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Specification and Formal Verification of Safety Properties in Point Automation System by Using Timed-Arc Petri Nets

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Abstract: In this study, control structure related to the safety of the point automation system, which has a critical significance on tram lines, was designed through Timed-Arc Petri Nets by taking CENELEC 50128 standard as reference. CENELEC 50128 strongly recommends the utilization of Timed-Arc Petri Nets during system modeling (Table A.17) and the utilization of formal proof methods during the verification and test phases of command and control structure developed (Table A.5). The verification was performed through CTL (Computational Tree Logic), which is one of the formal proof methods. Timed-Arc Petri Nets model has been used for the first time in this area through this study. Within this context, the structure was developed by taking the point automation system at the Bastabya Station on T4 Topkapı-Habibler line, operated by Istanbul Ulaşım as the reference. Moreover, safety requirements for the automation of the points were identified and denoted mathematically while their safety functions were designed.

Keywords: Point automation, Safety, Verification, Formal methods, Timed-arc Petri nets

1. INTRODUCTION

Points, which enable trains to maneuver to right or left, are one of the fundamental building blocks of railway systems. They play a crucial role in ensuring a safer and rapid journey on rails. For that reason, automation and controlling of points is as significant as their production and installation into the system. Efficiency, speed and reliability of a railway is highly influenced by the number and form of these points. Nowadays, in double track tramlines, performing the automation safely in places where points are located, rather than monitoring the entire line, is a method acknowledged today, which is generally due to cost factors. Therefore, fail-safe command and control of the points is conducted on tramlines, particularly at stations where points are concentrated. Safety and reliability issues become more significant for railway transportation systems than for roads when the length, weight and passenger capacities of the trains are taken into consideration. Point automation systems guide the movement of the vehicles on the tramlines for the safe conducting of vehicles. For this reason, automation of the points should be performed in a safe manner particularly near the stations so that casualties and material losses can be prevented.

Use of formal methods in modeling and verifying signalization and interlocking systems in far more complicated systems, like railways, where safety and reliability are of crucial importance is strongly recommended by CENELEC 50128 (Table A.17). There exist a great number of studies in literature regarding the designing of signalization and interlocking systems using formal methods (Russo and Ladenberger 2012 ; Jo et al. 2009 ; Kanso et al. 2009 ; Winter 2002). As the verifying of the system designed can be made by formal methods, Petri Nets have become a formal modeling tool used frequently for railway systems (Piotrowicz et al. 2007 ; Fanti et al. 2006 ; Cheng and Yang 2006 ; Khana et al. 2013 ; Jacobsen et al. 2011). Studies performed earlier considered the system as a whole rather than focusing on the points, which is one of the most important blocking blocks of railway systems (Okan et al. 2013 ; Mutlu et al. 2013 ; Lozano et. Al. 2011). This study, however, dwells on the automation and control of the points. It is important that safety requirements necessary for a safe journey be identified and based on a mathematical basis while conducting the automation of the points. In this study the safety requirements necessary for the automation of points were identified and their safety functions were designed by denoting such requirements mathematically. Another important issue is to test whether the models, which were formed to ensure the accurate and safe conduct of the point automation system, fulfill the identified safety requirements or not. Therefore, TAPAAL editor was used to verify the existence of anticipated safety requirements for the relevant functions.

This paper is structured as follows. Modeling method of system is mentioned in section 2. Section 3 introduces to Timed-Arc Petri Nets briefly. A short description about components in point automation system is given in section 4. Safety requirements are identified and denoted mathematically in section 5. Point automation components are designed through Timed-Arc Petri Nets in section 6. In section 7, point automation system of Bastabya Station, chosen as the model, is modeled and designed by using Timed-Arc Petri Nets based on CENELEC EN 50128 standard. Safety requirements are verified by using

TAPAAL in section 8 and finally, some discussions and results are given in section 9.

2. MODELING METHOD OF RAILWAY POINT AUTOMATION

Control and automation of the points in rail systems can be stated by discrete events that occur asynchronously. Thus, the system is modeled accordingly. Such events as designating the routes for trains, adjusting the point positions based on the designated route, giving applicable signalization and making the train get into the relevant track section constitute the discrete events occurring asynchronously in point automation. Sometimes such events occur simultaneously while at other times one event can trigger the occurrence of another one. Two methods used frequently in modeling discrete event systems are Automatas and Petri Nets. These two methods are used effectively both in academia and industry for the design and analysis of many systems regarding manufacturing, communications and transportation (Cansever and Küçükdemiral 2006 ; Uzam and Jones 2002). However, the problem of state-space explosion, encountered very often during the modeling phase of the system, has led the researchers to develop different Petri Net models. Within this context, developed Petri Net models, like Coloured Petri Nets, Automation Petri Nets and Timed-Arc Petri Nets, have been put forth recently, which are widely used nowadays. In addition, extra information has been included in the net for the purpose of modeling the system at a lower number of state (Jacobsen et al. 2011).

The point automation system of Bastabya Station on T4 Topkapı-Habibler line operated by Istanbul Ulaşım was designed by using Timed-Arc Petri Nets, one of the formal methods based on CENELEC EN 50128 standard (Table A.17-Modeling), which was also highly recommended to be used by the relevant standard, in the study unlike the other formal methods following the widening of Petri nets. This enabled the modeling and simulation of time bound system acts in a more realistic way. As a result, the movement of points and that of trains in the station occurred within a certain framework of time. In addition, temporal acts could be transferred into the model better, which enabled the empowering of the system modeling. It was not possible to form models that were powerful enough to reflect the system in previous studies since temporal movements in the system were not transferred into the model due to the fact that Timed Arc Petri Nets had not been used.

3. TIMED-ARC PETRI NETS

Timed Arc Petri Net (TAPN) is defined with a 7-tuple $TAPN = \{P, T, IA, OA, Transport, Inhib, Inv\}$, where P is a finite set of places, T is a finite set of transitions, $IA \subseteq P \; x \; \mathcal{T} x \; T$ is a finite set of input arcs, $OA \subseteq T \; x \; P$ is a finite set of output arcs, $Transport : IA \; x \; OA \rightarrow \{true, false\}$ is a function defining transport arcs which are pairs of input and output arcs connected to some transition, $Inhib : IA \rightarrow \{true, false\}$ is a function defining inhibitor arcs which do not collide with transport arcs, $Inv : P \rightarrow \mathcal{T}^{inv}$ is a function assigning age invariants to places. Here the preset of a transition $t \in T$ is defined as $°t = \{p \in P \mid (p, I, t) \in IA\}$. Similarly, the postset of a transition t is defined as $t° = \{p \in P \mid (t, p) \in OA\}$. Similar to a basic PN a marking M on N is a function $M : P \rightarrow B(\mathbb{R} \geq 0)$ where for every place $p \in P$ and every token $x \in M(p)$ thus $x \in Inv(p)$. So the set of all markings over N is denoted by $M(N)$. A marked TAPN is a pair (N, M_0) where N is a TAPN and M_0 is an initial marking on N where all tokens have the age 0.

The enabling rule of a TAPN is a little bit different from the basic PN. $t \in T$ is enabled in a marking M by tokens $In = \{(p, x_p) \mid p \in °t\} \subseteq M$ and $Out = \{(p', x_{p'}) \mid p' \in t°\}$ if $\forall (p, I, t) \in IA. \; \neg Inhib((p, I, t)) \Longrightarrow x \in I$ and $\forall (p, I, t) \in IA. Inhib((p, I, t)) \Longrightarrow \neg \exists x \in M(p). x \in I$ and $\forall (p, I, t) \; IA. \forall (t, p') \; OA.$ $Transport((p, I, t)) Inhib((p, I, t), (t, p')) \Longrightarrow$ $(x_p = x_{p'}) \wedge (x_p \in Inv(p'))$ and $\forall (t, p') \in OA. (\neg(\exists \alpha \in IA. \; Transport(\alpha(t, p'))) \Longrightarrow x_{p'} = 0$ conditions hold. The firing rule t is enabled in the marking M by tokens In and Out then it can fire and produce a marking M_0 defined as $M' = (M \setminus In) \cup Out$ where M is a marking on N and $t \in T$ is a transition. The time delay $d \in \mathbb{R} \geq 0$ is allowed in M if $(x + d) \in Inv(p)$ for all $\forall \mathrm{p} \in \mathrm{P}$ and $\forall \mathrm{x} \in \mathrm{M(p)}$. Also for detailed information about TAPN refer to (Jacobsen et al. 2011; Rakkay et al. 2009).

4. RAILWAY POINT AUTOMATION COMPONENTS

Other components of the railway in the station also play a significant role in the conducting of point automation at a station. This section gives brief introduction for each component.

4.1 Points

A railway point is a mechanical tool which is usually controlled with an electrical motor lets the trains to be guided from one track to another at a railway intersection according to the desired route.

4.2 Signals

Signals are systems that transmit colored light notice, notifying the trains regarding the proceeding of the trains and feed up until the next signal. Signals are placed in front of track circuits in every railway yard. Notifications of the signals provide information whether the destination line is available or not in stations.

4.3 Track Circuits

Track circuit is an electrical circuit used to detect whether the route is available or occupied by a railway vehicle. The relevant mechanism works by using the rails in one part of the road as conductors and short circuiting the rails by the train wheels.

5. POINT AUTOMATION SAFETY REQUIREMENTS

It is an accepted fact that the trains can be easily affected by any disorder at the railway traffic. The visibility ranges usually are not adequate enough to let the locomotive drivers stop the trains; furthermore stop distances of a train can be varied at a large interval based on its total mass. For this reason, railway signaling systems are developed to control railway traffic securely, fundamentally to prevent trains from colliding and derailing as well. Within this context, with tramlines having double tracks, the conduct of the vehicles is generally performed via point automation systems. For a safe journey it is important to ensure that the safety requirements are identified formally. In addition, it should be assured whether the control structure achieved as a result of system modeling fulfills the necessary requirements or not. It is important to bear in mind that fatal accidents are bound to happen in case there remains an unfulfilled requirement. Safety requirements (SR) to be fulfilled by the point automation system can be listed as follows:

SR1. The point should either be in its normal position or in diverging position.

SR2. For a point to be locked, the point should either be in its normal position or in diverging position. Otherwise, point position error should be notified, and the route should not be opened.

SR3. The point should not be moving while the train occupies any point, which means while the train is on its way over the point, it should not get any point engine command.

SR4. When the route selected is locked and opened, the points on the route should also be locked in the relevant position and there should be no proceeding until the route is free.

SR5. Points should firstly be locked based on the route chosen. Then, relevant signal notification should be given when the route is locked.

The safety requirements mentioned above are depicted as follows, where all the points in the field are represented as $P = \{p_1,\ p_2,\ p_3,\ \dots,\ p_i\}$, all track circuits as $RC = \{rc_1,\ rc_2,\ rc_3, \dots,\ rc_j\}$, signals as $S = \{s_1,\ s_2,\ s_3, \dots.,\ s_k\}$, all probable routes by $R = \{r_1,\ r_2,\ r_3, \dots.,\ r_m\}$ and trains as TR= $\{tr_1,\ tr_2,\ tr_3, \dots.,\ tr_n\}$.

I. $F : P \to Normal\ \vee\ P \to Diverging$

$\forall p\ \in P,\ F(p)$

$F \to p_k$ point is either in normal position or in diverging position.

II. $P : R\ X\ P\ \to Partof(r,p)\ \to Pointlocked$

$\forall r\ \in R,\ \forall p\ \in P,\ P(r,p)$

$(r_k\ ,p_k)\ \to Pointlocked\ \in P\ \Longrightarrow$

$(p_k\ ) \to Normal\ \ \vee\ \ (p_k\ ) \to Diverging\ \in F$

$P \to (r_k\ \ p_k)$ point is locked on the route specified. The locked m_k point is locked on the route specified. The locked m_k point is either in normal position or in diverging position.

III. $O : P\ X\ TR\ \to Occupied$

$\forall p\ \in P,\ \forall tr\ \in TR,\ O(p\ ,tr)$

$(p_k\ ,tr_k)\ \to Occupied\ \in O\ \Longrightarrow\ (r_k\ ,p_k)\ \to Pointlocked\ \in P$

O → p_k point is occupied by tr_k train. The occupied point is locked.

IV. $R : R\ \to Routelocked$

$\forall r\ \in R,\ R(r)$

$(r_k)\ \to Routelocked\ \in R\ \Longrightarrow\ (r_k\ ,p_k)\ \to Pointlocked\ \in P$

$R \to r_k$route is locked. Points on the route are also locked once the route is locked.

V. $S : R\ X\ S\ \to Partof(r,s) \to Signallocked$

$\forall r\ \in R,\ \forall s\ \in S,\ S(r,s)$

$(r_k)\ \to Routelocked\ \in R\ \Longrightarrow\ (r_k\ ,s_k)\ \to Signallocked\ \in S$

$(r_k\ ,s_k)\ \to Signallocked\ \in S\ \Longrightarrow$

$s_k\ \to Green \in K$

$S \to s_k$ signal is locked. The route should be locked for the locking of the signal. The locked signal indicates green.

6. TIMED-ARC PETRI NET MODELING OF POINT AUTOMATION COMPONENTS

CENELEC EN 50128 Table A.4-Software Design & Imp. requires the use of Modular Approach. Modeling and design of the system was conducted on modular basis considering the subcomponents to stick to the relevant requirement. For this reason, separate Timed-Arc Petri net models were formed for point and signal. After that the models were connected and Timed-Arc Petri Net model, belonging to the point automation system, was achieved. No model was formed for the track circuit. It was integrated into the system as the field model.

6.1 *Point Timed-Arc Petri Net Model*

Point model consists of six places and four transitions. For the point to change position, it should not be locked for any route in the enable status and there should be no tokens in the RCM section, which means the point is not occupied by a train. When enabled, the point moves towards diverging position. It is required to achieve diverging position by completing its movement (within [max1, max2] interval) within a certain time period. In case it does not achieve diverging position within a certain time period, this will be identified as point position error and the intended route is not opened. The same rule applies for the moving from diverging position to normal position. The relevant Timed-Arc Petri Net model formed can be seen at Fig. 1.

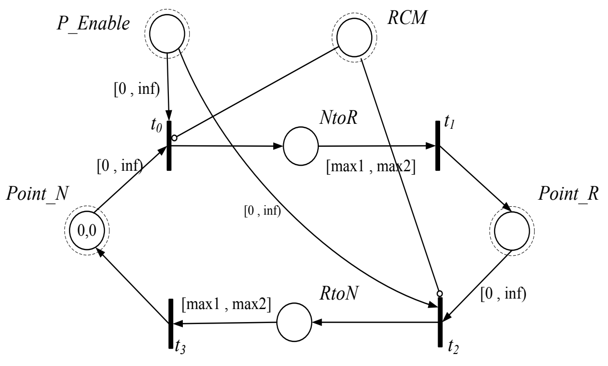

Fig. 1. Point Timed-Arc Petri Net Model

Table 1. Definitions of Places in Point Model

Point_N	Point is in normal position
Point_R	Point is in diverging position
P_Enable	Point can change its position
NtoR	Point goes from normal to diverging
RtoN	Point goes from diverging to normal
RCM	Point is occupied

6.2 *Signal Timed-Arc Petri Net Model*

Signal model consists of four places and two transitions. After the points on the route to be opened reach the relevant position, the signal is enabled and green notification is transmitted to the train for allowing pass. As the train passes the signal and occupies the first track circuit (TrEntM), the signal indicates red once again. Timed-Arc Petri Net model formed for the signal can be seen at Fig. 2.

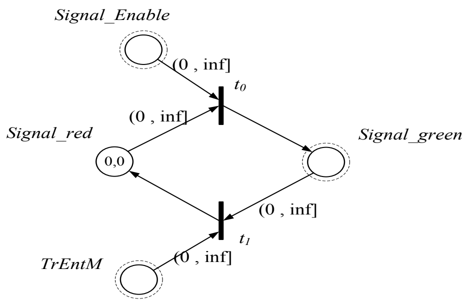

Fig. 2. Signal Timed-Arc Petri Net Model

Table 2. Definitions of Places in Signal Model

Signal_red	Signal indicates red
Signal_green	Signal indicates green
Signal_Enable	Signal is enabled
TrEntM	Train enters the first track circuit

7. POINT AUTOMATION SYSTEM OF BASTABYA STATION

Below can be seen the track scheme of the Bastabya Station on T4 Topkapı-Habibler line operated by Istanbul Ulaşım chosen as a model, the station has a station with five points, five signals and ten track circuits.

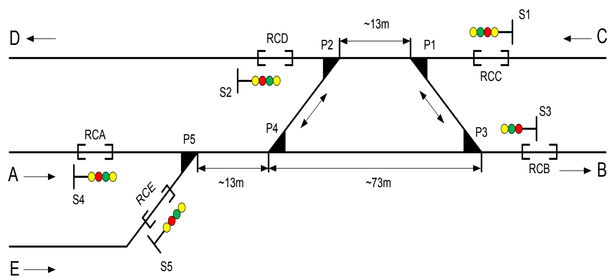

Fig. 3. Bastabya Station Track Scheme

Sets to represent the following items at Bastabya Station, whose track scheme is presented at Fig. 3, were defined: five points $P = \{p_1,\ p_2,\ p_3,\ p_4,\ p_5\}$, ten track circuits $RC = \{RCA,\ RCB,\ RCC,\ RCD,\ RCE,\ RCM1,\ RCM2,\ RCM3,\ RCM4,\ RCM5,\}$, first of five indicating the entering and departing of the station and the last five indicating the occupancy of the points as well as five signals $S = \{s_1,\ s_2,\ s_3,\ s_4,\ s_5\}$. In addition to these sets, other sets were also defined, for example, the set $TR = \{tr_1,\ tr_2,\ tr_3, \ldots\ldots tr_n\}$ to represent the trains and the route set $R = \{r_1,\ r_2,\ r_3,\ r_4,\ r_5,\ r_6,\ r_7,\}$ that can be opened for these trains.

The routes identified can be opened for the trains on the condition that the track circuits are not occupied and the train proceeding on the second route to be opened should not be facing the train proceeding on the first route. Based on this, separate Timed-Arc Petri Net models were formed for each route. As an example, below can be seen the route r_1 Timed-Arc Petri Net model, formed for a train which will be proceeding on CD route.

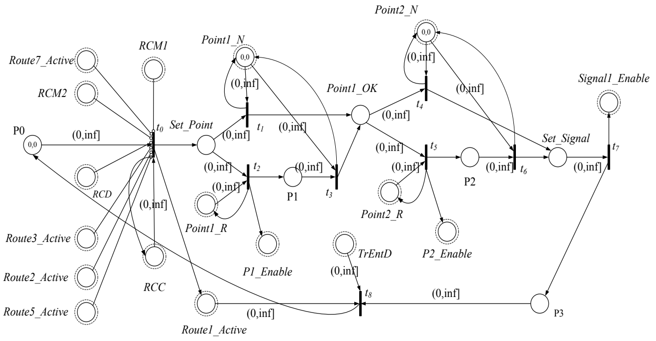

Fig. 4. Route r_1 Timed-Arc Petri Net Model

For route r_1, the table below represents the points, their relevant positions based on the routes to be opened, and which track circuits are controlled.

Table 3. Track Circuit, Point and Point Position by Route

Entrance into the station	Route	Controlled Point and its Position	Track Circuit Controlled
C	r_1(CD)	P1_N, P2_N	RCC, RCD RCM1,RCM2
	r_2(CA)	P1_N, P2_R P4_R, P5_N	RCC, RCA RCM1,RCM2 RCM4,RCM5
	r_3(CE)	P1_N, P2_R P4_R, P5_R	RCC, RCE RCM1,RCM2 RCM4,RCM5

Below can be seen the Track Circuit Timed-Arc Petri Net model, which indicates the actions of the trains that enter the station from C. Similarly, Timed-Arc Petri Net models for trains entering the station from A and E were also formed.

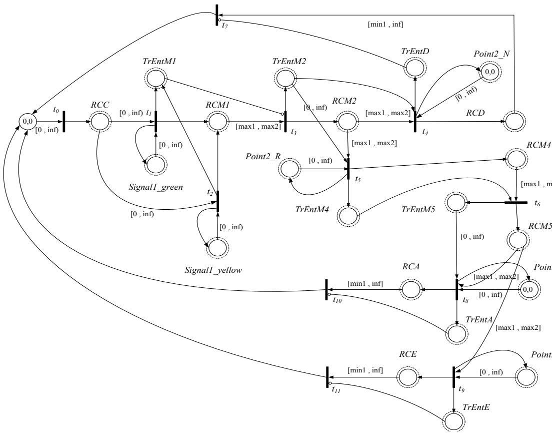

Fig. 5. Track Circuit Timed-Arc Petri Net Model for Trains that Entering the Station from C

As specified above and based on the model formed, the trains entering the station from C can leave the station from D, A or E depending on the route to be chosen. The train occupies the RCC track circuit initially. Then, it proceeds on the route opened, occupying one of the track circuits, which are RCD, RCA or RCE, and leaves the station.

8. VERIFICATION OF POINT AUTOMATION SYSTEM OF BASTABYA STATION

It is of great importance to verify and prove that the formed system models fulfill the identified safety requirements so that a safe journey can be ensured on railway systems. To verify the accuracy of the safety requirements identified in the point automation system designed for the Bastabya Station, TAPAAL editor was used. The editor allows the modeling, simulation and verification of the systems through Timed-Arc Petri nets. The verification of the identified safety requirements was made automatically as (EF, EG, AF, AG) was written on the Computational Tree Logic formulation, which is a subcategory of temporal logic. Thus, it is possible to determine whether the formulate verify the formed model or not as a result of the verification procedure.

It is conducted whether the queries, which were written in verification process, fulfill the identified safety requirements or not by considering all reachable markings (AG) in the Timed-Arc Petri Nets model of the system. The second query, which were written in SR5, are verified by considering some reachable markings (EF). Because, in cases where the route r_1 is not locked, points can be in their normal position. All queries are checked via TAPAAL Discrete Verification method based on the Breadth First search order in state space. As the Coverability Tree is too large, it is not given in the study.

SR1. The point should either be in its normal position or in diverging position.

For $\forall p \in P$,

$$AG\ \neg(\mathrm{Normal}(\mathrm{p_k}) \wedge \mathrm{Reverse}(\mathrm{p_k}))$$

$$\equiv AG\ \neg(Point_k\_N \geq 1 \wedge Point_k\_R \geq 1)$$

Table 4. Verification results and time for SR1

Query	Result	Verification time
Point1_SR1	Satisfied	0.166 s
Point2_SR1	Satisfied	0.163 s
Point3_SR1	Satisfied	0.163 s
Point4_SR1	Satisfied	0.165 s
Point5_SR1	Satisfied	0.165 s

SR2. For a point to be locked, the point should either be in its normal position or in diverging position. It cannot remain in the same position concurrently.

For $\forall p \in P$,

$$AG\neg(Pointlocked(r_k, p_k) \wedge (Normal(p_k) \wedge Reverse(p_k))$$

$$\equiv AG\neg(P_k\_Enable = 0 \wedge (\ Point_k\_N \geq 1 \wedge\ Point_k\_R \geq 1))$$

Table 5. Verification results and time for SR2

Query	Result	Verification time
Point1_SR2	Satisfied	0.164 s
Point2_SR2	Satisfied	0.165 s
Point3_SR2	Satisfied	0.166 s
Point4_SR2	Satisfied	0.165 s
Point5_SR2	Satisfied	0.169 s

SR3. The point should not be moving while the train occupies any point, which means while the train is on its way over the point, it should not get any point engine command or move.

For $\forall p \in P$,

$$AG(Occupied(p_k, tr_k)\ \wedge Pointlocked(r_k, p_k))$$

$$\equiv AG\neg(RCM_k\ \geq 1\ \wedge (P_k.NtoR \geq 1\ \vee\ P_k.RtoN \geq 1))$$

Table 6. Verification results and time for SR3

Query	Result	Verification time
Point1_SR3	Satisfied	0.166 s
Point2_SR3	Satisfied	0.167 s
Point3_SR3	Satisfied	0.166 s
Point4_SR3	Satisfied	0.17 s
Point5_SR3	Satisfied	0.165 s

SR4. When the route selected is locked and opened, the points on the route should also be locked in the relevant position and there should be no proceeding until the route is free.

For $\forall r \in R$ and $\forall p \in P$,

$$AG\neg(Routelocked(r_1)\ \wedge (Reverse(p_1) \vee Reverse(p_2)))$$

$$\equiv AG\neg(Route1locked \geq 1\ \wedge (Point1\_R \geq 1\ \ \vee\ Point2\_R \geq 1))$$

$$EF(Routelocked(r_1)\ \wedge (Normal(p_1) \wedge Normal(p_2)))$$

$$\equiv EF(Route1locked \geq 1\ \wedge (Point1\_N \geq 1\ \ \wedge\ Point2\_N \geq 1))$$

Property is satisfied

In order for route r_1 to be locked, Point1 and Point2 should definitely be in diverging position. The route can be locked provided that both of the points are in diverging position. Otherwise, route r_1 will not be opened or locked.

SR5. Points should firstly be locked based on the route chosen. Then, relevant signal notification should be given when the route is locked.

For $\forall r\ \in R$, $\forall p\ \in P$ and $\forall s\ \in S$

$$EF\ (Routelocked(r_1)\ \wedge (Normal(p_1) \wedge Normal(p_2)))$$

$$\equiv EF(Route1locked \geq 1\ \wedge (Point1\_N \geq 1\ \ \wedge\ Point2\_N \geq 1))$$

$$AG\ (Routelocked(r_1)\ \wedge Green(s_1))$$

$$\equiv AG(Route1locked \geq 1\ \wedge\ Signal1\_green \geq 1)$$

Property is satisfied

In order for route r_1 to be locked, Point1 and Point2 are locked in normal position. Then, green notification is given.

9. CONCLUSION

The point automation system of Bastabya Station, operated by Istanbul Ulaşım in Turkey, was successfully modeled and designed by using Timed-Arc Petri Nets based on CENELEC EN 50128 standard. The model of the system was formed based on such safety requirements. It was verified and proven through temporal logic, one of the formal methods recommended by CENELEC EN 50128 standard, that Timed-Arc Petri Net models fulfilled the identified safety requirements.

Our future work will focus on the development of a software tool to generate the discussed models automatically from the topology of the station.

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