Combining SysML with Petri Nets for the Design of an Urban Traffic Signal Control

Layse Santos Souza and Michel S. Soares(✉)

Department of Computing, Federal University of Sergipe, São Cristóvão, Brazil
michel@dcomp.ufs.br

Abstract. Urban roads are a crucial infrastructure highly demanded by citizens and organizations interested in their deployment, performance, and safety. Urban traffic signal control is an important and challenging real-world problem that aims to monitor and improve traffic congestion. Therefore, the deployment of traffic signals for vehicles or pedestrians at an intersection is a complex activity, as it is necessary to establish rules to control the flow of vehicles and pedestrians. Also, traffic flow at intersections changes constantly, depending, for instance, on weather conditions and day of the week, as well as road works and accidents that further influence complexity and performance. Thus, this work first uses the SysML Block Definition diagram to model the elements (sensor, controller, and actuator) of the architecture of an urban traffic signal control system. Next, Petri Nets models are proposed for the internal design of each of these elements. Finally, these Petri Nets models are combined into a complete model by merging common places. As a result, this article describes model integration, i.e., SysML Block Definition diagram and Petri Nets for modeling the architectural elements of an urban traffic signal control system.

Keywords: Urban traffic signal control · SysML Block Definition diagram · Petri Nets · System architecture

1 Introduction

Modern cities are highly dependent on infrastructures such as road, rail, and air traffic, energy distribution, water supply, and waste management. These infrastructures are highly demanded by citizens and organizations, their design and maintenance are crucial for daily activities, and they present high complexity and demand for their design, control, and management.

Urban traffic is considered a problem and a challenge for citizens and organizations in a city that aim to monitor and improve quality of life in a city [22]. Therefore, one of the most important infrastructure of a city is its urban road network, as traffic signals are the most basic elements for data acquisition, e.g., vehicle and pedestrian counts, congestion control, accident reports, speed

© Springer Nature Switzerland AG 2021
O. Gervasi et al. (Eds.): ICCSA 2021, LNCS 12957, pp. 115–126, 2021.
https://doi.org/10.1007/978-3-030-87013-3_9

management, and traffic control. The deployment of traffic signals both for vehicles and pedestrians is a complex activity as decisions have to be established to control the right-of-way for both vehicles and pedestrians [3,17].

At an intersection between two or more roads, there are conflicting movements that cannot be performed simultaneously. The control of an intersection is performed from the synchronization of traffic signals that minimizes fuel consumption, pollutant emissions and allows a better traffic flow by combining the green signal times (green wave), i.e., provides the passage of the maximum number of vehicles, reduces stops and delays for drivers at intersections [1,9,11].

Modeling for the control of infrastructure in cities is important to deliver better services and quality of life to the urban population, i.e., socioeconomic development. Currently, a large number of modeling languages are used to model the systems responsible for these infrastructures. For example, UML is used to design these systems with a focus on the software elements of the system, and SysML is used to model elements of systems that are not software [20]. Petri Nets are a formal graphical language that provides support for analysis of problems associated with systems, applicable to a wide variety of systems providing information about the structure and behavior of systems, e.g., resource sharing, concurrency, dynamic behavior, synchronous and asynchronous communication [10,15,27].

A Timed Petri Nets model for a traffic signal control policy system composed of two sensors for emergency vehicles preemption is proposed in [7], presenting the behavior of traffic signals in terms of conditions and events that cause phase preemption, i.e., it identifies and preempts urgent scenarios by conditions and events that control the alternating phases of the traffic signal (red, yellow, and green). After developing this model, the authors performed traffic analysis regarding the properties of liveliness and reversibility using the accessibility graph analysis method. In another related work, the authors of paper [20] used the SysML Requirements, Sequence, and Block Definition diagrams of the SmartCitySysML profile, an extension of SysML to include smart city elements as native SysML components, to model a road traffic control system, i.e., controller, actuator, and sensors for a specific region. The dynamic behavior of a group of traffic signals controlling a network of intersections is a complex discrete event system which can be modeled using Petri Nets [19]. Petri Nets have been considered as well to analyze good properties of models of road traffic signals, both for single intersections and for networks of roads. For instance, formal proofs of models can prove that unsafe states, such as two greens phases in a shared road intersection are not reached [18].

The proposal in this article is to address the architecture design problem of urban traffic signal control systems by using the SysML Block Definition diagram to model the architectural elements (sensor, controller, and actuator) of an urban traffic signal control, and Petri Nets to model the internal behavior of each of these elements, i.e., sub-models of Petri Nets, and then combine these sub-models into a single model to design the behavior of these elements in an urban traffic signal control.

2 Background

2.1 SysML

SysML [12] has been developed by the Object Management Group (OMG) and International Council on Systems Engineering (INCOSE) to develop a unified language for general-purpose modeling for systems engineering applications. SysML is a UML profile applied to systems that include hardware, software, information, processes, people, and procedures.

SysML reuses parts of UML and additionally offers new language elements, such as value types, type of quantity, and the opportunity to describe the functionality of systems. Therefore, it allows one to model a wide variety of systems from different perspectives [24].

It is worth mentioning that SysML also allows modeling in multiple architectural views, through diagrams that can model the structure, behavior, and requirements of a system. In this way, SysML is characterized through diagrams, models, structural and behavioral elements, effective in specifying requirements, allocations, and restrictions on system properties to support a systems engineering project [4,6].

Current version of SysML, named SysML 1.6, was released in December 2019. A full description of all SysML diagrams can be find in [12]. In this paper, the focus is on SysML Block Definition and SysML Internal Block diagrams, which are briefly introduced as follows, as the purpose is to model structural elements which will compose the system architecture.

SysML Blocks, as proposed by OMG, are based on UML Classes extended by UML Composite Structures. Blocks are modular units that are useful to create structural descriptions of a system. A block may include both structural and behavioral features, including properties and operations, to represent behavior and state of a system [12]. The SysML blocks are, respectively:

- **Block Definition Diagram:** defines resources and relationships between blocks, which includes associations, dependencies and generalizations. The Block Definition diagram characterizes blocks in terms of operations, properties, and relationships as a system hierarchy.
- **Internal Block Diagram:** captures the internal structure of a block in terms of properties and connectors between properties.

2.2 Petri Nets

Petri Nets are a graphical formal method applicable to a large variety of systems that provides important information about the structure and behavior of the modeled systems, i.e., simultaneity, concurrency, dynamic behavior, synchronous and asynchronous communication, and resource sharing need to be modeled [10,14–16].

A Petri Net is formally defined [10], as a tuple:

$$P = (P, T, F, W, M_0), \text{ where}$$

$$P = \{p_1, p_2, ..., p_3\} \quad \text{is a finite set of places;}$$
$$T = \{t_1, t_2, ..., t_3\} \quad \text{is a finite set of transitions;}$$
$$F \subseteq (P\text{x}T) \cup (T\text{x}P) \quad \text{is a set of arcs;}$$
$$W : F \rightarrow \{1, 2, 3, ...\} \quad \text{is a function of weights;}$$
$$M_0 : P \rightarrow \{1, 2, 3, ...\} \quad \text{is the initial marking,} \quad P \cap T = \varnothing \quad \text{e} \quad P \cup T \neq \varnothing;$$

According to Peterson [14], the graphic structure of a Petri Net is a bipartite directed graph composed of four elements, explained briefly below and shown in Fig. 1.

- *Places* can represent, for example, conditions, status, states, or operations;
- *Transitions* can represent, for example, start or stop events, which occurs to change the status of places;
- *Arcs* connect places and transitions;
- *Tokens* can represent the number of elements or the current availability of resources.

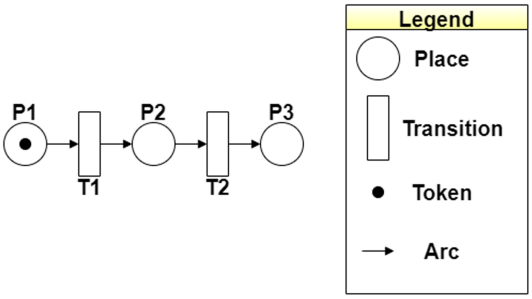


Fig. 1. Elements of Petri Nets.

An example of execution is shown in Fig. 2. Initially, places P1 and P2 with one token are enabling transition T1. After firing of transition T1, tokens in P1 and P2 are removed, and one token is deposited in place P3.

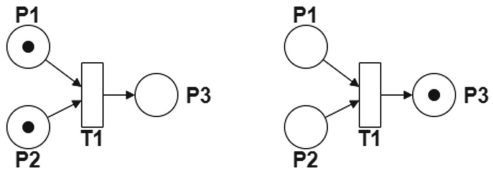


Fig. 2. Execution of a Petri Net.

3 Basic Architectural Elements of an Urban Traffic Signal Control

The design of city infrastructures is crucial for daily activities and is highly complex and demanding due to the need to apply processes and technologies for the control and management of architecture and system design. The main objective of this section is to model each architectural element of an urban traffic signal control system as a SysML Block Definition diagram and then as Petri Nets models.

Figure 3 shows a SysML Block Definition diagram that includes elements of the architecture of an urban traffic signal control. The controller, sensor, and actuator elements are specified using components of Petri Nets. The sensor sends data about the state of traffic to the controller. The controller sends signals to the actuator (traffic signals), and the actuator regulates traffic.

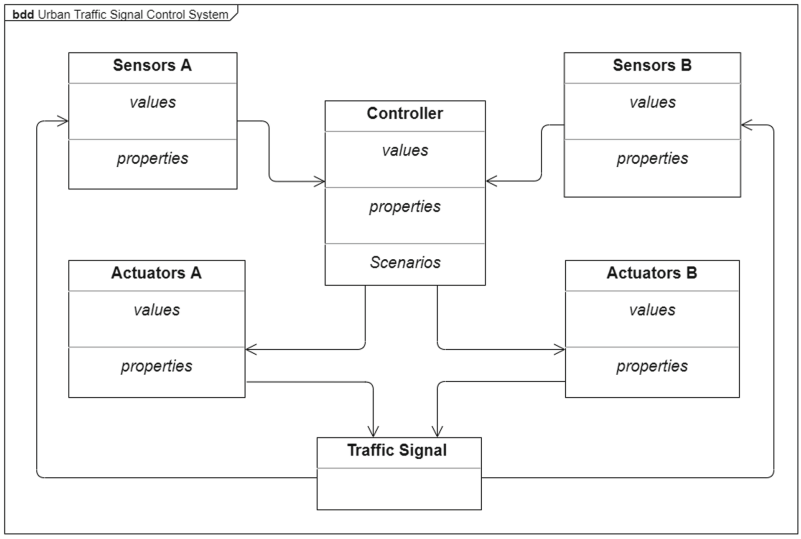


Fig. 3. SysML Block Definition diagram for the architecture of an urban traffic signal control.

Modeling of the controller, sensor, and actuator elements of an urban traffic control is modeled as a Petri Net with modular composition method, i.e., modular Petri Nets, as shown in Fig. 4, 5, 6, respectively.

Figure 4 shows the model of the actuator (traffic signal). This model consists of three phases (green, yellow, and red) together with the requests from the signal to the controller and the responses from the controller to the signal, i.e., places *Red, Green, Green_End, Yellow, and Yellow_End* represent the signal and places *Green_Start, Answers_Green, Yellow_Start, Answers_Yellow, and*

Red_Start represent the solicitations and responses between actuator and controller. For example, place *Green_Start* receives from the controller the response of the request to start the green phase of the corresponding road section, and place *Red_Start* receives from the controller the response of the request to start the red phase of the corresponding road section.

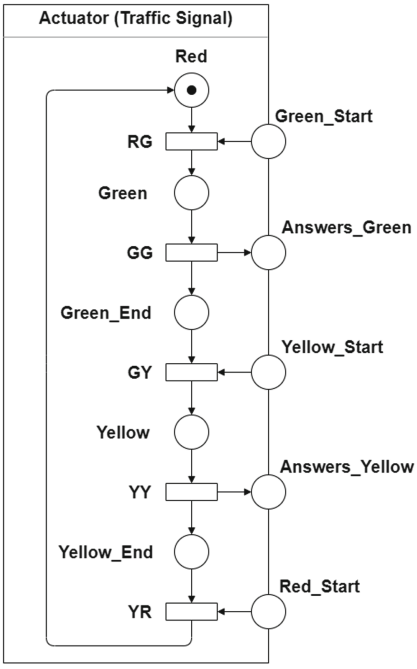


Fig. 4. SysML block definition diagram for the actuator components.

Figure 5 shows the controller model for controlling the traffic signal of an intersection. This model is composed of places *I, Green_Go, Yellow_Go, Green_Start, Answers_Green, Yellow_Start, Answers_Yellow, and Red_Start* and transitions *IGG, GGYG, and YGI*. For example, the controller *I* sends the green signal (token) command to the *Green_Go* actuator when the transition *IGG* is enabled and deposits a token in place *Green_Start*.

Figure 6 shows the sensor model. This model is composed of places *Detect_Vehicle and Answers_Detected_Vehicle*, place *Detect_Vehicle* sends information (token) to the controller warning that a vehicle has been detected and place *Answers_Detected_Vehicle* sends information (token) from the controller to the sensor as a form of response.

In these modular Petri Nets, each element (sensor, controller, and actuator) is modeled as a sub-model of the urban traffic control for easy understanding of future modifications. After these modular Petri Nets models have been developed, the sensor, controller, and actuator sub-models are integrated, forming a

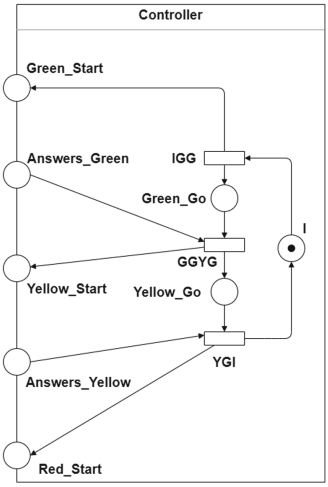


Fig. 5. SysML block definition diagram for the controller components.

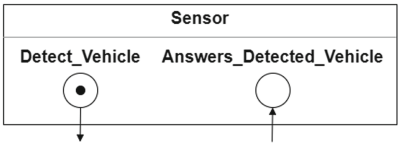


Fig. 6. SysML block definition diagram for the sensor components.

complete model of the urban traffic signal control system as shown in Fig. 9 in the next section.

4 Case Study: Urban Traffic Signal Control

The main objective of this section is to detail the architectural elements of an application for design an urban traffic signal control system. Traffic signal control is considered a competitive traffic management strategy to improve mobility and address environmental issues in urban areas, as they regulate traffic flows to achieve a more efficient traffic management strategy, i.e., one of the main tools to control congestion on roads [8], therefore, they are an important and challenging problem in the real world, which aims to monitor and improve traffic congestion [2,21,23,25].

Traffic signals are control devices applied to urban traffic that aim to optimize the flow of vehicles, allowing safe, efficient, and appropriate crossings, i.e., it is the most basic instrument for collecting traffic data in a city, because they allow to control and manage the flow of vehicles and pedestrians [17,26].

The deployment of traffic signals for vehicles or pedestrians at an intersection is a complex activity, as it is necessary to make decisions, e.g., to establish rules to



Fig. 7. Region of the urban network with visualization of traffic signals.

control the right of way, both for vehicles and pedestrians. Thus, it is necessary to determine new rules of priority between approaches to the intersection to permit crossing or prohibiting movement at the intersection, which could lead to accidents [5,13].

Current traffic signal control systems in use still rely heavily on simplified methods used in the control rules to decide whether to maintain or change the current phase [23]. An intersection between two or more roads is a complex infrastructure, thus the movements cannot be performed simultaneously, as they conflict with each other. As the traffic flow at the intersection changes constantly, depending on weather conditions, day of the week, and period of the day, in addition to works and accidents that further influence complexity and performance, it is necessary to make decisions, that is, to establish rules to control the right path for vehicles and pedestrians [3].

Figure 7 shows a region that presents high traffic flow in a city in north-eastern Brazil. This region is composed of six traffic signals, illustrated by the black circles. In this article, the two chosen intersections are controlled by traffic signals, limiting left turns on either road.

Figure 8 shows the traffic signals chosen from this region to model this case study. The intersections in this region can be improved by providing green waves for the main roads (A and B), that is, providing maximum time to the green phase in a sequence of junctions, so that vehicles can cross as much as possible with few stops.

Figure 9 shows, at an abstract modeling level, the combination of SysML Block Definition diagrams for the urban traffic control elements (actuator in

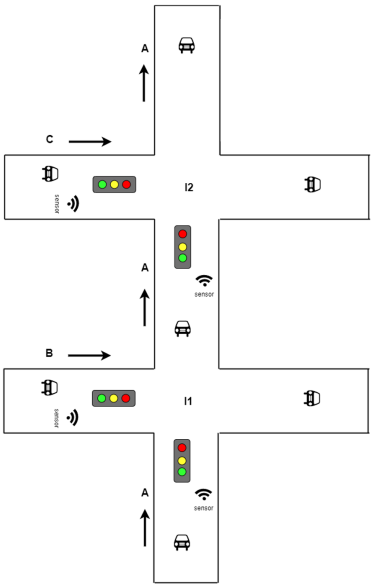


Fig. 8. Specific region of the urban network with visualization of traffic signals.

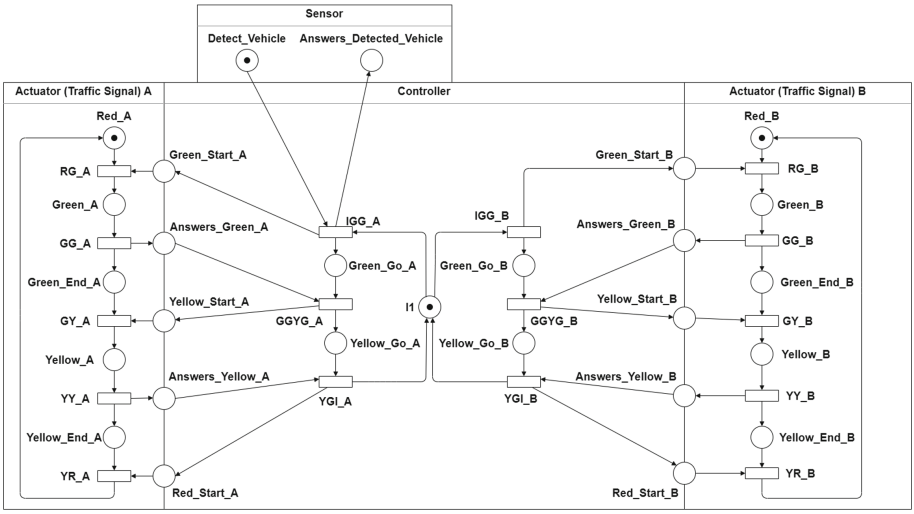


Fig. 9. SysML block definition diagrams of combined Petri Net elements for urban traffic signal control.

Fig. 4, controller in Fig. 5 and sensor in Fig. 6) for the region chosen in this case study, i.e., I1 composed of two traffic signals (A and B), a sensor and a controller for these signals. At this intersection, the A junction of the road has priority over the B one, thus the sensor is in the A junction of the road. A similar design is

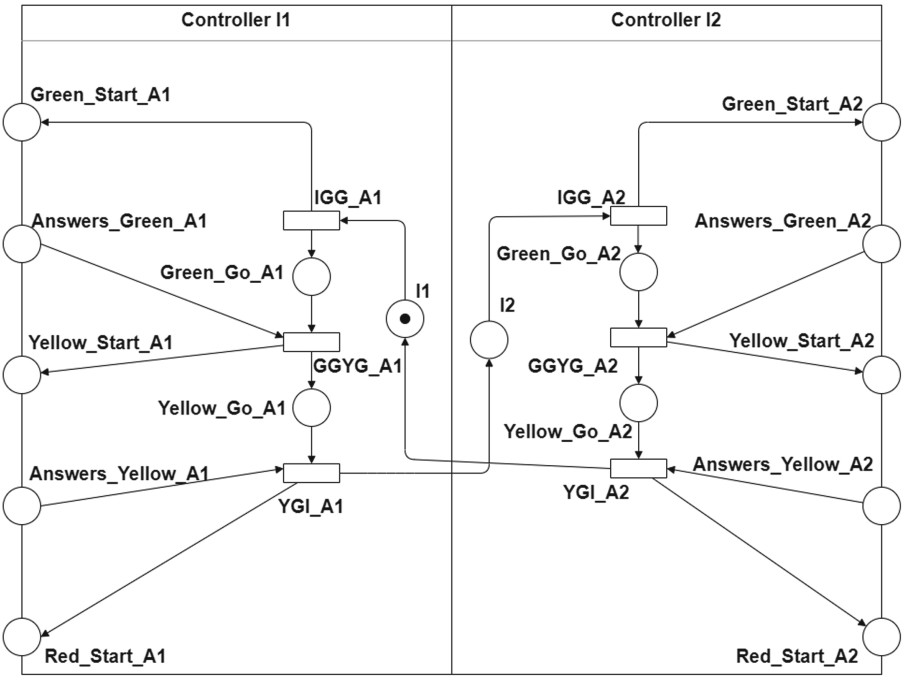


Fig. 10. Petri Nets for an urban traffic signal control (I1 and I2).

used for the sensor, controller, and actuator related to the other intersections of the region illustrated in Fig. 7. It is worth noting that Fig. 9 is depicted from the SysML Block Definition diagram in Fig. 3 and describes that it is possible to design the internal behavior of a SysML Block Definition diagram as a Petri Net model.

Figure 10 shows the behavior of the SysML Block Definition diagram of the controllers for intersections I1 and I2 shown in Fig. 8, that is, when the controller for intersection I1 sends the green signal to intersection I1, the controller for intersection I1 also sends the green signal to the controller for intersection I2. A similar design is used for the other controllers for the other intersections in the region shown in Fig. 7.

5 Conclusion

Modeling systems that control the infrastructure of a modern city is a complex activity, thus there is no single standard to be used, as there are many modeling languages proposed in the past decades for systems engineering activities. This paper proposed the modeling of architectural elements of an urban traffic control system using the SysML Block Definition diagram and Petri Nets to model the behavior of these elements.

The purpose of this paper is to describe the integration of models described using the SysML Block Definition diagram and Petri Nets to model the architectural elements of urban traffic signal control elements, i.e., controller, sensor, and actuator. Thus, the case study details the modeling of urban traffic signal control through the specification of the architectural elements of traffic signal control aiming at a better understanding of the problem. As a working example of a network of roads, a region of northeastern Brazil was defined, then the SysML Block Definition diagram was used to describe the characteristics of each element as a block. Then, Petri Nets models are proposed to represent the behavior of these elements of urban traffic signal control.

Future work will focus on modeling and software simulation of other case studies related to a city's infrastructure, as well as evaluating the Petri Net model developed for the case study (urban traffic signal control) by checking its performance and good behavioral properties to identify possible flaws and correct the functions of an urban traffic control system.

Acknowledgments. This study was financed by Fundação de Apoio à Pesquisa e à Inovação Tecnológica do estado de Sergipe (FAPITEC/SE) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

References

1. Adacher, L., Tiriolo, M.: A distributed approach for traffic signal synchronization problem. In: 2016 Third International Conference on Mathematics and Computers in Sciences and in Industry (MCSI), pp. 191–196 (2016)
2. An, Y., Zhu, C., Chen, P., Li, Y.: Modeling and analysis of transit signal priority control systems based on colored petri nets. In: IEEE International Conference on Systems, Man, and Cybernetics (SMC), pp. 2701–2706. IEEE (2017)
3. Asaithambi, G., Kuttan, M.O., Chandra, S.: Pedestrian road crossing behavior under mixed traffic conditions: a comparative study of an intersection before and after implementing control measures. Transp. Dev. Econ. **2**(2), 1–12 (2016). https://doi.org/10.1007/s40890-016-0018-5
4. Biggs, G., Sakamoto, T., Kotoku, T.: A profile and tool for modelling safety information with design information in SysML. Softw. Syst. Model. **15**(1), 147–178 (2016)
5. Castro, G.B., Hirakawa, A.R., Martini, J.S.: Adaptive traffic signal control based on bio-neural network. Procedia Comput. Sci. **109**, 1182–1187 (2017)
6. Friedenthal, S., Moore, A., Steiner, R.: A Practical Guide to SysML: The Systems Modeling Language. Morgan Kaufmann Publishers Inc., Burlington (2014)
7. Huang, Y.S., Shiue, J.Y., Luo, J.: A traffic signal control policy for emergency vehicles preemption using timed petri nets. IFAC-PapersOnLine **48**(3), 2183–2188 (2015)
8. Le, T., Kovács, P., Walton, N., Vu, H.L., Andrew, L.L., Hoogendoorn, S.S.: Decentralized signal control for urban road networks. Transp. Res. Part C Emerging Technol. **58**, 431–450 (2015)
9. Ma, C., He, R.: Green wave traffic control system optimization based on adaptive genetic-artificial fish swarm algorithm. Neural Comput. Appl. **31**(7), 2073–2083 (2019)

10. Murata, T.: Petri Nets: properties, analysis and applications. Proc. IEEE **77**(4), 541–580 (1989)
11. Ning, Z., Zhang, F., Remias, S.: Understanding the security of traffic signal infrastructure. In: Perdisci, R., Maurice, C., Giacinto, G., Almgren, M. (eds.) DIMVA 2019. LNCS, vol. 11543, pp. 154–174. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-22038-9_8
12. OMG: Systems Modeling Language (OMG SysML) Version 1.6 (2019)
13. Oviedo-Trespalacios, O., Haque, M.M., King, M., Washington, S.: Effects of road infrastructure and traffic complexity in speed adaptation behaviour of distracted drivers. Accid. Anal. Prev. **101**, 67–77 (2017)
14. Peterson, J.L.: Petri Nets. ACM Comput. Surv. **9**(3), 223–252 (1977)
15. Petri, C.A.: Kommunikation mit Automaten. Ph.D. thesis, Universität Hamburg (1962)
16. Reisig, W.: Petri Nets: An Introduction. Springer, New York (1985). https://doi.org/10.1007/978-3-642-69968-9
17. Silvestre, E.A., Soares, M.S.: Modeling road traffic signals control using UML and the MARTE profile. In: Murgante, B., et al. (eds.) ICCSA 2012. LNCS, vol. 7336, pp. 1–15. Springer, Heidelberg (2012). https://doi.org/10.1007/978-3-642-31128-4_1
18. Soares, M.S., Vrancken, J.L.M.: Road traffic signals modeling and analysis with petri nets and linear logic. In: Proceedings of the IEEE International Conference on Networking, Sensing and Control, ICNSC 2007, London, UK, 15–17 April 2007, pp. 169–174. IEEE (2007)
19. Soares, M.S., Vrancken, J.L.M.: Responsive traffic signals designed with petri nets. In: Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, Singapore, 12–15 October 2008, pp. 1942–1947. IEEE (2008)
20. Souza, L.S., Misra, S., Soares, M.S.: SmartCitySysML: a SysML profile for smart cities applications. In: Gervasi, O., et al. (eds.) ICCSA 2020. LNCS, vol. 12254, pp. 383–397. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-58817-5_29
21. Vilarinho, C., Tavares, J.P., Rossetti, R.J.F.: Design of a multiagent system for real-time traffic control. IEEE Intell. Syst. **31**(4), 68–80 (2016)
22. Vrancken, J.L.M., van Schuppen, J.H., Soares, M.S., Ottenhof, F.: A hierarchical model and implementation architecture for road traffic control. In: Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, San Antonio, TX, USA, 11–14 October 2009, pp. 3540–3544. IEEE (2009)
23. Wei, H., Zheng, G., Gayah, V., Li, Z.: A survey on traffic signal control methods. arXiv preprint arXiv:1904.08117 (2019)
24. Wolny, S., Mazak, A., Carpella, C., Geist, V., Wimmer, M.: Thirteen years of SysML: a systematic mapping study. Softw. Syst. Model. **19**(1), 111–169 (2020)
25. Yau, K.L.A., Qadir, J., Khoo, H.L., Ling, M.H., Komisarczuk, P.: A survey on reinforcement learning models and algorithms for traffic signal control. ACM Comput. Surv. **50**(3), 1–38 (2017)
26. Yuan, Y.: Application of intelligent technology in urban traffic congestion. In: 2020 International Conference on Computer Engineering and Application - ICCEA 2020, pp. 721–725 (2020)
27. Zhao, J., Duan, Z.: Verification of use case with petri nets in requirement analysis. In: Gervasi, O., Taniar, D., Murgante, B., Laganà, A., Mun, Y., Gavrilova, M.L. (eds.) ICCSA 2009. LNCS, vol. 5593, pp. 29–42. Springer, Heidelberg (2009). https://doi.org/10.1007/978-3-642-02457-3_3