Modeling & Simulation-Based Problem Solving Process in Sustainable Living Lab

Changbeom Choi 1, Seungho Yang 2, Seon Han Choi 3,* and Sooyoung Jang 4,*

1 Department of Computer Engineering, College of Information Technology, Hanbat National University, Daejeon 34158, Korea; cbchoi@hanbat.ac.kr
2 Department of Urban Engineering, College of Construction, Environment & Design, Hanbat National University, Daejeon 34158, Korea; sh.yang@hanbat.ac.kr
3 Department of IT Convergence and Application Engineering, College of Engineering, Pukyong National University, Busan 48513, Korea
4 Electronics and Telecommunications Research Institute, Daejeon 34129, Korea
* Correspondence: shchoi@pknu.ac.kr (S.H.C.); sy.jang@etri.re.kr (S.J.); Tel.: +82-051-629-6240 (S.H.C.); +82-042-860-5289 (S.J.)

Abstract: Modern society consists of various groups according to their respective interests. The importance of the citizen participation decision-making process in which such various groups get involved in the numerous decision-making of the society has been emerging. The living lab (LL) can be a sustainable approach in such a modern society because all stakeholders can participate in the problem-solving process. In LL, every group communicates, defines their problems, and discusses with experts to find the best solution. For this process to work effectively, the discussions should be based on clear scientific evidence instead of vague words. This study introduces the modeling and simulation (M&S) process to establish a theoretical basis to help the participants in LL identify problematic situations and analyze the solutions. This process involves discrete event system formalism with a set-theoretical modular form among various modeling and simulation theories and the execution environments. Based on them, participants can reuse or extend the existing simulation model to accelerate the problem-solving process of LL. The case study for multi-modal transit station analysis demonstrates the effectiveness of M&S in LL.

Keywords: modeling & simulation; Sustainable Living Lab; decision-making; policy assessments

1. Introduction

Urban spaces and services provided by the city government are the results of numerous decision-making in various administration fields. Citizens live in physical spaces that reflect the ideas and logic of urban planners, designers and developers, and receive administrative services determined by city government. All of them are based on the results of large and small decision-making. The decision-making process in city government can be classified according to the subjects participating in the process and the size of their influence on that process [1]. A representative type is a method in which decisions are made by a small group of experts, and the opposite is the citizen participation type. Whereas in the past, top-down decision-making process was more common, as society became more diversified along with technological progress, the importance of citizen participation in the decision-making process emerged [2–4]. Citizen participation in government decision-making might be time-consuming and costly, and lead to bad policy decisions according to participating groups; however, it also has the advantages that it is more democratic, educational, and better policy-making and implementation can derived if it works well [5].

Following the development of information technology (IT) infrastructures and services, various society members can easily interact, express their opinions and participate in defining and solving problems. Society’s investment in the infrastructure for gathering
information and estimating the possible results accelerates these changes. These types of
movements are known as Living Labs (LLs) [6]. LLs are an open innovation ecosystem for
society members used to (a) identify problems from their lives and (b) to propose solutions.
The LL integrates the research and innovation processes within a public–private–people
partnership [7,8]. LL is a tool and platform that can be used effectively in the process of
citizen participating decision-making in urban planning and design in terms of citizens
finding practical problems in real life and directly participating in solving those problems.
Therefore, the disadvantages shown in the citizen participation decision-making process
(i.e., time-consuming, costly, and possibility of worse decision-making) can be equally
problematic in LL, as well. Because more people can easily participate in decision-making
process through LL platform compared to general citizen participation process, such
disadvantages of the citizen participation decision-making described above can become
more prominent. For example, the members of LLs have different levels of scientific
knowledge, which makes in-depth discussion and consensus difficult. Conversely, a
solution from LLs is not applicable because the members of the LLs have no rights and
responsibilities for the execution of the solution and the consequences.

Meanwhile, several measures have been suggested to overcome the disadvantages of
citizen participation decision-making. For example, visualization techniques or information
technologies have been suggested as such solutions [9,10]. In a similar context, this study
proposes a problem-solving process using the modeling and simulation (M&S) technique
to provide the scientific basis for LLs. M&S has been established as a scientific basis
for defining and presenting solutions to engineering problems, including various social
problems. Experts who utilize M&S develop a model from the problem domain. The
experts generate alternative solutions and apply them to the model. Finally, the experts
analyze the results by executing the models using simulations. This study establishes
the requirements for embedding M&S into the problem-solving processes of the LLs. In
addition, this research introduces a comprehensive case study from the Pohang LL [11].

2. Related Works

LLs have various fields of application, such as service design, usability test, and city
planning [12–14].

This section introduces the definition of LLs and their fields of application. In addition,
this section illustrates the modeling notation and simulation algorithm the Discrete Event
System (DEVS) formalism.

2.1. Living Labs and Application

The core of the LLs is a user-driven process that defines a user as a prosumer. Unlike
other experimental laboratories, LLs try to solve problems close to our lives, such as
municipal waste problems or noise problems in a residential area. In the past, the residents
lacked information needed to define and solve problems owing to several limitations, and
government officials also viewed residents as passive beings who accept the solutions they
suggested. In contrast, the members of LLs are active. They gather information, define
a problem, and derive a solution with the support of the ITs. Figure 1 shows the typical
problem-solving process of LLs.

The first step in the problem-solving process of LLs is field research. As society may
comprise various groups according to their interests, the members of the LLs should gather
the necessary information to conduct further discussions. Each stakeholder should then
gather and define the problem. Given that several problematic situations may be tangled,
the members of the LLs should obtain accurate and fair arguments to support their logic.
After defining the problem, the next step is to establish alternative solutions. During the
establishment of the alternative solution phase, members may utilize design-thinking tools,
such as mindmap, fish-bone diagrams, and Scamper [15–17]. Before applying the solution,
the LL members may evaluate alternative solutions. After applying the solution to the field,
the members of the LLs may validate the solution by conducting field research. If a member finds a problematic situation, members may initiate the problem-solving loop again.

![Diagram](image_url)

**Figure 1.** Problem-solving loop of Living Labs (LLs).

The most critical issue during the problem-solving loop is to provide factual data to the members during a debate. In general, the members of the LLs may participate in the problem-solving process emotionally because of their interests. Therefore, the members of the LLs should assess the data and solution reasonably to prevent wasteful debates. Consequently, this research utilizes M&S as a tool to secure data and solution reliability during the problem-solving process of LLs. M&S were used to model the natural system and social systems to gain insight from models for decades [18]. Therefore, M&S may be the proper solution for the provision of a theoretical foundation for resolving wasteful debates and for providing a fair assessment method for alternative solutions.

The application of LLs is not limited to the solutions of social problems. In the case of LLs in Japan, senior citizens, companies, and municipalities are the LL members [13]. In the LLs, senior citizens and companies cooperate to plan, design, and create various products, such as childcare products, rehabilitation equipment, and welfare equipment. Conversely, when a company introduces a prototype, the members of LLs evaluate and report the pros and cons to the company. In addition, LLs in Cahors, France, utilized LLs to retrofit old buildings to resolve conflicts between heritage conservation policies and energy efficiency improvements. In the case of LLs, some Cahors lacked the technical knowledge for the development of a proper solution. Therefore, researchers have established LLs to obtain a potential solution to the complex problem. Some of the members in the LLs provided a simulation result of the orientation and solar radiation on different walls. As shown in the Cahors LLs, the Cahors LLs utilized the simulation software to model the old buildings’ layout and analyzed the solar radiation heat flux, which saves time and effort during decision-making. Our research utilizes M&S similar to Cahors LLs. However, our research utilizes the domain-specific M&S and the general M&S to help end users.

2.2. Discrete Event System Formalism and Simulation Algorithm

The essential points needed to consider in M&S to secure scientific grounds during problem solving are scalability, reconfigurability, and ease of use. Several M&S theories support the consideration points; however, this research adopts DEVS formalism. The DEVS formalism has a set-based modular form so that the users may model a system intuitively by describing the set of a system, input, and output [19,20]. The DEVS formalism uses an atomic model to capture the basic model, which cannot be divided into smaller models. A modeler may also compose several models into another model, such as building out of bricks. This model is denoted as a coupled model. Therefore, a modeler describes atomic models to capture the dynamic behaviors of subsystems and generate complex behaviors by composing atomic models in a coupled model. An atomic model is defined as follows:
Definition 1 (Atomic Model).

\[ AM = < X, Y, S, \delta_{\text{ext}}, \delta_{\text{int}}, \lambda, t_a > \]

where

- \( X \): a set of external input event types,
- \( Y \): an output set,
- \( S \): a sequential state set,
- \( \delta_{\text{ext}} \): \( Q \times X \rightarrow S \), an external transition function
  where \( Q \) is the total state set of
  \[ M = \{(s, e) | s \in S \text{ and } 0 \leq e \leq t_a(s)\} \],
- \( \delta_{\text{int}} \): \( S \rightarrow S \), an internal transition function,
- \( \lambda \): \( S \rightarrow Y \), an output function,
- \( t_a : S \rightarrow \mathbb{R}_0^+ \), a time advance function, where the \( \mathbb{R}_0^+ \)
  is the non-negative real numbers with \( \infty \) adjoined.

An atomic model \( AM \) is a model that generates a system’s behavior, which is the output event \( y \) based on the existence of an input event \( x \). The state set \( S \) represents a unique description of the model. Each state \( s \), which is \( s \in S \), represents the system’s status at a specific point in time. The internal transition function \( \delta_{\text{int}} \) and the external transition function \( \delta_{\text{ext}} \) are the set of rules that change the next state of the model. The function \( t_a \) returns the residence time for a given state, and the function \( \lambda \) denotes the pair between the state and output event. The atomic model only generates an output event at the given state according to the \( \lambda \) function. Figure 2 shows the diagram notation of the atomic model. The triangles in and on the box denote input and output events, respectively. The circle shows the state and the residence time. The solid line denotes the external transition, and \(?\text{in}\) means that an in event will trigger the external transition. Finally, the dotted line denotes the internal transition, and when elapse time of the model exceeds the residence time of a given state, the model will generate an output event \( y \). After generating the output event \( y \), the event will trigger the internal transition.

![Figure 2. Diagram of atomic model.](image)

The simulation algorithm of the \( AM \) is defined as follows: When an input event occurs at elapsed time \( e \), which is less than or equal to \( t_a(s) \) specified by the time advance function \( t_a \), a new state \( s' \) is computed by the external transition function \( \delta_{\text{ext}} \). A new \( t_a(s') \) is computed, and the elapsed time \( e \) is set to zero. Conversely, if an input event does not reach \( t_a(s) \), an output specified by the output function \( \lambda \) is produced based on state \( s \). After generating an output event, a new state \( s' \) is calculated with the internal transition function.

A coupled model is defined as follows:

Definition 2 (Coupled Model).

\[ CM = < D, \{M_i\}, \{I_i\}, \{Z_{ij}\}, \text{SELECT} > \]

where

- \( D \): a set of component names,
- For each \( i \) in \( D \),
  \( M_i \): a component basic model
  (an atomic or coupled model),
\( I_i: \) a set of influences of \( i, \)
and for each \( j \) in \( I_i, \)
\( Z_{i,j}: Y_i \rightarrow X_j, \) an i-to-j output translation,
\textit{SELECT}: \( 2^M - \phi \rightarrow M, \) a tie-breaking selector.

A coupled model \( CM \) consists of components \( \{ M_i \}, \) which are the atomic or coupled models. The influences \( \{ I_i \} \) and i-to-j output translations \( \{ Z_{i,j} \} \) that define the coupling specification, as follows:

- An external input coupling (\( EIC \)) connects the input event of the coupled model to the input event of one of its components.
- An external output coupling (\( EOC \)) connects the output event of a component to the output event of the coupled model.
- An internal coupling (\( IC \)) connects the output event of a component to another component’s input event.
- The \textit{SELECT} function resolves the processing order of internal events that are generated simultaneously.

An external output coupling (\( EOC \)) connects the output event of a component to the output event of the coupled model; An internal coupling (\( IC \)) connects the output event of a component to another component’s input event. The \textit{SELECT} function resolves the processing order of internal events, which are generated simultaneously.

Because the coupled model consists of other models, the modeler may build a new model with a prebuilt atomic or coupled models, as shown in Figure 3. The left side of the figure indicates that a modeler develops a model \( ABC \) with subsystems \( A, B, \) and \( C, \) where the line with the filled black diamond symbol denotes the composition relation. Given that the modeler chose to use \( A, B, \) and \( C \) as an atomic model, the modeler should develop each model. Conversely, the right side of the figure denotes that the modeler develops a model \( ABC \) using one coupled model, \( AB, \) and one atomic model, \( C. \) In this case, the modeler may utilize an existing model or may develop the model \( AB \) and reuse it for later usage.

\textbf{Figure 3.} Hierarchical modeling using coupled model.

Research utilizing M&S as a communication tool in LLs was introduced by Choi et al. (2017). In their case study, researchers at a university, city council members, stakeholders, and government employees collaborated to solve the Pohang’s issues in university-oriented LLs similar to LLs in Cahors. In the Pohang LLs, the Professors identified and introduced students’ problematic issues as an open problem. Professors and students then developed various alternative solutions, and proposed feasible solutions to stakeholders and city council members. As introduced in Choi et al. (2017), when a project is established, the members of the LLs collect information to develop a scenario and a simulation model. After developing the scenario and simulation model, the members of the LLs conduct experiments and analyze the results. The limitation of the LLs described by Choi et al. (2017) pertains to the fact that the members of the LLs cannot easily gain
problem-solving experience owing to the fact that the problem-solving process relies on the university’s semester. Given that the students are temporary members of LLs, the members of the LLs are easily replaced after the semester. Another limitation is the lack of professionalism of the solution. Each student expended a considerable amount of efforts in the identification of the solution; however, a single semester is not enough to derive a reliable solution. To overcome this limitation and provide a sustainable problem-solving process, this research supplements the problem-solving process using M&S.

3. Extended Problem Solving Process Using M&S for Living Lab

To overcome the limitations of the existing problem-solving process of LLs, we introduce the problem-solving process with M&S for LLs. Unfortunately, most LLs do not have the experience of building their simulation model. Therefore, the process with M&S should support members in developing the simulation model and help the simulation experiments. This research separates two activities, the LL activity and M&S activity during the problem-solving process in LLs. LL activities are similar to the existing problem-solving process of the LLs. The difference between the existing process and the extended process is that the additional phases are defined to develop, execute, and manage a simulation model. The M&S activities are activities that bring a real-world system to the computer world to utilize computational resources to help solve real-world problems. Figure 4 illustrates the extended problem-solving process.

![Extended problem-solving process using modeling and simulation (M&S) for LLs.](image)

The light gray region of Figure 4 denotes the LL activities, and the dark gray region denotes the M&S activities. The dotted arrow shows the interactions between LL and M&S activities. The extended problem-solving process starts with field research to obtain initial data. The extended problem-solving process is refined into informal information for (a) discussion with stakeholders and (b) presentation of a scientific basis. Based on the data delivered in an informal form, members of LLs collaborate to identify a problem, define the problem, and collect necessary data to build a computer simulation model. Table 1 shows an example output of the process.

As shown in Table 1, the contents of the output are the statements of the members of LLs in a natural language form. Thus, it may be ambiguous or not enough to derive a solution for the problem. To support members’ decision-making at the LLs, the members refine the dialog-based statement into a simulation model with formal notation. The simulation model may represent real-world systems, which may reproduce the problematic situation for a given problem. The next step in the activities of LLs is to establish alternative
solutions. In this phase, the members of the LLs develop various ideas to solve problematic situations. At this stage, an intense debate may arise and then subside because the members' interests can vary depending on the derived alternatives. As a result, a foundation that can eliminate controversy should be provided to LLs. Figure 5 shows the concepts on how the M&S activities support the elimination of controversy by assessing the alternatives.

### Table 1. Example output of LL activity.

| Types                     | Contents                                                                                     |
|---------------------------|----------------------------------------------------------------------------------------------|
| Name                      | Environmental Issues Caused by the Use of Disposable Plastic Cups                           |
| Dialog from field research| The environmental problems caused by the use of disposable plastic cups have been a problem in our society from the past to the present. Excessive use of disposable plastic cups affects precocious puberty in young children, the survival crisis of animals and plants due to microplastics, and the health threat of seafood eaters in many ways. Recently, several methods, such as the use of paper straws in franchise cafes and the amount of the discount when using a personal tumbler, were used to solve this problem. However, in reality, there is no noticeable effect yet. Problems, such as this, continue to be social problems that need to be solved at a worldwide scale. |
| Causes                    | Except for the franchise, this is a regulation that is not well followed. Currently, there are legal measures enforced to restrict the use of disposable cups and plastic straws in stores. However, if you actually visit several cafes and restaurants, it is easy to observe that smaller stores still provide disposable cups and plastic straws to customers. It can be said that the cause of this problem is the lack of strengthening inspection of legal regulations. Franchise branches that can be easily become popular or less popular in social media where people visit regularly observe closely these laws and regulations owing to the influence of the points mentioned above. Therefore, to solve the environmental problems caused by genuine disposable plastic cups, it is necessary to ensure that all stores can adhere to this area. |

As our previous research has shown, all LL members may not have a deep understanding of the M&S theories or implementing a computer simulation model. M&S experts analyze the informal dialog-based data to develop a simulation model. With the help of M&S experts, LLs may maintain a sustainable problem-solving loop so that the LL members may improve their solutions. Figures 6 and 7 illustrate the modeling results to estimate the number of disposable plastic cups generated in a local cafe. Figure 6a illustrates the generator model of the local café. The generator model does not exist in the real world; however, the model may simulate the arrival patterns of customers. The LLs may conduct various experiments by changing the random variable PrX. Figure 6b shows the processor model. The processor model simulates the service time for a given customer. In addition, the member may change the random variable to simulate the service time pattern for a customer.
Figure 6c is the collector model. The collector model collects the customers and may calculate the total waiting time of a customer. Finally, Figure 6d denotes the buffer model. The buffer model has three states, which are vacant, occupy, and move. Each state represents the waiting line of a cafe. The vacant state is used when the waiting line is empty. If a customer arrives at the line, the model’s state will change to the occupy state. The customer will wait at the occupy state until the server calls the customer so that the buffer model will not change the occupy state until the call event arrives. When a call event arrives, the model transfers the customer and changes the state into vacant.

Figure 6. Atomic models of local cafe: (a) Generator model. (b) Processor model. (c) Collector model. (d) Buffer model.

Figure 7. Coupled model of local cafe.

Figure 7 shows the connection among atomic model. The coupled model has the generator, buffer, and server model. The generator and buffer models are the atomic models, and the server model is a coupled model. The server model contains a collector and processor models to simulate the cafe staff that calls the next customer at the local cafe. Owing to the modular characteristics of the DEVS formalism, several models may be reused on different domains. For example, the generator model can simulate the arrival patterns of the taxi and passenger on the multi-transit station, and the buffer model can be applied to model a waiting line.
4. Case Study: Multi-Modal Transit Station Analysis

A multimodal transit station is a complex system in which various types of passengers and transportation methods interact. There are two types of lanes at the multimodal station: the vehicle and the passenger lanes. The designer should consider the characteristics of transportation and passengers and the station layouts to design the multimodal transit station. In general, the passengers use three types of transportation means at the transit station. The first method is fast, expensive, and comfortable for passengers who want to travel to the destination quickly, such as a taxi, and only a few passengers may form a group to take a taxi. In general, many taxis are waiting at the vehicle lane, and passengers grab taxis when they arrive at the station. Therefore, if there are more taxis than passengers, many taxis may occupy the lane and cause congestion. On the contrary, if there are more passengers than taxis, passengers’ waiting time will increase, and unsatisfied passengers will file a complaint. The second method is to take a bus. When the dispatch interval is too short, the bus will not pick up all the passengers. Correspondingly, this will lead to resource wasting. Conversely, if the dispatch interval is too long, many passengers wait, and the transfer station will become crowded. Finally, passengers may use their private cars. In this case, private cars are waiting at the waiting lane to pick up passengers.

This research analyzed the Korea Train eXpress (KTX) station in Pohang. The Pohang KTX station is used by approximately 5000 passengers per day on average who utilize private cars, taxis, and buses. The major problem of the Pohang KTX station is traffic congestion. When a KTX train arrives at Pohang station, taxis, buses, and private cars cause traffic congestion at the entry road. Figure 8 shows the layout of the station. The entry road of the station has three lanes, and the road expands to six lanes. There are three types of lanes: taxi, bus, and private. Two lanes are allocated: one for drop-off or pick up of passengers, and one for vehicle to pass the drop-off/pick-up zones.

![Figure 8. Representation of multi-modal transit station at Pohang station.](image)

Figure 8 shows the problematic situation at the Pohang Station. In general, the taxi lane causes the traffic congestion at the entry road. As shown in the figure, when the taxis waiting for passengers exceed the taxi lane’s capability, the remaining numbers of taxis occupy the entry road. Moreover, taxis cannot occupy the middle lane of the entry road so that the taxis occupy the side of the road. This triggers the second problem. The second problem is related to the fact that when a bus arrives at the station, the bus should cross the taxi lane which amplifies traffic congestion.

To analyze and define the problem, the members of the LLs conducted field research. They had conversations with taxi drivers. They claim that the passengers do not recognize the waiting line and hire the taxis at wrong locations along the waiting lane. Therefore, the members of the LLs participate in the reproduction of the problematic situation and in the development of alternative solutions. The members of the LLs measured the average numbers of taxis and passengers and the average waiting time of the taxis and passengers to develop a simulation scenario. In addition, the members of LLs observed the behaviors
of a passenger and the taxis, and how they formed a waiting lane. During the observation, we found several interesting facts.

- Taxis and the passengers should be served based on the First Come First Serve rule; otherwise, a quarrel will happen.
- A vehicle should wait for the passenger to cross the road, and some passengers do not obey the traffic signals.
- A taxi cannot overtake the preceding taxi in the single lane.
- If a taxi is at the front in line, a passenger takes the taxi.

![Traffic Flow: One way](image)

**Figure 9.** Congestion situation at Pohang station.

Based on these observations, we modeled the KTX station. Figure 10 shows the modeling results of the KTX. The Generator and Buffer models were reused when the station’s spatial layout was modeled. Because the taxi and passenger arrival patterns are different, we reused the Generator model by modifying the random variables. For the buffer model, we modified the model to evaluate the next model’s vacancy so that when the next position becomes vacant, the model changes its state to vacant and changes the next model’s state to occupied. Finally, we added a new model, the Matching model, to model passengers and taxi interactions.

After the implementation of the simulation models, we conducted an experiment and found two situations: matching at the end of the line and matching at the random point. Because the arrival of taxis and passengers in the simulation has a random behavior, we executed multiple simulation runs to identify the taxi and passenger behaviors in various scenarios. As a result, we found that matching was always achieved at the end of the line if the taxi line was full. However, when the taxis were not densely arranged but were relatively sparse in the taxi lane, the passengers and taxis were matched. Once we identified the problematic situation, we analyzed the simulation results to find the causes. Based on the simulation results, we found that the traffic signal may misdirect passengers and cause traffic congestion.

**Figure 11** illustrates the problematic situation which the traffic signal causes. When passengers arrive at the KTX station, the passengers should cross the crosswalk to take various transportation means so the traffic signal should stop the taxi lane flows. As a result, taxis that pass the traffic light were matched with passengers and exited the transfer station. Conversely, passengers were matched with taxis that waited in front of the traffic signal because they could be matched with taxis at the front of the line. As a result, some taxis that passed the traffic signal did not match the passengers. This forced the taxi drivers
to wait in front of the traffic lights, and resulted in shorter platforms than the designed taxi stands. Accordingly, this led to occupation of the road beyond the entry road by the taxis. Solving problematic situations was simple. This was achieved by (a) installing fences to prohibit unexpected matching, and by (b) ensuring that passengers hired a taxi to the desired location. Currently, fences are installed at the Pohang KTX station to reduce traffic congestion; however, congestion still exists owing to other transportation methods.

![Diagram](image)

**Figure 10.** Modeling output of the KTX station.

![Diagram](image)

**Figure 11.** Unexpected behavior of taxi-passenger matching.

Interestingly, some simulation models, which we have used to model the cafe, were reused in the KTX station simulation. Since the simulation models were based on the DEVS formalism, each simulation model has modular characteristics. The simulation model users may instantiate several simulation models and build a large-scale simulation by connecting their input/output interfaces. As a result, the simulation model users may reuse the pre-built simulation model, as shown in Figure 10. These characteristics are important in problem-solving in the LLs. During the problem-solving phase in the LLs, several stakeholders may participate with other members in the LLs and may have a different perspective on the problem. Therefore, to accelerate the problem-solving, the M&S tools may react quickly to reflect the perspective. As shown in the case study, the DEVS formalism-based simulation models may be used for the large-scale simulation by reconfiguring and reusing the existing simulation models.
5. Conclusions

Building a sustainable society has become a complex problem. Various interests are tangled, and resolving the problematic situation may consume considerable amounts of time and effort. In addition, when some society members identify a solution to resolve a problematic situation, the solution may cause another problematic situation to other society members. Therefore, problem-solving should not be responsible for some society members, but all members must participate in the problem-solving loop to make the society sustainable. This research introduced the LL method based on M&S to help decision-making. First, M&S helped members recognize problematic situations by modeling and simulating the real world. After the identification of the problematic situations, the members derived alternative solutions to identify the optimal solution. When members propose an alternative, the members of the LLs may estimate the results of the solution by modeling and simulating the solution. To help the members of LLs to use M&S as a tool, we proposed the discrete event system formalism and its execution environments. Given that the formalism has a set theoretical modular form, the members of LLs may reuse or modify the simulation model to solve problems in various domains.

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