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Research Article

Information Exchange Pairs Simulation Method Based on Discrete Event Simulation for Autonomous Transportation System

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Research on the complicated and indeterminate autonomous transportation system (ATS) has drawn increased interest in order to better address issues associated with contemporary transportation development. Hoping to make transportation more sustainable, economical, safe, convenient, and efficient, researchers try to address the expanding demands with the help of ATS characteristics, i.e., sensing, learning, deciding, and reacting autonomously. The majority of research is focused on the ATS architecture, which is currently in the design phase. To refine the relationship between entities in the architecture, this paper proposes DESIEP, a method based on discrete event simulation (DES) for information exchange pairs (IEPs) in ATS. This method can provide an intelligible description of the information stream while conveniently illustrating the control relationship of sequential logic amongst the entities in the architecture. It helps researchers better understand the running mechanisms driven by internal demands and external technologies of the system so as to diagnose, evaluate, verify, and optimize the designed architecture. Meanwhile, this method also supports further research on the system evolution and architecture analysis, including the functions, logic, and physical architectures of each generation, as well as their mapping relationships and parallel evolution mechanisms.

1. Introduction

With the rapid increase in volume of information, number of systems, and pace of iterative updates, the current transportation systems relying on people to command is difficult to meet the demand. It is vital to construct system architectures that adapt to the new generation of transportation system, i.e., autonomous transportation system (ATS). Additionally, the transportation system needs to transform from partial automation to full automation as a result of emerging technologies such as artificial intelligence, big data, mobile communication, and satellite positioning.

ATS stands for the trend in transportation development that is focused on the future. In addition to roads, vehicles, and pedestrians, ATS involves many elements, including roadside equipment and technical facilities, etc. In the design of the system, it is necessary to consider the problem of cooperative work in the multiautonomous individual network and the adaptive design of the system. Yue et al. [1] considered the joint design of UAV-USV-UUV networks for cooperative target hunting in the maritime battlefield when designing the intelligent control system composition and intelligent control structure of unmanned combat systems. Gan et al. [2] mainly consider how to choose the optimal communication network link to maximize energy efficiency in the process of UAV-assisted vehicle network communication. Xue et al. [3] considered the influence of the high-speed mobile environment on the new multi-access scheme of the 5G-Rlarge-scale Internet of Things and proposed the corresponding improvement scheme. It exhibits unique characteristics compared to other systems, including sensing, learning, deciding, and reacting autonomously. These characteristics determine that ATS is a dynamic and evolving system rather than a static one. Therefore, comprehensive principles are needed for the design of ATS architecture. By establishing an ATS architecture, the system generation will be divided depending on the running mechanism that is driven by internal demands and external technologies of the system. The architecture is also examined in conjunction with the evolution method, including the functions, logic, and physical architectures of each generation, as well as their mapping relationships and parallel evolution mechanisms. The analysis method of system architecture can also refer to some algorithms from other fields. Chen et al. [4] proposed an efficient hybrid optimization algorithm based on mesh search and improved Nelder-Mead simplex (GS-INMS) for parameter identification of the PV model. Although the application field is different, the algorithm optimization ideas can be referenced in the optimization of architecture parameters.

In short, according to principles of ATS architecture, the standardized architecture design and implementation technology are eventually made possible, and the design reference scheme may be offered for typical transportation scenarios. In other words, it is first important to assure the accuracy of the existing system architecture or design principles in order to ensure that the research on ATS may be conducted properly.

Intelligent transportation system (ITS), which includes architecture reference for cooperative and intelligent transportation (ARC-IT) in the USA [5], ITS Canada [6], ITS in China [7], etc., are representative of the existing and reasonably mature research on transportation systems. For better research on the association and running mechanisms of various elements in the system architecture, many approaches to describing and modifying the logical and physical relationships between entities have been proposed. E.g., Michal and Moler [8] developed a modular framework called AgentPolis, which can support the implementation and simulation of transportation systems with a high level of interaction, but its abstraction of entities and agent behavior has to be perfected. Salazar-Cabrera and Pachon [9] proposed an ITS architecture design method allowing the integration and interoperability of new services with current technologies and service platforms, but its scenario has urban or regional restrictions.

However, ATS is more complicated, changeable, and understudied when compared to ITS. As mentioned by You et al. [10], component analysis, evolution prediction, and six other challenges must be addressed when creating ATS services, and current approaches have certain flaws and may be improved. One of these, component analysis, is closely tied to the internal attributes and relationships that characterize the ATS architecture and is specifically focused on the two entities that exchange information in the ATS, i.e., the information exchange pair (IEP).

The initial focus of information exchange research was on human relationships, but it has now evolved to include Internet data sharing situations. The research subject of the information exchange for the transportation system may be identified as the transportation entities that can be merged in pairs. Shen et al. [11] developed IoT-IDIVS, which incorporates data from transportation systems and can monitor vehicles in real-time with the assistance of roadside units. Gao et al. [12] proposed a vehicle-consensus scheme to realize traffic information retrieval and vehicle route management with information exchange. Jacobsson et al. [13] explored the automatic sharing of interoperable information on intermodal freight transportation systems. These studies utilize paired transportation entities, including travelers, carriers, infrastructures, etc., to discuss their data exchange process. However, IEPs in ATS also need to talk about the large-scale entity group and characterize the pair's particular impact connection, which is not covered in the previous study.

It is found that there is no corresponding research on IEP, and an appropriate method should satisfy the following criteria:

(1) The method can fulfill the demand of dynamic analysis in ATS architecture design.

(2) The method can be directly applied to various IEPs, and the application procedure is convenient and simple.

(3) The method can always meet the emerging application demands.

Simulation is a suitable strategy since there is a research demand for a dynamic analysis of the ATS design. Many researchers in the transportation field frequently use simulation to back up the viability of a proposal. The tools can be off-the-shelf simulation software [14–16] or a self-built simulation system platform [17–19], but the majority of them are based primarily on the defined scenarios to simulate and assess the functioning of certain entities. In the field of transportation, Kogler and Rauch [20] summarized the pertinent research on the analysis of multimodal and unimodal transportation supply chains using DES, pointing out that the existing research has an imprecise interpretation of the simulation model and scant details about the verification and validation process, and there are research gaps in many simulation details. Felde et al. [21] developed a transportation system simulator that enables parallel DESs on high-performance computers, but its current analysis of model validation and performance outcomes is insufficient. Sebastiani et al. [22] conduct DESs of urban BRT public transportation to optimize operations, but their scenarios are lightly constrained and concentrate more on energy consumption. Moreover, there is currently no method to support the description of the information exchange process or to apply it to the level of the transportation system architecture design.

To fill the current gaps, this work proposes a DES-based method for IEPs in ATS, named as DESIEP. The major contributions are summarized as follows:

(1) A modeling and simulation method is proposed to describe the IEPs in the ATS architecture. This method can also be applied to study diverse system structures.

(2) This method can visually describe the IEP and calculate the efficiency of information transfer. It will promptly provide feedback to the system for ATS

architecture design, which is convenient for users to design and modify.

(3) Through the building simulation model of the IEP for a concrete scenario, the results show that the model can be well compatible with the IEP in this scenario. The information retention of all links in each time step of the information exchange process can be counted, and the user can judge the rationality of the structure of the information interaction pairs by the value of the retention and the law of change.

The reminder in this paper is arranged as follows. In Section 2, some related work is presented to summarize the current challenges and related solutions in IEP. Section 3 introduces the related concepts and methods of IEP and DES. Section 4 describes the process and details of constructing the simulation. In Section 5, a scenario example is presented to demonstrate and analyze the simulation result. Finally, Section 6 concludes this study and discusses the future work.

2. Related Work

This section summarizes the challenges encountered in IEPs studies using simulation methods as well as related work to address them.

2.1. Emerging Challenges. In order to describe the interaction behavior of IEPs more accurately and make the research work efficient, three main challenges need to be faced, namely:

2.1.1. The Expression Ability of Exchange Behavior. The most basic function of IEPs is to express the logical control relationship between each module in the ATS architecture. Therefore, the simulation model of IEPs should have the ability to express the control relationship. The influence of this ability should include two aspects. One is that the information receiver changes with the information transmitted by the information producer, which is common in simulation scenarios for classical network communication [23] or data transmission [24]. The second is that the information generator includes a feedback mechanism based on the status of the information receiver, similar to how the state and control in a simulation of a traffic stream operate as a feedback loop to act constantly in real-time [25].

2.1.2. Description of the Amount of Information Transmitted. When the quantitative expression of ATS architecture is involved, the IEPs also need to express the amount of information transmitted per unit time. Therefore, the simulation model should be able to transmit information which is expressed discretely or describe the amount of information transmitted per unit time [26, 27].

2.1.3. Individual Differentiation. Different IEPs have different attributes, physical meaning, amount of received information and meaning, so the simulation model should be able to express the differences in the above points. Additionally, this would offer architecture-based customized configuration and have high levels of flexibility, stability, scalability, etc [28, 29].

2.2. Related Solutions. Analyzing the research methods that have been applied to IEPs, it is found that there are usually two research approaches: one is to build mathematical models, and the other is to build detailed ATS architectural models.

Build mathematical models: the simplest way is to directly set some basic parameter values. Most of the ATS architecture research is based on qualitative research, and IEPs mainly represent the logical control relationship between modules. As for the quantitative description, usually define some basic parameter values directly or according to the different levels set several parameters. But directly defining parameters can only extend the description of the results of qualitative analysis. It cannot accurately describe the information interaction on the specific interaction. So, a mathematical model related to the information receiver can be established, and it can be used to describe the amount of information transmitted by IEP [30, 31]. In this way, with the help of mathematical formulas, individual differences between different IEP can be expressed, and their sensitivity to receiving incoming information can be described. The mathematical model can express the individual differences of different IEPs, and the information amount of each IEP per unit time will change with the different information amount. Additionally, the model is optimized using data-driven concepts. For example, Hao et al. [32] optimize the decision equation based on rough set theory to facilitate car-following among cars with various features. The effect, which cannot be simply stated by a mathematical formula, will be significantly impacted if it is oriented to a complicated structure due to the implausible assumptions and laborious parameter calibration procedure. Therefore, some papers construct neural network models to describe IEPs [33–35]. However, none of these methods can effectively and intuitively obtain the physical meaning of IEP. In particular, the more complex the model is, the more difficult it is to understand its physical meaning.

Build detailed ATS architectural models: Research on the ATS architecture, there has been a lot of use system dynamics modeling for architecture. There is a split process in the modeling process. And IEP will be subdivided into multiple modules. Modules are connected by a fixed relation or a concrete equation, so IEPs can be viewed as a combination of several relationships.

Table 1 provides a thorough review of various strategies. In light of these methods, this paper investigates IEPS using the DES model. In Section 3, IEP and DES will be introduced in detail.

3. Concepts and Methods

3.1. Information Exchange Pair. Early on in the field of design, the idea of information exchange was employed to characterize design behavior [36]. It was progressively

Table 1: Challenges and representative solutions in the IEP (●: solved; ○: not-solved; ◎: partially).

Related solutions	The expression ability of exchange behavior	Description of the amount of information transmitted	Individual differentiation
Define some basic parameter	◎	◎	○
Establish a mathematical equation	●	◎	●
Construct the neural network model	◎	◎	○
Build detailed ATS architectural models	●	○	◎

described as the method of exchanging information amongst communicators, and today it is primarily used in computer science and Internet technology. The logical control relationship is represented by behaviors that are comparable in both physical objects and functional modules in ATS design. To exclusively express this control relationship in ATS architecture, researchers provide the idea of IEP.

IEP is different from the typical information exchange behavior. The behavior of information interaction is specifically directed at two individuals who have specific information interaction, which are particular objects with fine granularity. The physical granularity of objects in ATS architecture, however, is not just restricted to microscopic levels, but may also refer to a group with coarse granularity, as shown in Figure 1. And the items stated here pertain to more than just concrete physical things. Furthermore, the information exchange behavior typically only represents the logical relationship between the two described parties, while the IEP also needs to describe the specific influence relationship between the two, and the information transmitted is represented by the information stream contained in the IEP.

The relationship between the two must be fully outlined in the IEP. Information generator (IG), information receiver (IR), control relationship of sequential logic (CRSL), and information stream (IS) should all be included in the IEP as a whole. Some characteristics of the IEP have been described in Section 2, The following is a detailed description:

(1) *Independence*. All IS and CRSL are exclusive to the IG and IR of this IEP and have no connection to the other architecture components.

(2) *Closure*. There will be no external transmission of any IS or CRSL, which will only take place within this IEP.

(3) *Directionality*. IS is from IG to IR.

(4) *Information-Volume*. This is the data volume of IS delivered by IEP.

(5) *CRSL-Feedback-Mechanism*. In IEP, there is a CRSL whose direction is the direction of IS, i.e., usually from IG to IR. Due to its control relationship, the information transmission process will alter. Additionally, there will be information feedback effects, meaning that when IR gets information, it may respond by providing feedback to IG.

(6) *Physical-Meaning*. All processes of IEPs can be mapped in reality and find their realistic meaning.

IEP can describe the CRSL between various ATS architecture components, which is a further statement of the architecture relationship. The research on IEP enables users to design while also assisting scholars in their understanding of the interactions between components.

3.2. Discrete Event Simulation. A group of entities that interact and associate with certain rules in order to accomplish specific goals is referred to as a discrete event system. The discrete event system has discrete events, each of which takes place in a certain order or under specific circumstances [37].

After analyzing previous DES situations, the modeled items may often be split into different basic logical structural relationships, as shown in Figure 2 in the form of Petri nets.

In principle, DES may be used to replicate the IEPs of ATS since the internal sequential logic of IEPs in the ATS architecture can likewise be roughly separated into the aforementioned basic structures. Among DES models, the process model is based on specific process activities, and a comprehensive discrete event model is formed through the logical relationship between each process link. As shown in Figure 3, the bus's whole route, from departure to arrival, is simulated. Figure 3 shows the entire operation of the bus from the start to the end of the station. In Figure 3, These Modules ("BusSource," "LineToRoadnet," "Roadnet," "trafficmangement," el at.) respectively represent the factors affecting the efficiency of bus operation. Buses select specific routes according to the target stations and are affected by road structure and grade, traffic control facilities such as traffic lights, road conditions, possible emergencies, and queuing when entering the station. The whole process is complete when the bus completes its inbound behavior. Process simulation can describe the phases and processes of sequential flow. It is a technology based on process testing and quantitative analysis, whose essence is a numerical simulation technology based on running sequential processes. Process simulation may therefore effectively illustrate how IS is conveyed across IEPs.

This work constructs some fundamental process components in process simulation, and a process simulation model based on IEPs will be constructed through the disassembly and assembly of components. We can comprehend the functioning of IEPs through the statistics of information

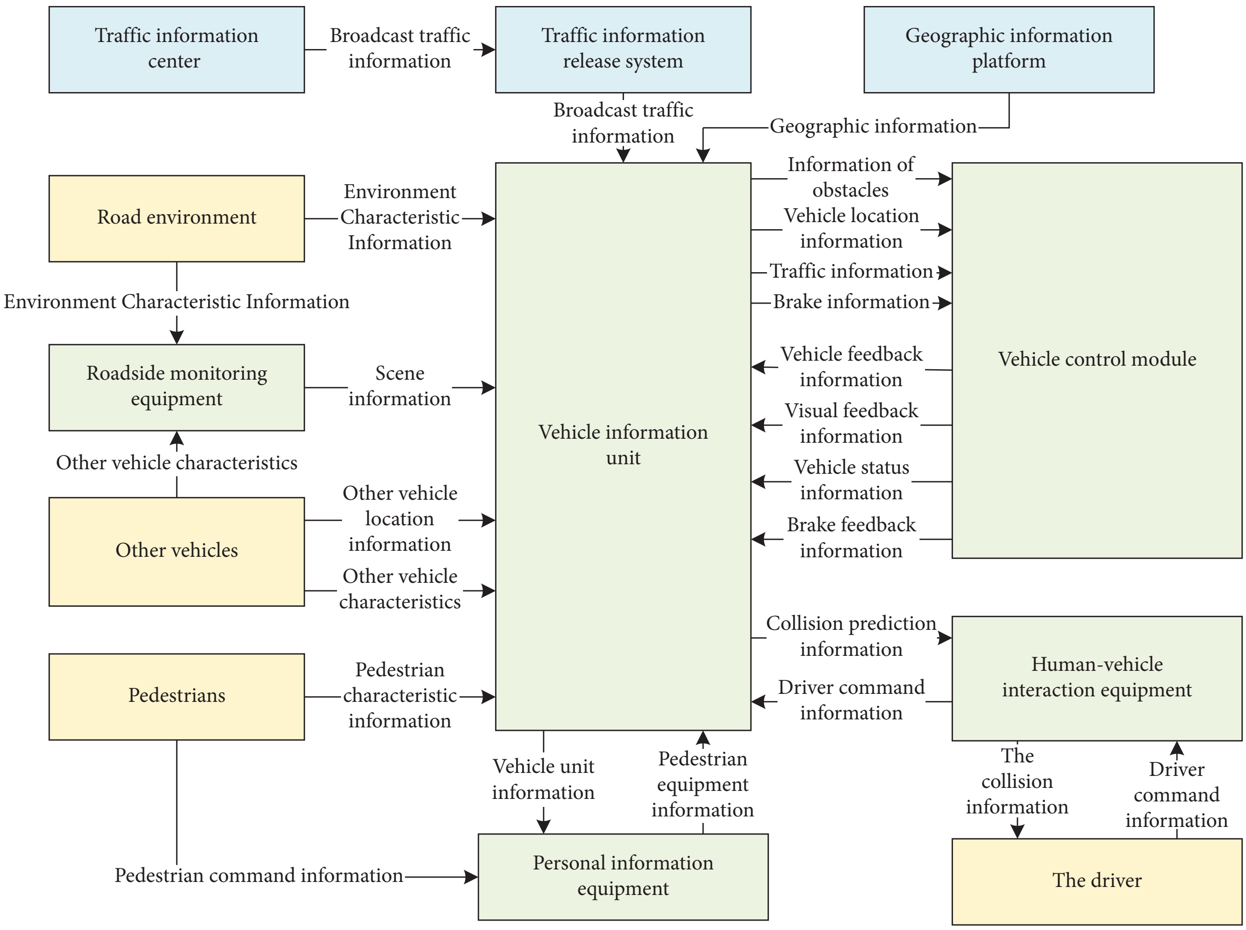

Figure 1: Example diagram of the ATS physical architecture.

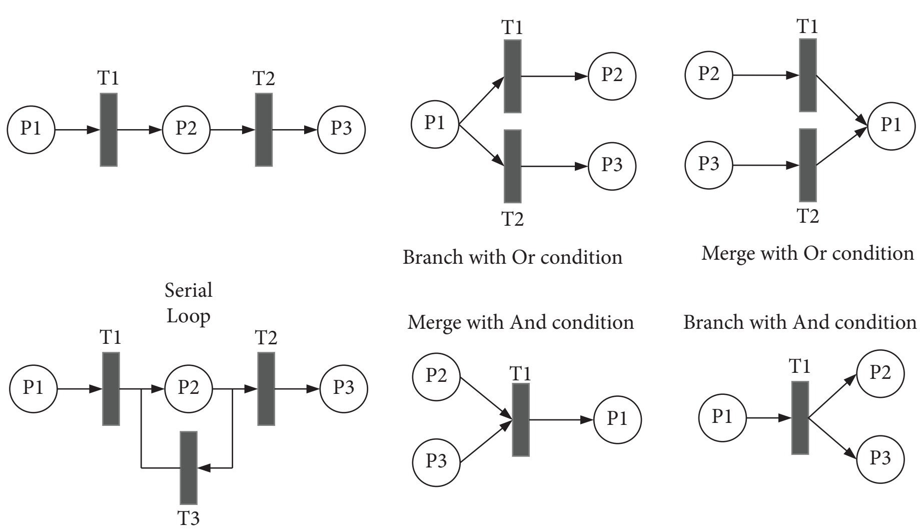

Figure 2: Basic logical relations.

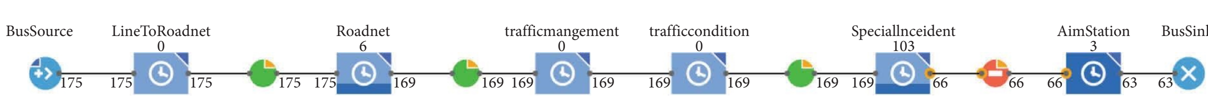

Figure 3: Discrete event simulation flow.

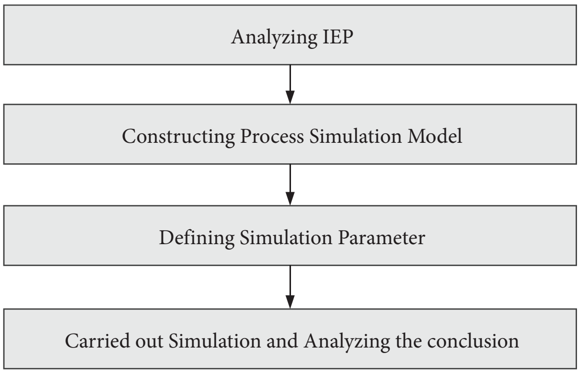

Figure 4: Overall workflow of simulation construction.

volume in each process module during simulation, and some calculation parameters can also be set to obtain the information desired by users.

4. Simulation Construction

The overall workflow of simulation construction is shown in Figure 4, which is divided into four parts, i.e., analyzing IEP, constructing process simulation model, defining simulation parameter, and drawing conclusion from simulation. The CRSL of IEP can be expressed intuitively through simulation. Regarding the information feedback mechanism that should also exist between IEPs, it is possible to track changes in the original link using the specific modifications to each link in the sequential process.

4.1. Analyzing IEP. IEPs in ATS are influenced by physical objects in the architecture and the IS between physical objects. The related process activity may be found by analyzing the physical object information of architecture that is provided in IEPs. The cornerstone for building process simulation models is process activities, and process activities may often be obtained through IEP in two different ways:

(1) Generally, in order to characterize IS transmitted by IEPs, architecture researchers would develop the unique process present in IEPs. Therefore, it is feasible to immediately locate relevant process activities utilizing the IG and IR of IEP.
(2) According to relevant data, users can query discrete activity events that are a part of the process. Then in accordance with the logical relationship (e.g., Or, And, Union, Serial, etc.), they can arrange and combine these activity events to obtain the process activities that are suitable for IEPs.

4.2. Constructing Process Simulation Model. The process activity model defines fundamental modules including Source, Sink, Delay, Split, Combine, Select, Hold, etc. Several modules can be merged to reflect the logical relationship mentioned above, and Figure 5 depicts their combined expressions.

The information entity is crucial to completing all process links in a process simulation. The full process simulation is finished when it is created from source and flows via each component module into sink in the direction of the connecting line. The process module can carry information entities and will specify particular functions upon initialization. The roles of the aforementioned modules and their corresponding construction features are as follows:

(1) *Source*. It produces information entities and is where all information entity processing begins. All processes begin with the generation of information flow, Source is the first component and has no upstream process activities.
(2) *Sink*. It acts as the end of the process for all information entities. All processes end with the collection of IS, Sink is the final component and has no downstream process activities.
(3) *Delay*. It is the basic component module. The module is delay if there are no exceptional events. The information entity will be stuck when passing through the module. Therefore, by giving its actual meaning, it is possible to characterize that an information entity is doing some activity when passing through the module. When modeling, delay is employed if there is just one process activity upstream and downstream of a process activity and the sequential information only remains in this location for a short while.
(4) *Split*. It divides a number of information entities. There will be several process activities downstream but only one upstream for the process activity that corresponds to this component. Examining if the two downstream processes are on the same logical timing level is crucial when modeling. Split will be utilized if the two processes are run simultaneously.
(5) *Combine*. It generates a new information entity by combining multiple existing information entities. Combine will be utilized if the process activity corresponding to the component contains more than one downstream process activity but only one upstream process activity, and there is a process activity corresponding to Split before that.
(6) *Select*. It provides multiple processing directions for information entities. This component's associated process activity is similar to Split, i.e., there are several downstream process activities. Only one of the branches, though, can be selected to carry out the further processing steps. For instance, while approaching a fork in the road, a person can only proceed in one direction. Select will be employed in this case.
(7) *Hold*. It prevents the information object from moving on to the following the module, forcing it to stay in the current one. The process activities corresponding to this component are subject to clear restrictions. E.g., when there are too many

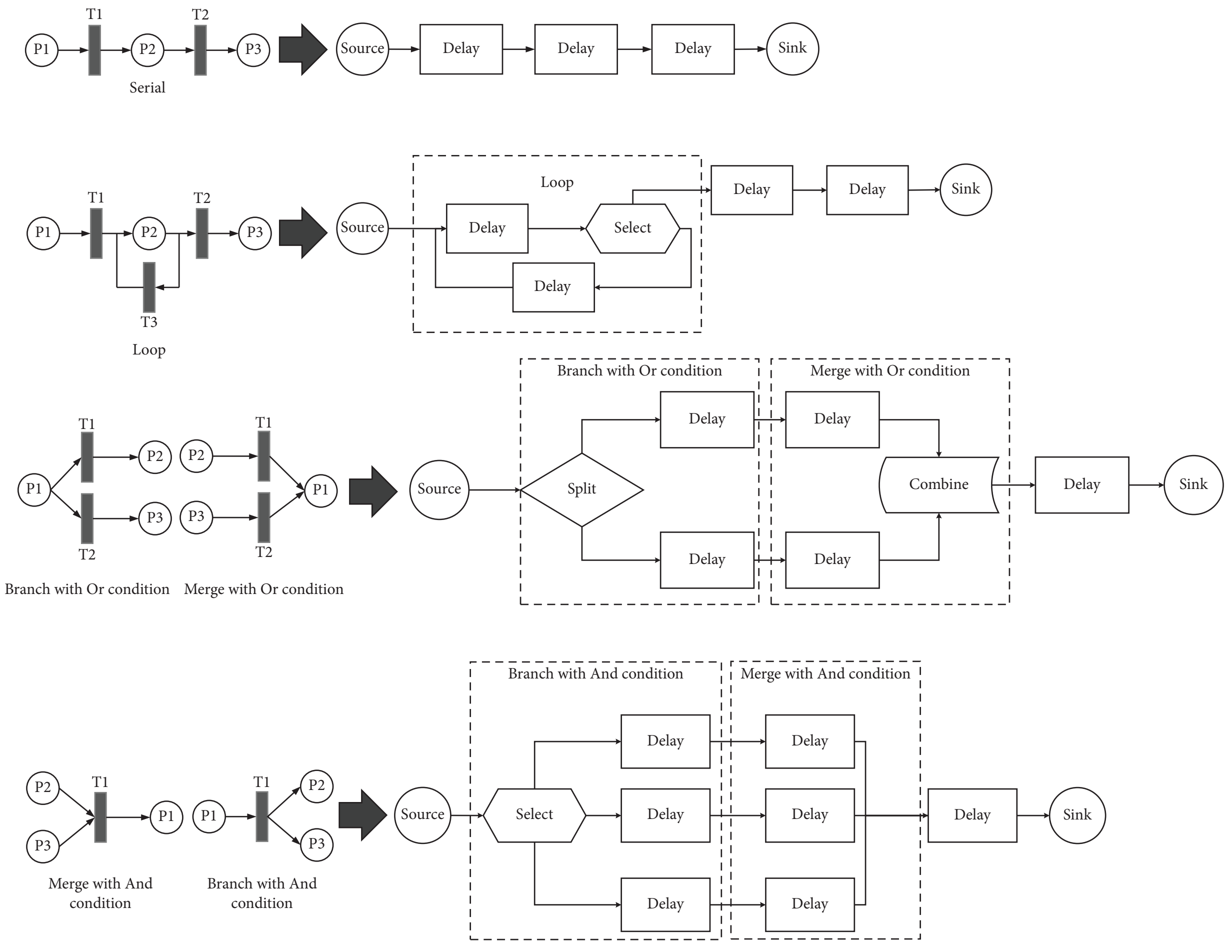

Figure 5: Expressing logical relationships in process simulation.

passengers in the subway station during peak hours, the staff would set up barriers to keep people out until the number of passengers lowered to a particular threshold. Hold can be used to illustrate this process.

Additionally, users may regulate how the aforementioned modules behave by establishing conditions. E.g., the number limit can be specified. The effectiveness of source producing information entities may decrease as the number of reaching sinks exceeds a particular threshold.

Following their extraction from IEPs, process activities are converted into process components based on the characteristics of each component. The aforementioned component modules are then joined by directed lines to create a process simulation model based on the logical relationships before and after the process activities.

4.3. Defining Simulation Parameter. There are two kinds of parameters for process simulation. The settings for the simulation's general running are one (e.g., simulation step length, simulation time, amount of information expressed by process entities, etc.). The second is the parameters set for the function of process modules, which should account for the actual basis and be tied to the physical meaning of the process activity module. Below is an explanation of the aforementioned ideas with an example.

Figure 6 depicts a process simulation representation of the aforementioned concept. The parameters for the simulation's running parameters are shown in Table 2. Several ones are set according to their physical meaning, such as the simulation step size of 10 ms for the process in 1 s and the IGs' recurring generation of 10 kb data.

Meanwhile, when setting the parameters of flow module functions, the actual situation is the reference, and the following are some examples: (1) Hard disk drives (HDDs) or solid-state drives (SSDs) are usually employed as backup storage. HDDs operate at a speed of roughly 120 M/s, whereas SSDs operate at a speed of 500 M/s to 3500 M/s. In this case, the storage speed of the simulation is set to 1000 M/s, and the time required for backup storage is 0.01 ms. (2) For video data, a two-stage target detection algorithm (detection speed is about 11 frames/s) or a single-stage target detection algorithm (detection speed ranges from 5.4 frames/S–65.8 frames/s) is usually adopted [38–40]. We selected 10 frames as the default speed for algorithm processing. Assuming that a frame of $1280 * 720$ video is about 10 kb, it takes about 0.4 s to process entity. (3) The speed of 5G data transmission is set to 1 Gb/s, and the time required for data transmission is 0.01 ms.

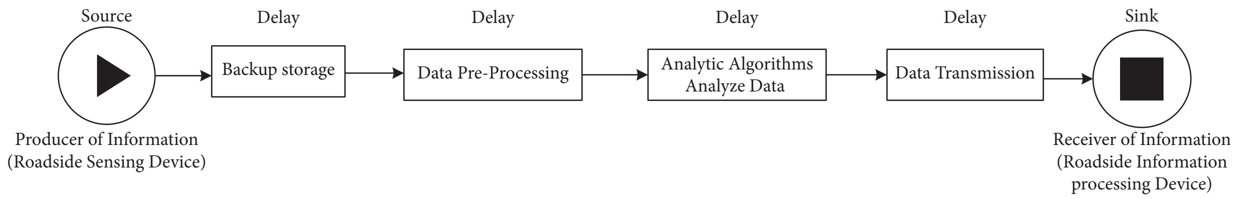

Figure 6: Diagram of process simulation (from "roadside sensing device" to "roadside information processing device").

Table 2: Table of simulation parameters.

Parameter names	Parameter values	Parameter units
Simulation time	1	Second (s)
Simulation step size	10	Millisecond (ms)
Process entity	10	Kilobyte (kb)
Backup storage (delay)	0.01	Millisecond (ms)
Data preprocessing (delay)	0.5	Millisecond (s)
Analytic algorithms analyze data (delay)	0.2	Millisecond (s)
Data transmission (delay)	0.01	Millisecond (ms)

5. Simulation Effect Analysis

The simulation scenario exemplified in this paper is shown in Figure 7 (see the Tables 3–5 for module meanings), in which information about environmental feature collected by the route is processed and transmitted before eventually entering the roadside sensing device. The information on environmental features collected from routes is divided into two categories, i.e., road pavement data and road structure data. They disassemble and model the format specification, transmission, and storage of data, respectively, and then the processed data is fused and collected into the roadside sensing device.

The structure of the simulation model has been determined not to change in the simulation process, and the set parameters are fixed without setting random variables. The simulation is conducted for the structure itself; the final simulation results will not change with the number of simulation. In this scenario, we assume that the data transmission rate over the line is constant. Therefore, the process of transmitting IS is considered to be a stable transmission process and can be divided into a certain time granularity. This time, the simulation time is 1s, and the simulation step is 10 ms. During transmitting IS of the environmental feature, the entities in all the processes represent a single data volume of 10 kb.

Different output parameters can be set to characterize the impact of user demands. E.g., we can directly count the number of information entities received by Sink throughout each simulation step if we want to find out the final response status to the information transmission of IR. And the period between modules is approximately 0.18, which is related to the simulation scenario.

As shown in Figure 8, the X-axis is simulation step, which records the duration of simulation, and the Y-axis is simulation count, which records the statistics of the transmitted process entities. The IS sent by IG goes through each link in the process, and the time when the IS reaches each module can be counted in simulation. We counted the time when IS arrived at the IR module and counted the number of IS arriving at IR at each moment according to the time series, so that the change in IS quantity received by IR with the simulation time could be obtained. Figure 8 shows the amount of IR received accumulation at each moment, and the relationship diagram shown in the figure is obtained in chronological order. So, Figure 8 reflects the change of the amount of IS received by IR with the simulation time. Firstly, we found that IR begins to receive information at 0.07 s. Then the volume of information keeps on growing over time, and a total of 63.7 Mb of data is received in a single second. When designing architecture, the information processing effectiveness of IEPs can be utilized as a guide to appropriately set the attribute values of the associated physical objects.

In the process, IG will set the information generation situation, and the process entities will flow through each module of the simulation. In this process, the number of process entities in each module of each simulation step is counted. The users can obtain the location of the information blockage from the output data. The location of the information jam is the bottleneck point of the simulation. By keeping track of the amount of information entities held in each Delay, the running bottleneck of the process can be determined. Figure 9 shows the number of information entities counted by each delay at the first second. The result indicates that while the majority of the information in Delay is dynamically balanced, some of it exhibits abnormalities. In a normal net, there are upstream and downstream modules except IG and IR. If the information received by the module from the upstream module cannot be consumed in time, the information will accumulate continuously. In a normal system structure, each component has an upper limit for storing information. If the information accumulates continuously, it will reach the storage capacity of the module, resulting in information blockage in the system. In reality, there is no actual object that can hold information indefinitely. Therefore, abnormal links should be dealt with first in optimization to avoid information blockage in system

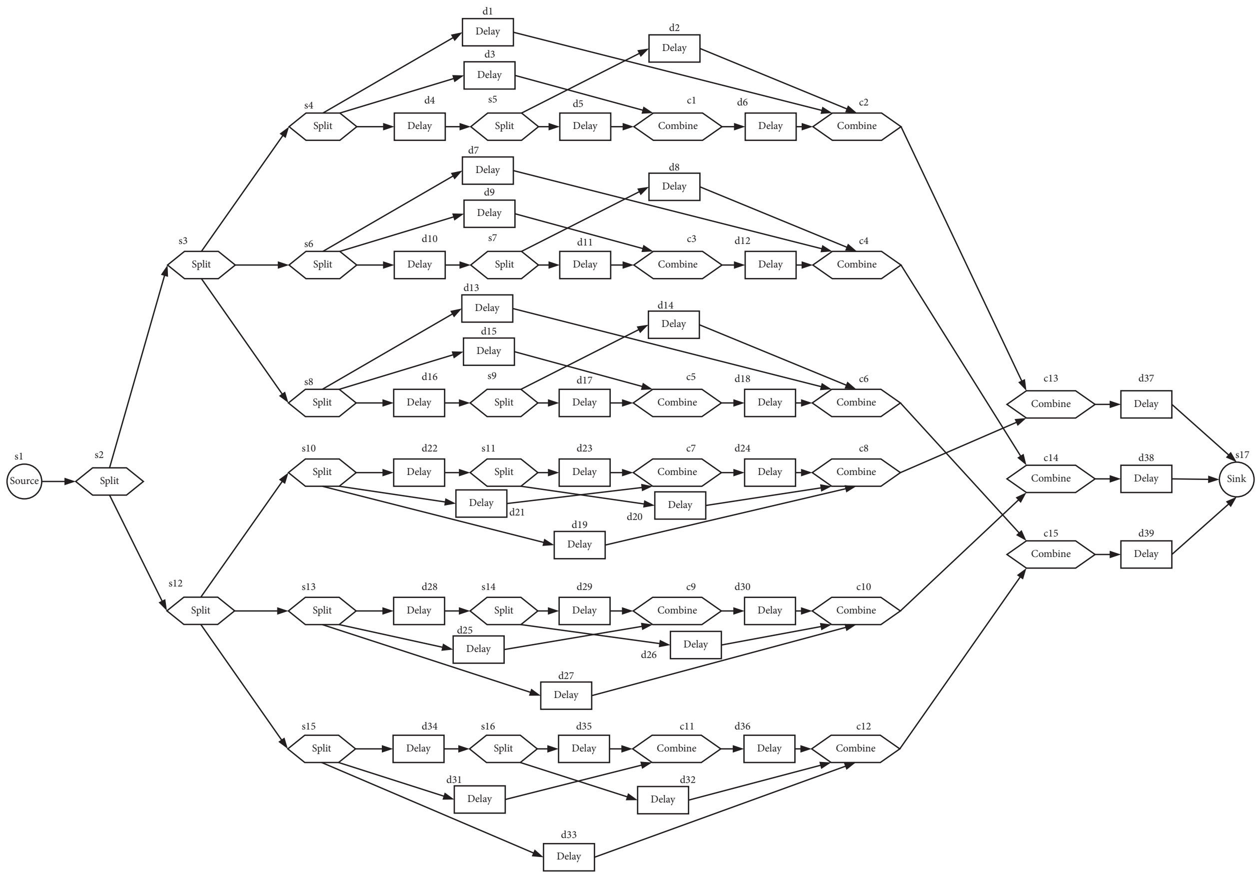

Figure 7: IEPs simulation (from “route” to “roadside sensing device”).

architecture. Such abnormal links in the process might be prioritized for optimization when the ATS architecture is optimized based on the sequential logic in the architecture.

Furthermore, the eight special modules in Figure 9 are selected, and Figure 10 displays the temporal relationship between the quantity of internal storage entities. For each individual module, the change in the quantity of internal storage has an obvious periodicity. The period among modules is approximately 0.18, which is related to the simulation scenario. Meanwhile, it can be found that the modules located upstream of the same Combine module have basically the same value and trend, e.g., d7 and d12, or d13 and d18. Notably, d37 showed a delayed change trend with respect to d38 and d39, which may have been a result of the scenario setup or may have served as the point of penetration for the anomaly investigation.

Scenario experiments show how DESIEP may be used to characterize the architecture and its elements in an intuitive and effective manner. On the one hand, the process simulation model constructed based on IEPs analysis clearly describes the architecture structure and the transfer of IS. On the other hand, the execution of the simulation visualizes the internal operation of the architecture and the CRSL, and the simulation results can efficiently and accurately assist researchers in parsing, understanding, and improving the system designs in ATS.

In this case, we can be clearly observed that different technologies have direct influences on simulation parameter settings, such as different storage technologies affecting data storage time and different data transmission technologies affecting data transmission time. All these are directly related to the efficiency of the transmission of information flow. When designing the architecture, researchers can use this method to find the specific impact of different technologies on the efficiency of information transfer between architectural elements. Researchers can also adjust the architecture according to the degree of impact. For the already designed architecture, it can also evaluate and find the position of the architecture to be improved, so as to facilitate the researchers to adjust and optimize the already designed architecture. In addition, the results obtained by simulation statistics can also confirm the correctness of the structure of the IEP. The accessibility of the structure can be guaranteed if there is an information flow that completes the whole process. Recording each module can provide feedback on the change in sensitivity of the overall architecture to the transmitted information, which is convenient for users to observe the boundedness of the IEP.

Table 3: Table of simulation module (source/split/sink).

Module IDs	Module roles	Module names	Upstream modules	Downstream modules
s1	Source	Route	—	s2
s2	Split	Splitting data stream	s1	s3, s12
s3	Split	Road raw data format division	s2	s4, s6, s8
s4	Split	Standardized disassembly of road video data	s3	d1, d3, d4
s6	Split	Standardized disassembly of road millimeter wave radar data	s3	d7, d9, d10
s8	Split	Standardized disassembly of road lidar data	s3	d13, d15, d16
s12	Split	Road structure raw data format distinction	s2	s10, s13, s15
s10	Split	Standardized dismantling of road structure video data	s12	d22, d21, d19
s13	Split	Road structure millimeter wave radar data standardized disassembly	s12	d28, d25, d27
s15	Split	Standardized disassembly of lidar original data of road structure	s12	d34, d31, d33
s5	Split	Distinguish the road surface video data which has be stored	d4	d2, d5
s7	Split	Distinguish the road surface millimeter microwave radar data which has be stored	d10	d11
s9	Split	Distinguish the road surface lidar data which has be stored	d16	d14, d17
s11	Split	Distinguish the road structure video data which has be stored	d22	d23, d20
s14	Split	Distinguish the road structure millimeter microwave radar data which has be stored	d28	d29
s16	Split	Distinguish the road structure lidar data which has be stored	d34	d32, d35
s17	Sink	Roadside sensing device	d37, d38, d39	—

Table 4: Table of simulation module (delay).

Module IDs	Module roles	Module names	Upstream modules	Downstream modules
d1	Delay	Road surface video data transfer without specification and storage	s4	c2
d3	Delay	Road surface video data transfer without storage	s4	c1
d4	Delay	Road surface video data format normalization	s4	s5
d7	Delay	Road surface millimeter wave radar data transfer without specification and storage	s6	c4
d9	Delay	No specification of road surface millimeter wave radar data storage	s6	c3
d10	Delay	Road surface millimeter wave radar data format normalization	s6	s7
d13	Delay	Road surface lidar data transfer without specification and storage	s8	c6
d15	Delay	No standardized road surface lidar data storage	s8	c5
d16	Delay	Road surface lidar data format normalization	s8	s9
d22	Delay	Road structure video data format normalization	s10	s11
d21	Delay	Road structure video data storage without specification	s10	c7
d19	Delay	Road structure video data transfer without specification and storage	s10	c8
d28	Delay	Road structure millimeter wave radar data format normalization	s13	s14
d25	Delay	Mm-wave radar data storage without specification of road structure	s13	c9
d27	Delay	Mm-wave radar data transfer of road structures without specification and storage	s13	c10
d34	Delay	Road structure lidar data format normalization	s15	s16
d31	Delay	Road structure lidar data storage without specification	s15	c11
d33	Delay	Road structure lidar data transfer without specification and storage	s15	c12
d2	Delay	Road surface video data transfer without storage	s5	c2
d5	Delay	Standardized road surface video data storage	s5	c1
d6	Delay	All stored road surface video data transfer	c1	c2
d8	Delay	Road surface millimeter microwave radar data transfer without storage	s7	c4
d11	Delay	Standardized road surface millimeter microwave radar data storage	s7	c3
d12	Delay	All stored road surface lidar data transfer	c3	c4
d14	Delay	Road surface lidar data transfer without storage	s9	c6
d17	Delay	Standardized road surface lidar data storage	s9	c5
d18	Delay	All stored road surface lidar data transfer	c5	c6
d20	Delay	Road structure video data transfer without storage	s11	c8
d23	Delay	Standardized road structure video data storage	s11	c7
d24	Delay	All stored road structure video data transfer	c7	c8
d26	Delay	Road structure millimeter microwave radar data transfer without storage	s14	c10
d29	Delay	Standardized road structure millimeter microwave radar data storage	s14	c9
d30	Delay	All stored road structure lidar data transfer	c9	c10
d32	Delay	Road structure lidar data transfer without storage	s16	c12
d35	Delay	Standardized road structure lidar data storage	s16	c11
d36	Delay	All stored road structure lidar data transfer	c11	c12
d37	Delay	Multi-device video data processing	c13	s17
d38	Delay	Multi-device millimeter wave radar data processing	c14	s17
d39	Delay	Multi-device lidar data processing	c15	s17

Table 5: Table of simulation module (combine).

Module ID	Module role	Module name	Upstream modules	Downstream modules
c1	Combine	Collect all stored road surface video data	d3, d5	d6
c2	Combine	All road surface video data collection	d1, d2, d6	c13
c3	Combine	Collect all stored road surface millimeter microwave radar data	d9, d11	d12
c4	Combine	All road surface millimeter microwave radar data collection	d7, d8, d12	c14
c5	Combine	Collect all stored road surface lidar data	d15, d17	d18
c6	Combine	All road surface lidar data collection	d13, d14, d18	c15
c7	Combine	Collect all stored road structure video data	d21, d23	d24
c8	Combine	All road structure video data collection	d19, d20, d24	c13
c9	Combine	Collect all stored road structure millimeter microwave radar data	d25, d29	d30
c10	Combine	All road structure millimeter microwave radar data collection	d26, d27, d30	c14
c11	Combine	Collect all stored road structure lidar data	d31, d35	d36
c12	Combine	All road structure lidar data collection	d32, d33, d36	c15
c13	Combine	video data fusion	c2, c8	d37
c14	Combine	Millimeter wave radar data fusion	c4, c10	d38
c15	Combine	Lidar data fusion	c6, c12	d39

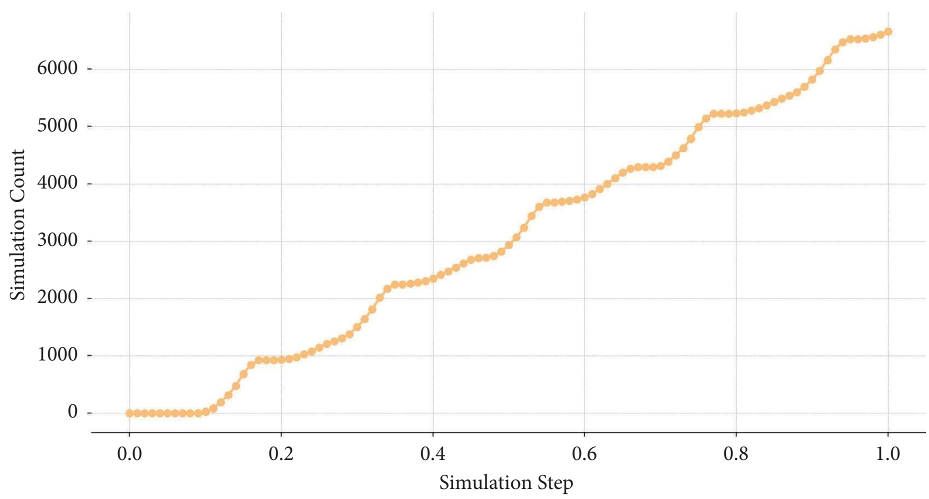

Figure 8: Number of entities having completed the process as a function of simulation time.

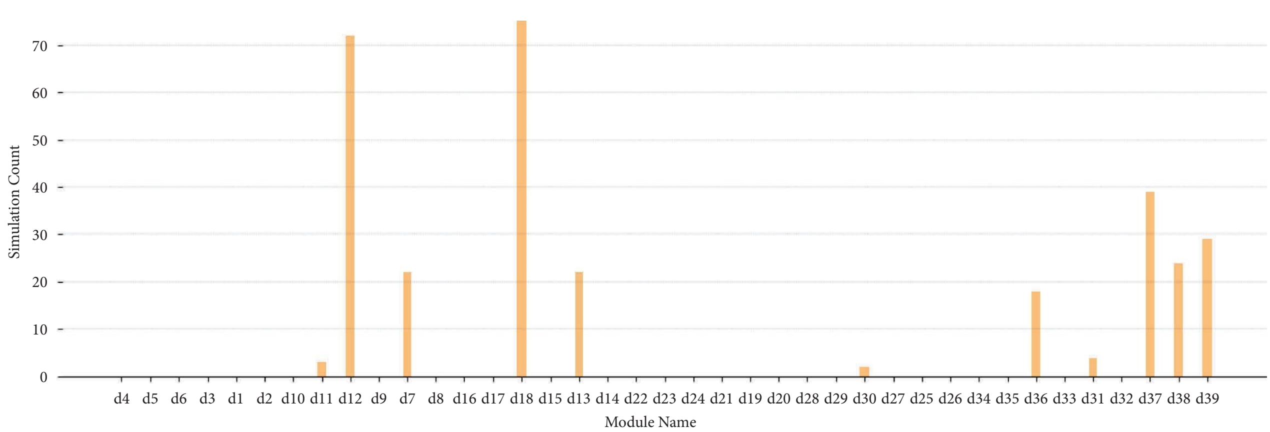

Figure 9: Number of entities stored in each module after simulation.

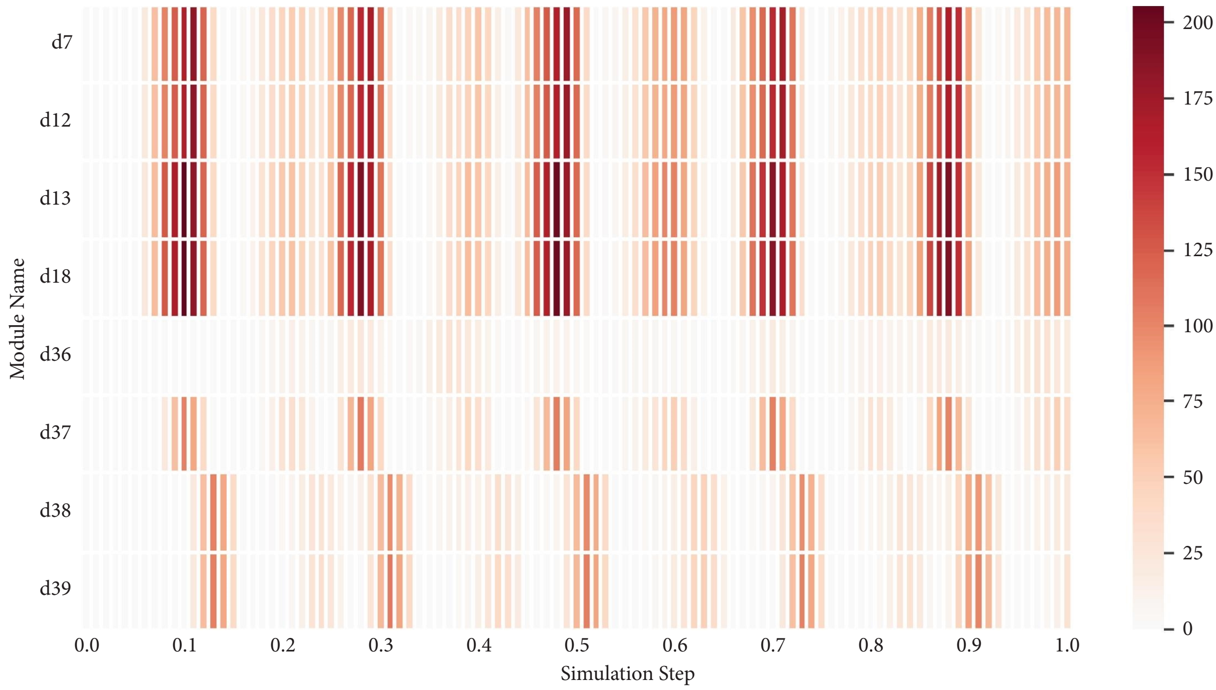

FIGURE 10: Timing heatmap of the number of entities stored in each module.

6. Conclusions

The above chapter introduces the application of discrete event simulation in the modeling of the ATS information interaction surface through application examples. In essence, this work is a supplement and extension of ATS architecture research and effectively solves the problem that most current simulation studies on ATS architecture modeling do not pay attention to the operating mechanism of IEP. There are several advantages to establish a discrete event simulation system for IEP:

(1) *Grasp the overall changes*: Researchers can obtain the changes of each part of the target object with the simulation time during the simulation process.

(2) *Quantitative impact*: Different statistical indicators are set according to the information flow changes in the simulation. When the architecture design or related technologies used in the architecture change, it is convenient for researchers to directly evaluate the degree of change according to the statistical situation of the indicators.

(3) *Dynamic adjustment*: Researchers can adjust the architecture according to the simulation results. After the adjustment, the architecture can be simulated again, and the adjustment can be evaluated objectively by comparing the simulation results before and after the adjustment.

Research on the CRSL between its entities can assist relevant researchers in more thoroughly analyzing the running mechanism, which is driven by both internal demands and external technologies of the system. The relationship between various entities may well be efficiently described using the DES for IEPs in ATS suggested in this research. Researchers could use this to enhance the architecture's pertinent design and do more research on the diagnosis, evaluation, verification, and optimization.

Many different industries can benefit from DES. The simulation modeling technique for IEPs in the ATS architecture described in this work, namely DESIEP, can also be used to examine other structures with the same characteristics, such as the process of Internet information transmission. Similarly, DES can be applied to study information-interactive system architecture. Nonetheless, it should be noted that modeling the design of a complicated system will become increasingly challenging.

IEP simulation and architecture simulation could be combined in future research. Through the simulation calculation of IEPs, the volume of IS between components in the architecture will be obtained, and the architecture simulation might benefit from receiving the feedback information to improve its accuracy.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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References

[1] L. J. Yue, F. Wang, and C. X. Zhao, "Cooperative application and command and control assumption of unmanned combat system in sea battlefield," *Command Control and Simulation*, vol. 44, no. 4, pp. 1–17, 2022.

[2] R. M. Gan, Z. K. Jia, Y. Y. Wang, J. Li, and Z. Xiao, "Optimization of network transmission link in UAV assisted vehicle network," *Journal of Terahertz Science and Electronic Information Technology*, vol. 20, no. 7, pp. 673–677, 2022.

[3] Z. Xue, B. Ai, G. Y. Ma, Y. Y. Ma, and G. Q. Li, "A novel multiple access approach for 5G-R massive IoT scenario," *Journal of the China Railway Society*, vol. 44, no. 2, pp. 56–63, 2022.

[4] Z. Chen, Y. Lin, L. Wu, S. Cheng, and P. Lin, "Development of a capacitor charging based quick I-V curve tracer with automatic parameter extraction for photovoltaic arrays," *Energy Conversion and Management*, vol. 226, Article ID 113521, 2020.

[5] United States Department of Transportation, "Architecture reference for cooperative and intelligent transportation," 2022, https://www.arc-it.net/.

[6] Its Canada, "Intelligent transportation system Canada," 2022, https://www.itscanada.ca/index.html.

[7] F. Zhang, "The current situation and development thinking of the intelligent transportation system in China," in *Proceedings of the 2010 International Conference on Mechanic Automation and Control Engineering*, pp. 2826–2829, IEEE, Wuhan, China, June 2010.

[8] J. Michal and Z. Moler, "Modular framework for simulation modelling of interaction-rich transport systems," in *Proceedings of the 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, pp. 2152–2159, IEEE, Indianapolis, IN, USA, October 2013.

[9] R. Salazar-Cabrera and A. Pachon, "Methodology for design of an intelligent transport system (ITS) architecture for intermediate colombian city," *Ingeniería y competitividad*, vol. 21, no. 1, pp. 49–62, 2019.

[10] L. You, J. He, W. Wang, and M. Cai, "Autonomous transportation systems and services enabled by the next-generation network," *IEEE Network*, vol. 36, no. 3, pp. 66–72, 2022.

[11] X. Shen, Y. Lu, Y. Zhang, X. Liu, and L. Zhang, "An innovative data integrity verification scheme in the Internet of things assisted information exchange in transportation systems," *Cluster Computing*, vol. 25, no. 3, pp. 1791–1803, 2022.

[12] J. Gao, G. Manogaran, T. N. Nguyen, S. Kadry, C. H. Hsu, and P. M. Kumar, "A vehicle-consensus information exchange scheme for traffic management in vehicular ad-hoc networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 10, pp. 19602–19612, 2022.

[13] S. Jacobsson, P. O. Arnäs, and G. Stefansson, "Automatic information exchange between interoperable information systems: potential improvement of access management in a seaport terminal," *Research in Transportation Business and Management*, vol. 35, Article ID 100429, 2020.

[14] W. ShangGuan, J. Yu, B. Cai, and J. Wang, "Research on unsigned intersection control method based on cooperative vehicle infrastructure system," in *Proceedings of the 2017 Chinese Automation Congress (CAC)*, pp. 6436–6441, IEEE, Hangzhou, China, November 2019.

[15] Y. Li, Y. Song, T. Zheng, and H. Feng, "TransModeler based implementation of autonomous vehicular platoon control," in *Proceedings of the 2017 29th Chinese Control and Decision Conference (CCDC)*, pp. 4087–4092, IEEE, Chongqing, China, May 2017.

[16] M. Tahmidul Haq, F. Ahmed, and K. Ksaibati, "Estimating passing sight distances for overtaking truck platoons–Calibration and validation using VISSIM," *International Journal of Transportation Science and Technology*, vol. 11, no. 2, 2021.

[17] M. İ. Akbaş, C. A. Long, S. K. Hanumanthu, E. Anderson, and R. Razdan, "FpolyOS: A simulation platform to explore breakthrough concepts in intelligent transportation," in *Proceedings of the 2019 SoutheastCon*, pp. 1–6, IEEE, Huntsville, AL, USA, April 2019.

[18] X. Koutsoukos, G. Karsai, A. Laszka et al., "SURE: a modeling and simulation integration platform for evaluation of secure and resilient cyber–physical systems," *Proceedings of the IEEE*, vol. 106, no. 1, pp. 93–112, 2018.

[19] M. Aramrattana, T. Larsson, J. Jansson, and A. Nåbo, "A simulation framework for cooperative intelligent transport systems testing and evaluation," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 61, pp. 268–280, 2019.

[20] C. Kogler and P. Rauch, "Discrete event simulation of multimodal and unimodal transportation in the wood supply chain: a literature review," *Silva Fennica*, vol. 52, no. 4, 2018.

[21] J. Z. Felde, C. Alias, and G. Alexander, "Comparing generic and dedicated tools of discrete-event simulation for examining inland waterway transportation services," in *Proceedings of the 2022 IEEE 6th International Conference on Logistics Operations Management (GOL)*, pp. 1–10, IEEE, Strasbourg, France, June 2022.

[22] M. T. Sebastiani, R. Lüders, and K. V. O. Fonseca, "Evaluating electric bus operation for a real-world BRT public transportation using simulation optimization," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 10, pp. 2777–2786, 2016.

[23] L. Wang, R. Iida, and A. M. Wyglinski, "Vehicular network simulation environment via discrete event system modeling," *IEEE Access*, vol. 7, pp. 87246–87264, 2019.

[24] S. Treber and G. Lanza, "Transparency in global production networks: improving disruption management by increased information exchange," *Procedia CIRP*, vol. 72, pp. 898–903, 2018.

[25] H. Yang and H. Rakha, "Feedback control speed harmonization algorithm: methodology and preliminary testing," *Transportation Research Part C: Emerging Technologies*, vol. 81, pp. 209–226, 2017.

[26] N. E. Friedkin, A. V. Proskurnikov, R. Tempo, and S. E. Parsegov, "Network science on belief system dynamics under logic constraints," *Science*, vol. 354, pp. 321–326, 2016.

[27] B. Kanti Bala, F. Mohamed Arshad, and K. M. Noh, "System dynamics," *Modeling and Simulation*, p. 274, Springer, Berlin, Germany, 2017.

[28] D. J. van der Zee, "Model simplification in manufacturing simulation–Review and framework," *Computers & Industrial Engineering*, vol. 127, pp. 1056–1067, 2019.

[29] S. Robinson, *Simulation: The Practice of Model Development and Use*, Bloomsbury Publishing, London, UK, 2014.

[30] M. Morrison, *Reconstructing Reality: Models, Mathematics, and Simulations*, University of Oxford, Oxford, UK, 2015.

[31] B.-X. Dong, M. Shan, and B.-G. Hwang, "Simulation of transportation infrastructures resilience: a comprehensive review," *Environmental Science and Pollution Research*, vol. 29, no. 9, pp. 12965–12983, 2022.

[32] S. Hao, L. Yang, and Y. Shi, "Data-driven car-following model based on rough set theory," *IET Intelligent Transport Systems*, vol. 12, no. 1, pp. 49–57, 2018.

[33] X. Ma, H. Yu, Y. Wang, and Y. Wang, "Large-scale transportation network congestion evolution prediction using deep learning theory," *PLoS One*, vol. 10, no. 3, Article ID 119044, 2015.

[34] A. Mukherjee, D. K. Jain, P. Goswami, Q. Xin, L. Yang, and J. J. Rodrigues, "Back propagation neural network based cluster head identification in MIMO sensor networks for intelligent transportation systems," *IEEE Access*, vol. 8, pp. 28524–28532, 2020.

[35] Z. Lv, R. Lou, and A. K. Singh, "AI empowered communication systems for intelligent transportation systems," *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 7, pp. 4579–4587, 2021.

[36] A. D. Christian and W. P. Seering, "A model of information exchange in the design process," in *Proceedings of the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, vol. 17179, pp. 323–328, American Society of Mechanical Engineers, St. Louis, MO, USA, August 1995.

[37] C. G. Cassandras and S. Lafortune, *Introduction to Discrete Event Systems*, Springer US, New York, NY, USA, 2008.

[38] K. Wang and X. Han, "Real-time vehicle detection based on optimized You only look once V2 algorithm," *Journal of University of Jinan (Science and Technology)*, vol. 34, no. 5, pp. 443–449, 2020.

[39] Z. Liu, Y. Zhu, and H. Wang, "Multi-target real-time detection based on convolutional neural network," *Computer Engineering and Design*, vol. 40, no. 4, pp. 1085–1090, 2019.

[40] J. Yang, X. Wang, and H. Lin, "Review of one-stage vehicle detection algorithms based on deep learning," *Computer Engineering and Applications*, vol. 58, no. 7, pp. 56–67, 2022.