# 4. Simulation modelling and analysis

By simulation modelling and analysis (SMA) one strives to fulfil the demands of the Conant–Ashby theorem (Conant and Ashby, 1970), defining a model of the system as a good regulator, having as many handles, parts and states as its original physical counterpart; thus, providing the possibility to build its digital model and establish a digital laboratory that will enable its exploration, adaption and optimization. The resulting simulation models are abstract, dynamic and in most cases stochastic, since their system variables are modelled by probability distributions.

## 4.1 Simulation in logistics

In logistics SMA can provide valuable inputs to Supply Chain (SC) and traffic network (TN) optimization. Simulation modelling can be used to graphically visualize temporal flows through complex SC and TN processes and resources, allowing the prediction and quantification of possible outcomes from different scenarios. This helps SC and TN entities to gain valuable insights and understand the effects of their potential decisions on SC and TN performance including SC lead-times, TN travel times and costs. Hence, SMA in SC and TN modelling can contribute to the SC and TN analysis and to the improvement of their designs toward achieving higher performance and sustainability.

There are many facets of a SC, representing different SC management perspectives. A production manager's view of the SC differs from the marketing manager's view, which again differs from supply manager's view, etc. Hence, the models used are different, even for the same company, let alone the whole SC.

When solving SMA problems in logistics, managers need to make decisions on strategic, tactical and operational levels, depending on their effect on the SC or TN as a whole. Due to their interdependences, managers are often unable to solve problems on any single level. At the same time, it is also difficult to observe all three levels from the perspective of any individual entity. From SMA perspective, one can observe a SC or TN on two levels:

1. Macro level

- self-organization,
- co-evolution of entities,
- dependency on connections/transport routes.

2. Micro level

- multiple and heterogeneous entities,
- local interactions among entities,
- structured entities,
- adaptive entities.

Although they are performed in real time, the temporal aspect of SC operations is somewhat ambiguous. Depending on the level and perspective the durations of operations may be measured in days, weeks or even months when considering inter-organizational activities, while on the other hand, intra-organizational operations are measured in hours or even seconds. Depending on the nature of the modelled problem, the duration of the shortest operation or the maximum frequency of incoming/outgoing requests determines not only the representation of time in an SMA model, but also its granularity. The shorter the minimum duration of the shortest operation or the higher the highest frequency of requests is, the finer is the granularity of time or in other words the precision of time keeping in the model. This is important for the modeller, since the model's reaction time cannot be shorter than the predefined time granularity. Hence, one needs to estimate the duration of all operations and inter-arrival times of incoming/outgoing signals in advance to be able to determine the time units of a system model correctly.

In a simulation model, time can either progress by critical events from transaction to transaction or continuously. In the latter case, the progression of time in the model is independent from the frequency of operations. With critical event triggered time flow, the operations are invoked according to their occurrence times, namely critical events. The benefit of SMA is that during a simulation, one may speed up the progression of time in the model, so the processes perform faster than in real time. Thus, one can make early predictions of following events.

The times between incoming simulation units and their processing/transit times may result from observations and measurements. If they don't vary, they are deterministic. However, usually they are stochastic in their nature. Hence, the introduction of constructs modelling their probability distribution functions (e.g., triangular, uniform, exponential, etc.).

## 4.2 Discrete event simulation

DES analysis offers the most detailed insight into a logistic (production) process to the production manager by a consistent and coherent model. Thus, DES is highly regarded tool to determine real-time behaviour and resource utilization in process industry, including logistics.

Constructs:

- Flow units represent simulation units (e.g., orders, materials, etc.) which enter the system on the input(s) and progress through the system model.
- Processors represent mobile (e.g., people, forklifts, etc.) and fixed (e.g., machines, production lines, etc.) resources which process the simulation units.
- Queues store the flow units until their transition to the next available processor.
- Connectors define the promotion of units through the system model.

Properties:

- Process-oriented.
- Focuses on detailed process modelling.
- Heterogeneous entities.
- Micro-entities are passive objects.
- Events introduce dynamics into the system.
- Discrete time-progression; from one (time) event to the next.
- Flexibility is achieved by changing the structure of the model; system structure during simulation is fixed.

## Example

The DES example (Figure 4.1, extracted from the JaamSim (JaamSim Development Team, 2023) simulation environment) comprises a model of variant production, where four different products are being produced (Gumzej and Rakovska, 2020). According to the production plan, some 10, 30, 40, 20% of product types 1, 2, 3, and 4, respectively, are being produced. Choosing a product type is induced by the triangular distribution between 1 and 4 with modulo at 3. Each product type has a dedicated production line. The production orders are fulfilled according to the exponential distribution around the 30 s mean time value. The production of every single product takes 100–120s according to the uniform distribution. After they are finalized, the products are checked for quality at a dedicated test site. The quality check takes 10 s. From the company's experience, on average every 1 out of 10 products doesn't pass inspection. Products of insufficient quality are transported back to the original production line. Their reprocessing takes 120–130s according to the uniform distribution. The durations of production and quality inspection and reprocessing don't depend on product type. After they have successfully passed their quality control the finished products are transported from the production site to the finished products warehouse. Re-manufacturing defective products while still in production is an effective way to reduce both environmental impacts and manufacturing costs.

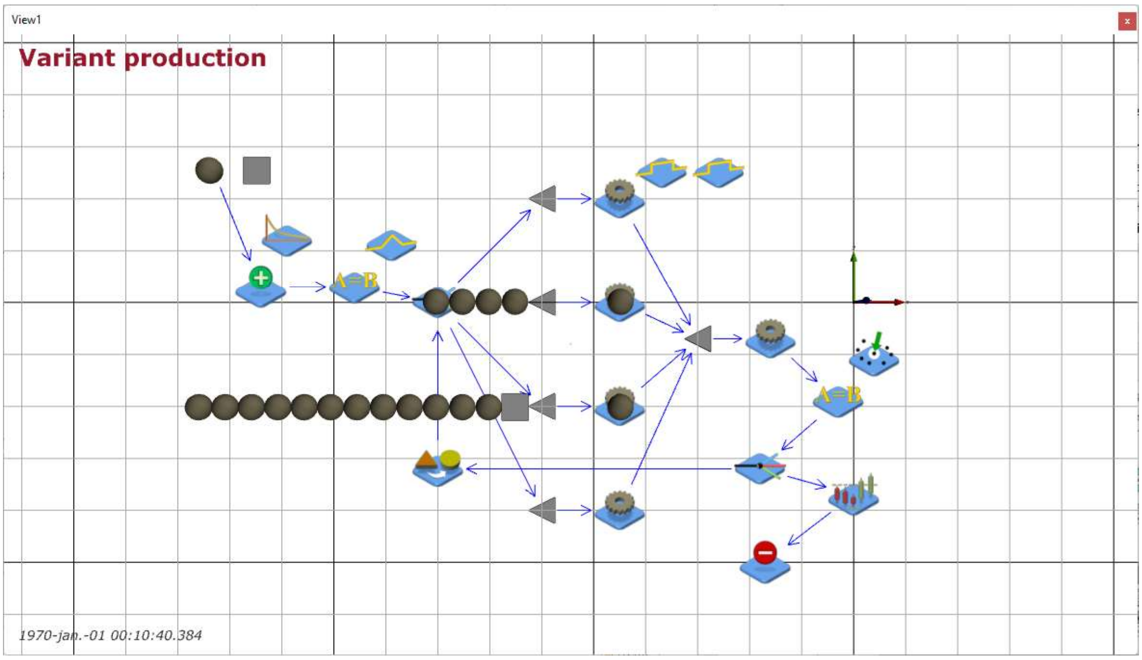


**Figure 4.1 Variant production with quality control.**

Synopsis

The following process parameters can be analysed and optimized by DES:

- Production cycle-time and performance.
- Utilization of production cells and spaces.
- Capacity of storage spaces as well as storage unit's dwell-times.
- Utilization of mobile resources (e.g., operators, conveyors, forklifts).

## 4.3 System dynamics

SD analysis represents a SC manager´s view of a production process by a consistent and coherent model. SD is regarded as a tool best suited to determine the structure as well as optimal volumes (when and how much of individuals site´s inputs, stocks, and outputs. Therefore, it allows for the efficient utilization of production and storage facilities.

Constructs:

- Stocks represent buffers which can store delivery items on the supply chain.
- Flows represent supply channels.
- Feedback loops represent fine-tuning parameters for stock replenishment.

Properties:

- System-centred.
- Key performance-indicators' oriented modelling of system variables.
- Homogeneous entities.
- Entities on micro-level are disregarded.
- Dynamics is introduced by feedback loop coupling.
- Continuous time-progression; time progresses synchronously for all components of the system model.
- Flexibility is achieved by changing the structure of the model.

- System structure during simulation is fixed.

### Example

The SD example (Figure 4.2, extracted from the NetLogo (Wilensky, 1999) simulation environment) comprises a home appliance company's SC and describes material flows between its subsidiaries (Gumzej and Rakovska, 2020). The company has multiple production sites: main site in Slovenia (SI) as well as affiliate firms in Germany (DE), Poland (PL), Hungary (H), and Bosnia–Herzegovina (BIH). In addition to production sites, its gross-sales sites are situated in Russia (RUS), Ukraine (UKR), and Romania (RU). The production sites supply their own markets with finished products and each other with product components.

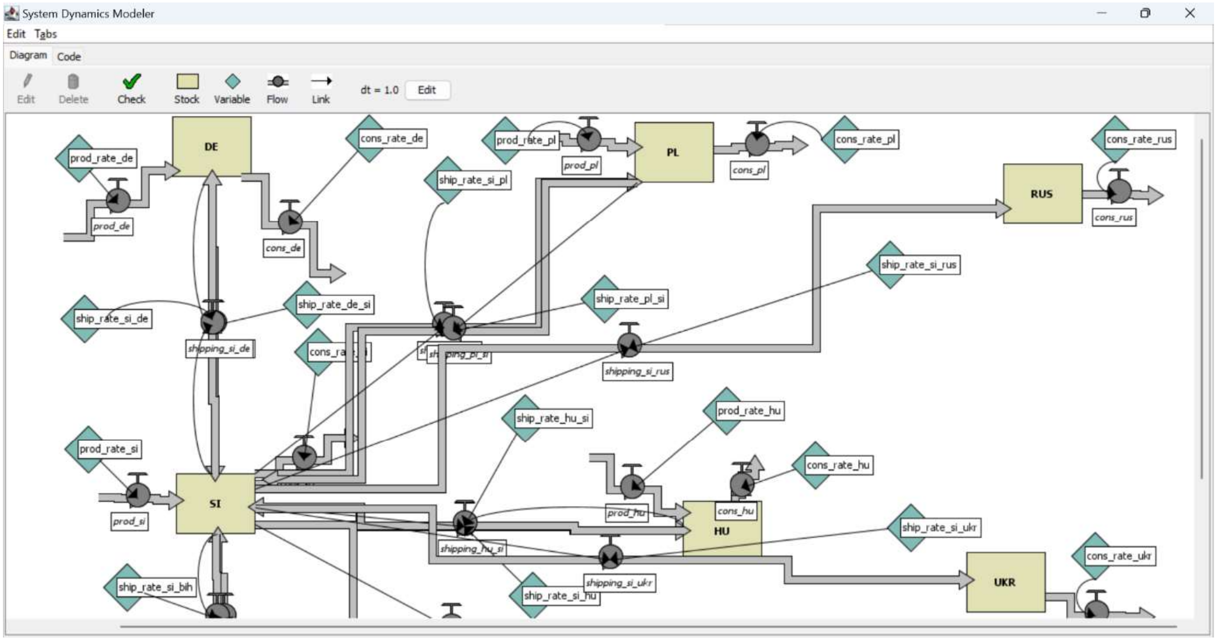


**Figure 4.2 SC layout.**

The associated NetLogo dashboard (Figure 4.3) serves as a decision support tool (DST), to covenant the production- and stock quantities with the predispositions and their physical distribution. The time flow is continuous throughout every day's transactions, i.e., every day a certain number of components are shipped between production sites and a certain number of finished products are consumed on site or shipped to the distribution sites. Based on an initial stock of 300 units at SI location and 0 stock at other locations and the distribution model, the stock quantities at individual locations represent the average stock according to given production (pcs), consumption (%) and shipping (%) rates.

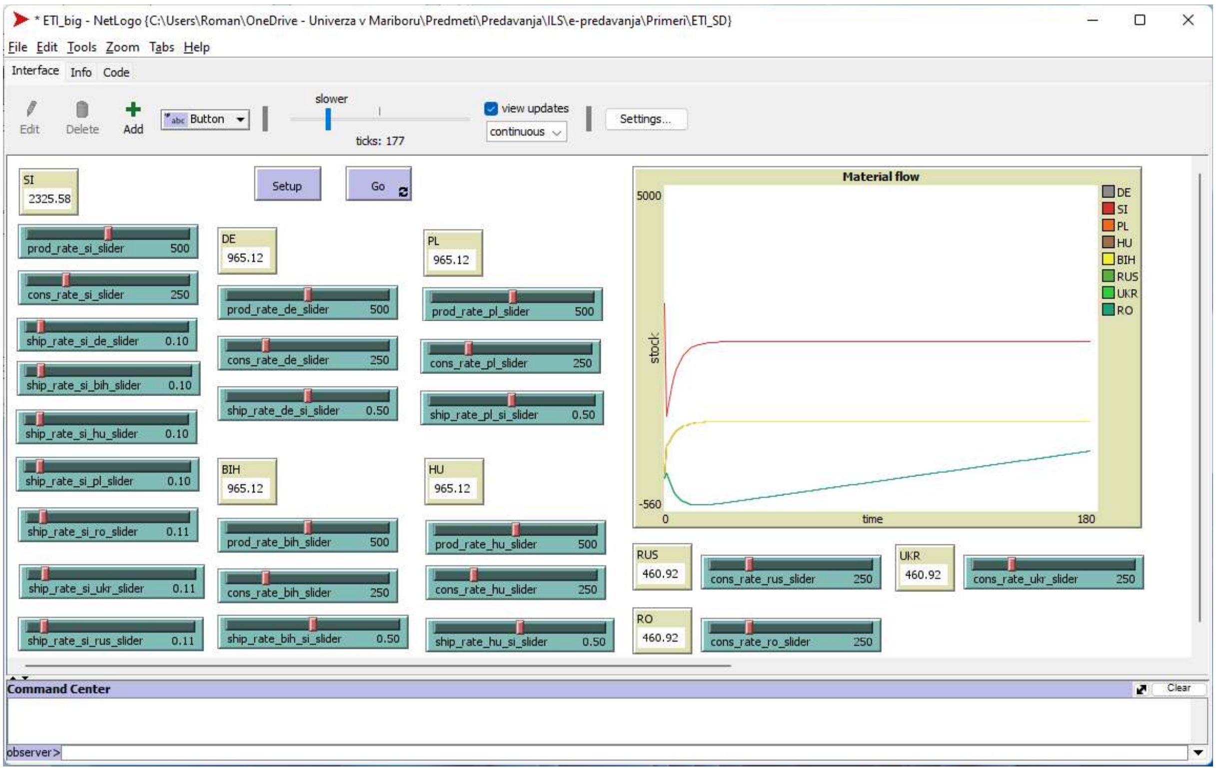


**Figure 4.3 SC Dashboard.**

## Synopsis

System dynamics simulation allows for:

- Planning the layout of a SC.
- Optimization of production and distribution capacities.
- Estimation of distribution channels' loads and associated costs.

# 4.4 Agent-based Simulation

ABS analysis offers a strategic manager´s or market regulator´s view of the marketplace. Hence, ABS is regarded as a tool best suited to determine the optimal structure and layout/assortment of one´s market and/or SC by considering their global characteristics (e.g., demography, climate, GDP, quality, awareness, etc.).

Constructs:

Agents representing supply chain nodes (e.g., suppliers, retailers and inspectors) with their properties, relations and behaviour.

Properties:

- Entity-centred.
- Problem-oriented modelling of entities and their interactions.
- Heterogeneity of entities.
- Micro-entities are active objects that act in their environments, communicate among each other and autonomously make decisions.
- Decisions and interactions between agents introduce dynamics into systems.
- Agents and their environments constitute formal models.
- Time flow is discrete and universal on model-level; model timing is consistent with the frequency of SC transactions and the life cycles of SC nodes.
- Model flexibility is achieved by the changing system structure and behaviour of agents.
- System structure during simulation is variable.

### Example

The ABS example (Figure 4.4, extracted from the NetLogo (Wilensky, 1999) simulation environment) was used to analyse the behaviour SC echelons in an open market (Gumzej and Rakovska, 2020), with respect to their Quality of Service (QoS). In the example, the different policies concerning the company's total quality management were investigated by a model, comprising its suppliers, customers and market regulators.

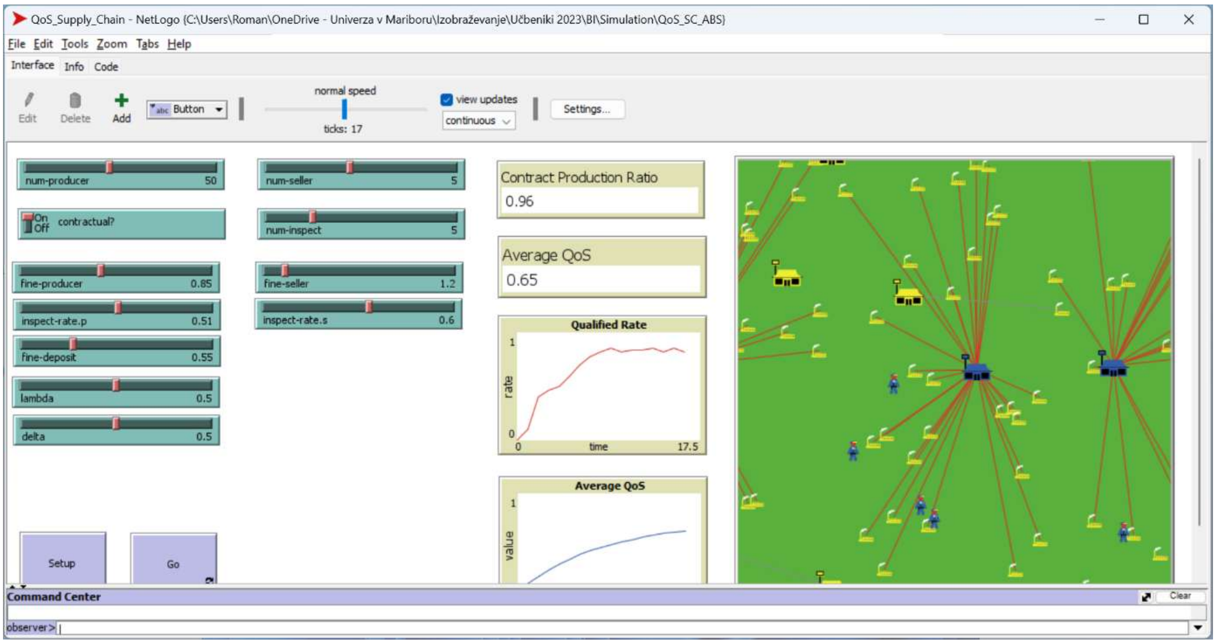


Figure 4.4 Marketplace regulation.

### Synopsis

Agent-based simulation allows for:

- Planning the layout of an SC.
- Modelling the dynamic growth of an SC.
- Modelling the behaviour of partners within SCs.
- Optimization of global indicators.

## 4.5 Network simulation

NS analysis offers a network regulator´s view of the network. Hence, NS is regarded as a tool best suited to determine the optimal structure, layout and assortment of one´s network by considering its global characteristics (e.g., throughput, emissions, QoS indicators, etc.).

Constructs:

Agents representing the flow objects with their properties, relations and behaviour.

Network representing the overlay network (e.g., traffic network) on which the flow objects commute.

Properties:

- System-centred.
- Problem-oriented modelling of entities and their interactions.
- Heterogeneity of entities.
- Micro-entities are active objects that act in their environments, communicate among each other and autonomously make decisions.
- Decisions and interactions between agents introduce dynamics into systems.
- Agents and their environments constitute formal models.
- Time flow is discrete and universal on model-level; timing is consistent with the relative speeds of flow objects.
- Model flexibility is achieved by changing the network structure, which is fixed during simulation, and behaviours of agents which vary according to the (traffic) network state and their goals.

### Example

The presented example (Figure 4.5, extracted from the SUMO (Pablo et.al., 2018) simulation environment) was used to determine the traffic flows and throughputs of streets in a city centre affected by a planned road blockage (Šinko and Gumzej, 2021). In addition, traffic related indicators like travel times, fuel consumptions and emissions were measured.

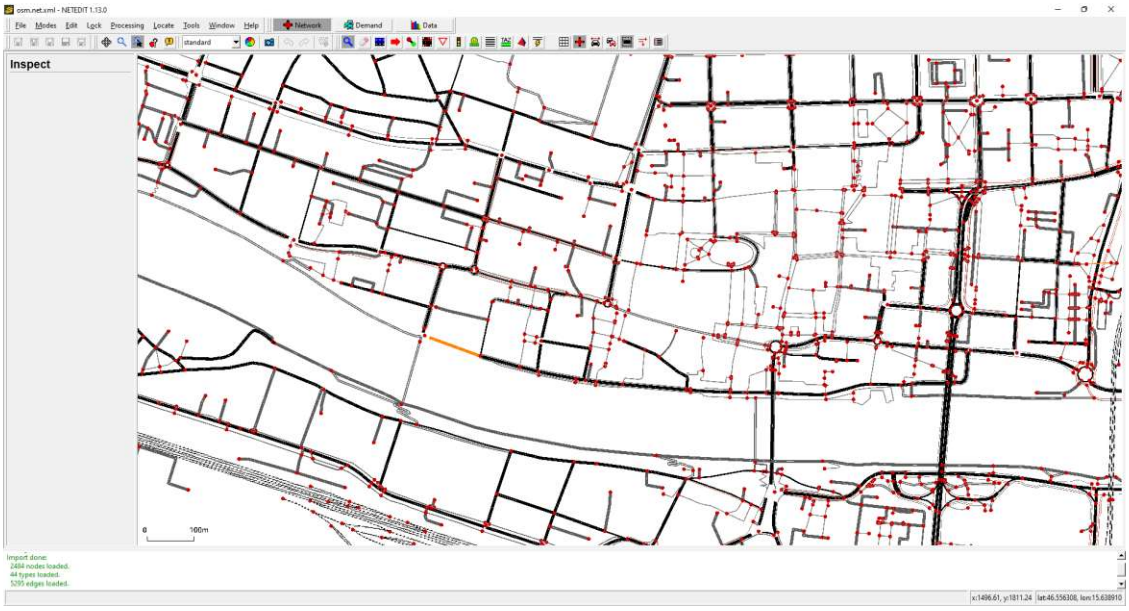


**Figure 4.5 Traffic situation & network.**

### Synopsis

Network simulation allows for:

- Planning the layout of a network.
- Modelling the dynamic behaviour of a network to determine bottlenecks and weak links.
- Modelling the flow of network items.
- Optimization of global network indicators.

## 4.6 Logistics simulation projects

Logistics simulation projects are designed in concordance with Design for Six Sigma (DFSS) paradigm and are based on the Deming's cycle of improvement:

- Planning: definition of the system and goals.
- Execution: design of the simulation model.
- Analysis: experimenting with the simulation model and evaluating alternatives.

- Action: utilization of simulation results to implement improvements.

Any logistics simulation project (Figure 4.6) is composed of seven phases:

1. Strategic plan: analysis of existing and suggested resources and processes.
2. Conceptual model: abstract system model and predispositions definition, data collection.
3. Logical model: object-flow, stock and flow or network diagram of the system model.
4. Simulation model: development of an adequate simulation model.
5. Verification and validation of the simulation model: checking model consistency and coherence.
6. Analysis based on the simulation model: design and execution of experiments.
7. Utilization of simulation results to devise an action plan: projection of system improvements.

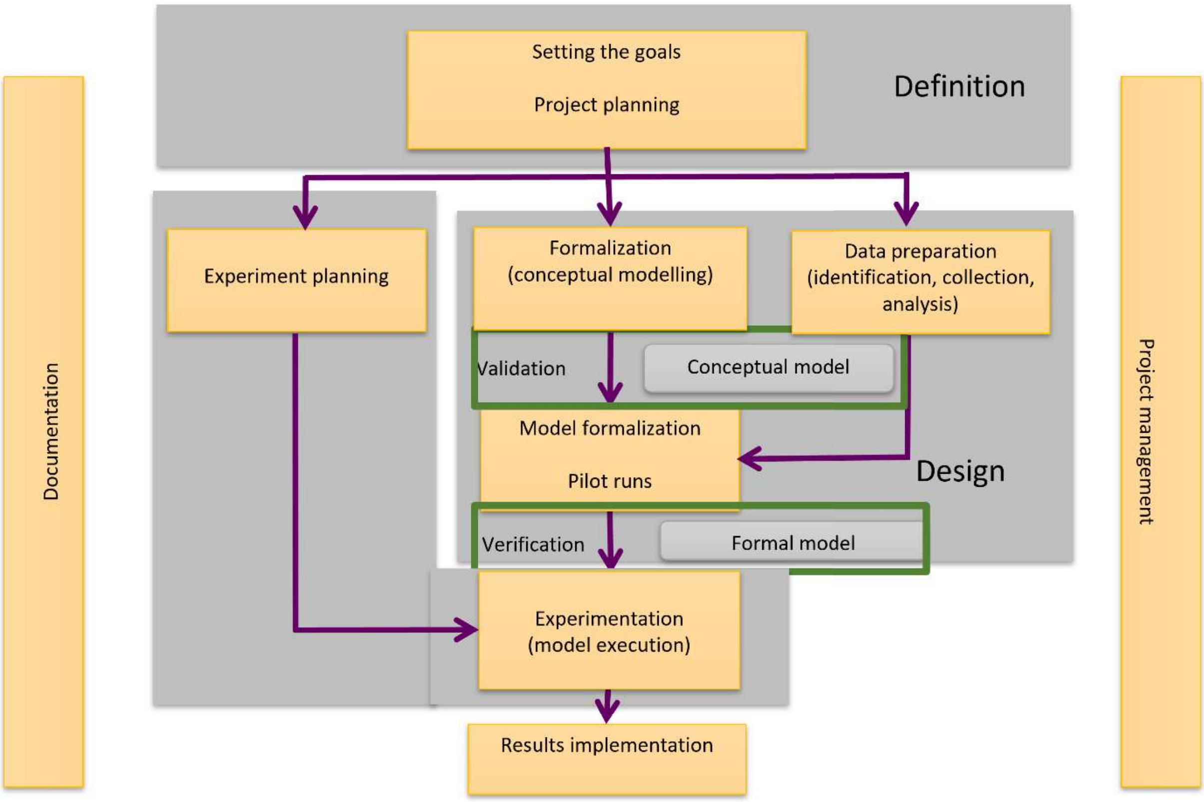


**Figure 4.6 Simulation modelling and analysis (SMA) process.**

## 4.7 Conclusion

In logistics SMA is an important component of operations research (OR) to enable process optimization.

System dynamics (SD) is a methodology for analysing complex, dynamic and non-linear interactions in systems, resulting in new structures and policies to improve the system behaviour. Here, physical and information flows are addressed with the aim to reduce their delay and ultimately SC inventory.

Another popular process-oriented methodology is Discrete event simulation (DES). It is one of the most widely used and flexible analytical tools in SMA of manufacturing systems. It successfully handles uncertainty and provides possibilities to compare alternative ways for lead-time reduction as well as optimization of machine and resource utilization.

A helpful methodology to understanding the behaviours of organizations and their interactions (e.g., SCs and their entities) is Agent-Based Simulation (ABS). Network simulation (NS), being a special kind of ABS, allows for modelling and optimization of (traffic) overlay networks.

This leads to the conclusion that a holistic approach of applying SMA in logistics contributes greatly to complex system design decisions, where there are many variables interacting with each other. A useful integrated approach, including SD, DES and ABS methodologies, which can quantify the workflows on different supply chain levels, has been presented in (Gumzej & Rakovska, 2020). In traffic flow analysis and optimization, the NS methodology provides for the necessary framework, regarding the monitoring and fine-tuning of key performance indicators (Šinko and Gumzej, 2021).

## References Chapter 4


- Conant R.C. and Ashby W.R. (1970). Every good regulator of a system must be a model of that system, Int. J. Systems Sci., 1(2), pp. 89-97.
- Gumzej, R. and Rakovska, M. (2020). Simulation modeling and analysis for sustainable supply chains. In Ecoproduction – Sustainable logistics and production in industry 4.0 : new opportunities and challenges, Grzybowska, K., Awasthi, A., Sawhney, R. (ed.). Springer Nature, pp. 145-160.

- JaamSim Development Team (2023). JaamSim: Discrete-Event Simulation Software. Version 2023-08. [Available at: https://jaamsim.com, access November 8th, 2023]
- Šinko, S. and Gumzej, R. (2021). Towards smart traffic planning by traffic simulation on microscopic level. International journal of applied logistics, 11(1), pp. 1-17.
- Wilensky, U. (1999). NetLogo. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. [Available at: http://ccl.northwestern.edu/netlogo/, access November 8th, 2023]
- Pablo A.L., Behrisch, M., Bieker-Walz, L., Erdmann, J., Flötteröd, Y.-P., Hilbrich, R., Lücken, L., Rummel, J., Wagner, P. and Wießner, E. (2018). Microscopic Traffic Simulation using SUMO. In: 2019 IEEE Intelligent Transportation Systems Conference (ITSC), IEEE. The 21st IEEE International Conference on Intelligent Transportation Systems, 4.-7. Nov. 2018, Maui, USA, pp. 2575-2582.