].?Load) = [Sensor]
TE([Transportation].!Unload) = [Transportation]
TE([Sensor].!Recognize) = [Sensor]

< Coupled model for the conveyor_D entity >
X = {?Load, ?Recognize}
Y = {!Unload, !Recognize}
M = {DC Conveyor Operation Control as DOC, [Sensor], [Transportation]}
EIC = {(?Recognize * DOC.?Operate), (?Load * [Transportation].?Load), (?Load * [Sensor].?Load)}
EOC = {( [Transportation].!Unload * !Unload), ([Sensor].!Recognize * !Recognize)}
IC = {( [Sensor].!Recognize * DOC.?Operate)}
DI(?Load * [Transportation].?Load) = Part
DI([Transportation].!Unload * !Unload) = Part
IE([Transportation].?Load) = [Transportation]
IE([Sensor].?Load) = [Sensor]
TE([Transportation].!Unload) = [Transportation]
TE([Sensor].!Recognize) = [Sensor]
  
```

The conveyor system is the top-level coupled model that is composed of the simulation entities. The short conveyor systems, as examples, are depicted by the two conveyor operation types in Fig. 15.

4. Implementation

The software application that implements the proposed methodology has been developed using the C# language and DEVSIM++ (Kim, 1994) for the simulation engine and conveyor models, and the Syncfusion® library for the graphical user-interface. To validate the modeling formalism and reverse energy models of this paper, we constructed a demo conveyor system and had experiments with measurement devices in controlled operation conditions as Fig. 16. It is difficult to measure the energy consumption of a conveyor system in a real plant, because the consumption rates are variable by operation conditions and the electricity consumption only for a conveyor network cannot be derived from total energy consumption. Therefore, we developed the demo conveyor system to demonstrate simulation results to compare with experimental results. The demo conveyor systems, which has length of 12 M, are composed of two AC conveyors (with two types; 0.5 and 1 HP) for continuous operation and twelve DC conveyors for discrete operation as Fig. 17. Experimental conditions are as follows: (a) Speed: 40 M/Min, (b) Inter-arrival time: 4 s, 8 s and 16 s, (c) Experiment time: 24 h. The measured energy consumption rates of each conveyor type are described in Fig. 18. The simulation results are represented in Table 5, and the experiment results are similar with the simulation results (in the range of $\pm 3\%$ for AC conveyors and $\pm 5\%$ for DC conveyors). The difference could be from signal noises and experimental errors.

As an example, the implemented system was applied to design a conveyor network for the order-picking-based warehouse of a clothing goods company in Korea. The example conveyor network has a length of 354 m, and the conveyor system models for the network were constructed using the candidate conveyors of the previous chapter (two continuous and one discrete conveyors). As represented in Fig. 19, the constructed models were composed of simulation entities as follows: the simulation entities of each model were composed of a continuous (59 units for the Conv1- and Conv2-based models) or a discrete (354 units for the Conv3-based model) conveyor, a junction (9 units), a source (3 units), and a sink (1 unit). In the implemented system, the conveyors were rectangles colored green for the work state and yellow for the idle state. Materials flowing on conveyors were represented as orange colored squares. Simulation screenshots depicted in Fig. 20 show that all conveyors in the continuous conveyor-based model are in operation and the conveyors related exclusively to material transportation function in a discrete conveyor-based model.

To validate the E-DEVS-based simulation entities and the conveyor system models in this paper, we compared the real and simulated energy consumption trends of each candidate conveyor during 1000 s of an operation scenario that has 8 s as material input time interval. Identical results were found from the comparison, as illustrated in Fig. 21. For the estimation of energy consumption by candidate conveyor types, the constructed models were simulated with three different time interval conditions (4, 8, and 16 s) of material input during a period of 24 h. In this research, the total energy consumption amount of a conveyor was computed by the sum of the multiplying energy consumption rates with the idle time in the corresponding states. In addition, the total energy consumption of a conveyor system was calculated as the sum of energy consumptions of each conveyor. During simulations, the energy consumption trends of the constructed models in each operation condition are described in Fig. 22. The results describe that the discrete conveyor-based system is more efficient with irregular material input than with continuous material flows, thus showing that

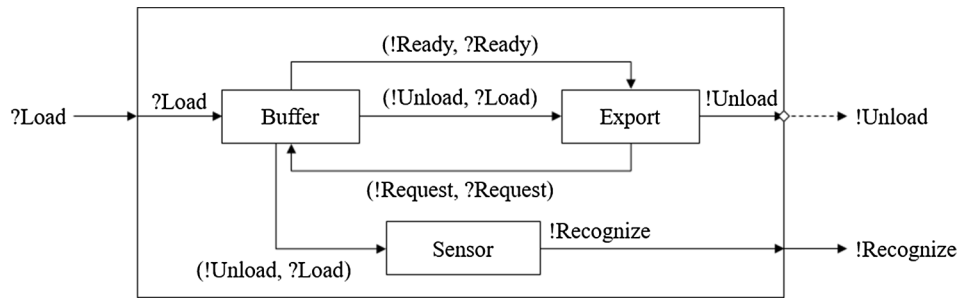


Fig. 12. Diagram for the junction entity.

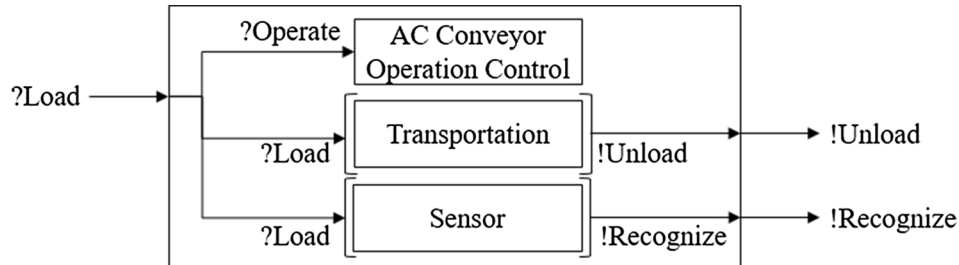


Fig. 13. Diagram for the conveyor_C entity.

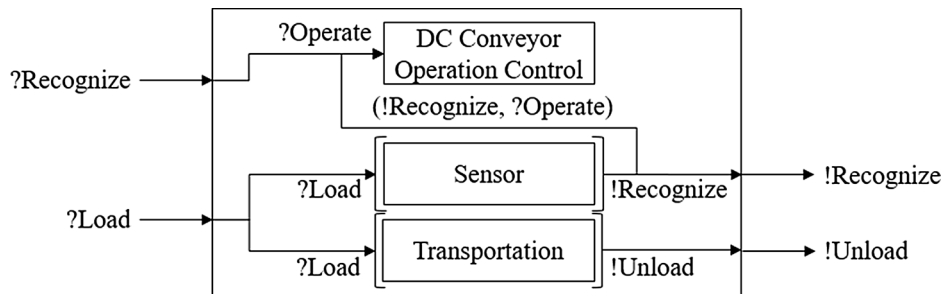
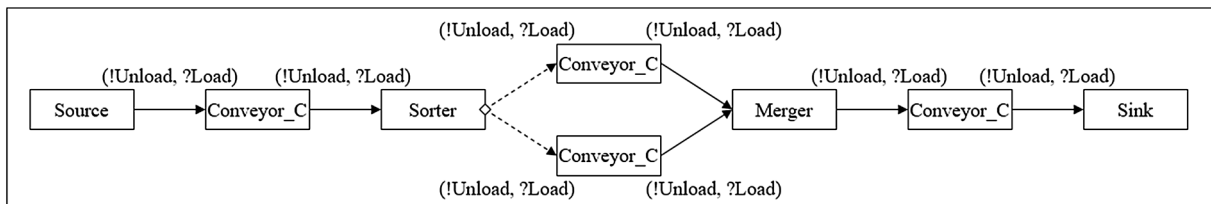
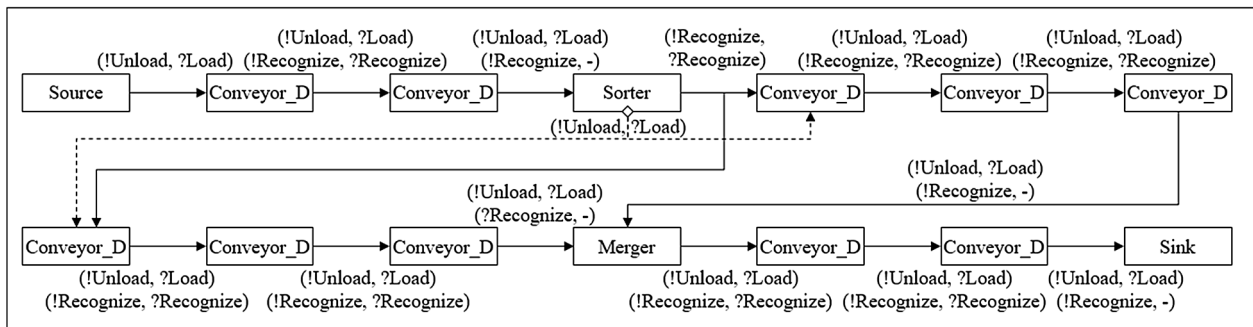


Fig. 14. Diagram for the conveyor_D entity.



(a) Continuous conveyor based model



(b) Discrete conveyor based model

Fig. 15. Example conveyor systems using E-DEVS.

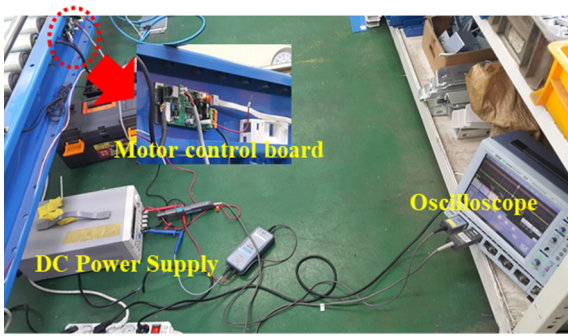
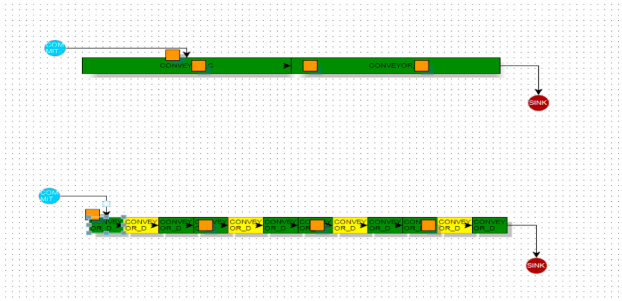


Fig. 16. Experiment environment.



(a) AC conveyor system for continuous operation
(b) DC conveyor system for discrete operation



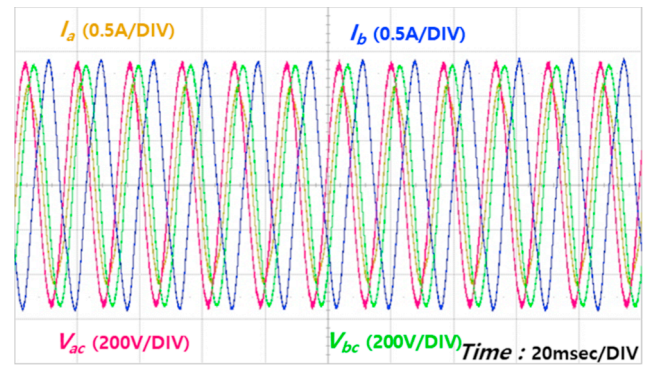
(c) Simulation models

Fig. 17. Demo conveyor systems.

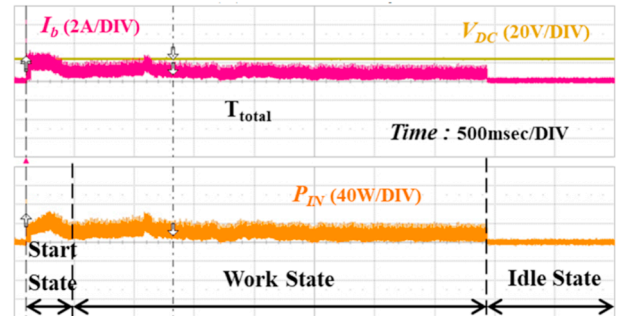
the highest energy efficiency of the warehouse conveyor system is achieved by using discrete conveyors in every possible location.

5. Concluding remarks

This paper proposed the E-DEVS modeling methodology for the construction and simulation of conveyor system models. The proposed E-DEVS formalism was able to represent the conveyor operational characteristics that describe the conditional operations by material load states and the concurrent operations for multiple materials transportation. The proposed methodology describes the operations of components in conveyor systems as operation states based on the E-DEVS formalism, and assigns each conveyor operation state to a



(a) AC conveyor



(b) DC conveyor

Fig. 18. Measured energy consumption rates.

Table 5
Simulation results for the demo conveyor system.

		Energy consumption (Wh)		
		4 s	8 s	16 s
AC conveyor	0.5 HP	14812.042	14812.042	14812.042
	1 HP	32494.338	32494.338	32494.338
DC conveyor		5508.448	3030.757	1791.903

corresponding energy consumption state by containing an energy model. The energy model, which was defined using reverse engineering, identifies the energy consumption states of a conveyor and derives the energy consumption rate of each energy consumption state. Using the E-DEVS-based simulation entities, this research constructs example conveyor system models and simulates the models in several operational conditions. The simulation application of the proposed methodology was implemented, and the conveyor system models were simulated using the application. The simulated energy consumption trends were compared with the real operation results of the conveyors to validate the E-DEVS formalism, and the simulation results were successfully applied to the revision of a warehouse conveyor system in Korea. In future research, we will apply the E-DEVS formalism to modeling other logistic systems that need to respond to irregular transportation demands, such as parcel delivery and military logistic systems, and simulate the systems to forecast various performance indicators, for example, fuel consumption efficiency, optimal traveling routes, and delivery time.

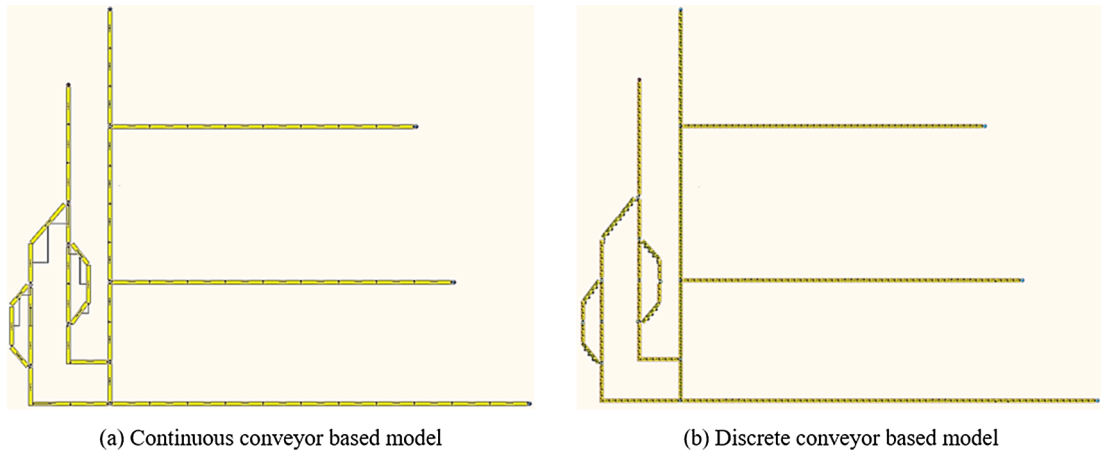


Fig. 19. Example conveyor system models.

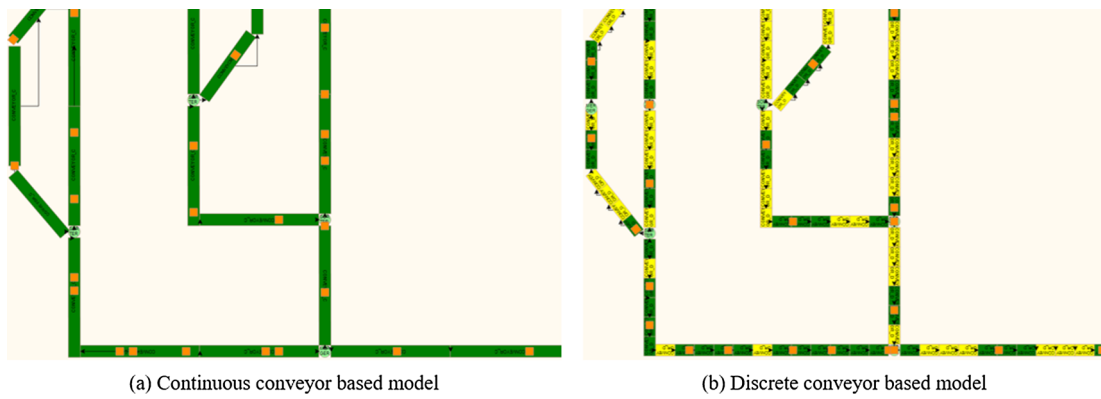


Fig. 20. Simulation screenshots.

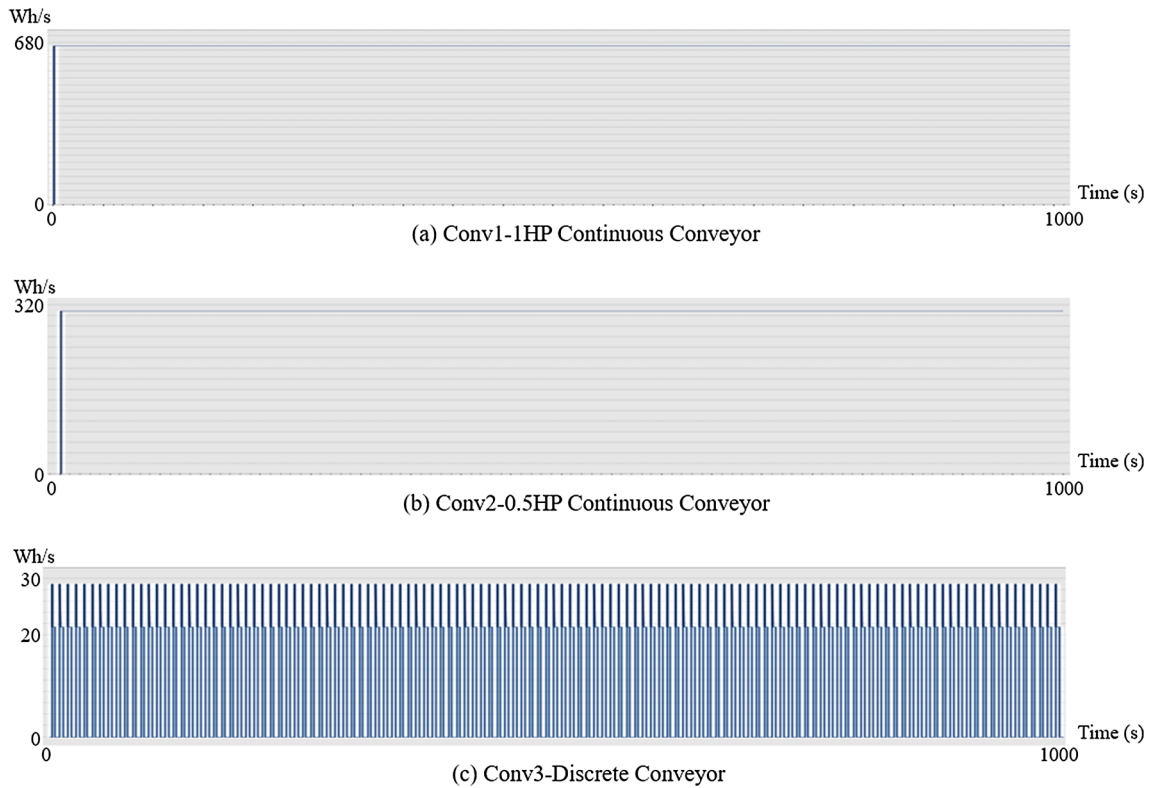


Fig. 21. Instantaneous energy consumption trends of candidate conveyors.

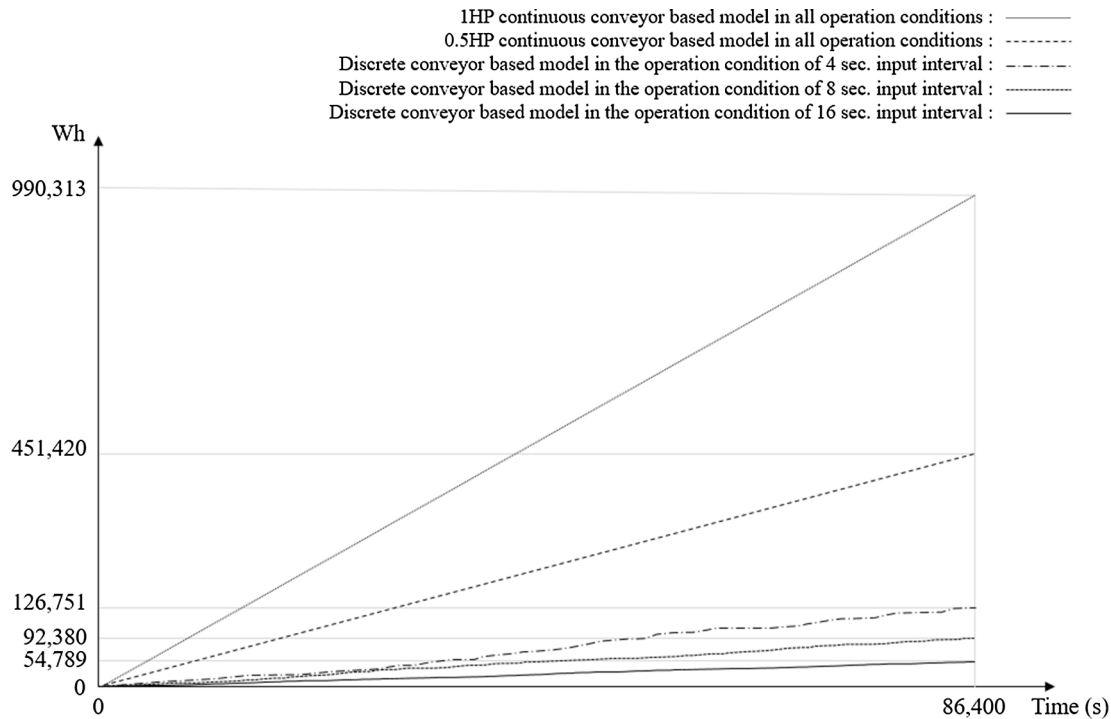


Fig. 22. Energy consumption trends of simulation models.

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