ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
AFRICAN RAILWAY CENTER OF EXCELLENCE

INVESTIGATION of COMMON SECTION INTERLOCKING SYSTEM for ADDIS ABABA LIGHT RAIL TRANSIT

A Thesis in Railway Engineering (Traction and Train control)

BY: Genet Belay

October, 2019

Addis Ababa

A Thesis

Submitted In Partial Fulfillment of the Requirement for the Degree of Master of Science in Railway Electrical (Traction and Train Control) Engineering

The undersigned have examined the thesis entitled "Investigation of common section Interlocking System for Addis Ababa Light Rail Transit"' presented by Genet Belay, a candidate for the degree of Master of Science and hereby certify that it is worthy of acceptance.

Dr. Yalemzewd Negash	________________	________________
Advisor	Signature	Date
Dr. Getachew Alemu	________________	______________
Internal Examiner	Signature	Date
Dr. Fetene Mulugeta	________________	_______________
External Examiner	Signature	Date
Mr. Zewdie Moges	________________	______________
Chairperson	Signature	Date

UNDERTAKING

I hereby declare that the work which is being presented in this thesis entitled “Investigation of common section Interlocking System for Addis Ababa Light Rail Transit” is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis been duly acknowledged.

Genet Belay

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ABSTRACT

An interlocking is "an arrangement of signals and signal appliances so interconnected that their movements must succeed each other in proper sequence". Railway interlocking is a safety, monetary and environmentally critical system because its failure may cause serious consequences such as loss of human life, severe injuries, and large scale of environmental damages or considerable economic penalties. The safety and complexity of this system requires formal modeling and step by step refinement for its construction and development. Computer-based interlocking (CBI) is a device controlling the signaling equipment by computerizing both the electrical and mechanical systems of the existing interlocking device. CBI is preferred in Addis Ababa Light Rail Transit (AALRT) because of its simple lightweight structure, failsafe configuration, high-speed processing of data and simplicity in changing hardware and software. This paper dealt with an investigation of common sections interlocking system which ensured system a synchronization and concurrency by modeling suitable interlocking systems with the help of Petri net. Petri nets are a graphical and mathematical modeling tool applicable to many systems. Petri net is also used in railway application like scheduling rail operation, in supervisory control approach for railway network, modeling train control system for level crossing, and in developing interlocking and signaling system with safety verifications. At first, the physical layout of five stations of AALRT are being drawn using AutoCAD with its full components, such as signals, switches, and track circuits. After that, a proper model of interlocking system is being modeled with the help of Petri net software and the model alleviates the problem which has been encountered in the interlocking system by allowing the interlocking to check the trains asynchronously without any collision.

Keywords: - CBI, Interlocking, Petri net, AALRT, Interlocking table

ACKNOWLEDGMENT

Firstly, I thank my God, for letting me through all the difficulties. I would like to express my special appreciation and thanks to my advisor Dr. Yalemzewd Negash for his lead, encouragement, tolerance, and understanding when supervising my work in this thesis. I would also like to extend my deepest gratitude to my parents, whose love and guidance are with me in whatever I pursue. Most importantly, I wish to thank my mother Letemaryam Tesfay and my beloved husband, Kinfe for supporting me for everything. Finally, I would like to acknowledge, Addis Ababa University and ARCE for giving me the chance to study masters of my degree and their kindness and help during those academic years.

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ABBREVIATIONS

ATC	Automatic Train Control
ATP	Automatic Train Protection
ATS	Automatic Train Supervision
CBI	Computer Based Interlocking
AALRT	Addis Ababa Light Rail Transit
LRT	Light Rail Transit
IPS	Interlocking Process Systems
AC	Axle Counter
CPU	Computer Processing Unit
EW	East West
NS	North South
PN	Petri Net
APNs	Automation Petri-Nets
SIL	Safety Integrity Level
CENELEC	Comité européen de normalisation electrotechnique
HMI	Human Machine Interface
OCC	Operation Control Centre

CHAPTER 1

INTRODUCTION

1.1 Introduction

The importance of transport for the socio-economic development of a given country is inevitable, and advances in technology have allowed people to travel farther, faster, explore more territory, and expand their influence over larger and larger areas. Nowadays, the railway is one of the most widely used transport mechanism, especially in developed nations. Importance of railway transport as one of the most crucial systems in the world, which allows mass transport, very high speed, safety, and durability.

The railway line construction in Ethiopia was first started in October 1897 from Ethiopia to the port of Djibouti during the emperor Menelek 2. The first commercial service began in July 1901, from Djibouti to Dire Dawa, with growing up as the imperial Ethiopian railway depot for nearby Harar. The single track 781 Km railway has a 1000 mm gauge, most of it on Ethiopian territory, and about 100Km in Djibouti. Today the old line is out of service [1]. The latest Addis Ababa LRT began operation on September 20, 2015. It is the first light rail in rapid transit in eastern and sub-Saharan Africa with comprising 2 lines, 2 depots, 39 stations, and 41 vehicles. AALRT contains one common section with ten stations.

Safety is a very important issue in the railway domain with railway signaling, being the basic safety-critical part for controlling the movements of trains on the railway system. The main purposes of railway signaling are; to maintain a safe distance between successive trains on the same track, to safeguard the movement of trains and to regulate the passage of trains according to the service density and speed required in the event of equipment failure to ensure the safety of trains. Once the signal is being instructed by a signaler or an automatic system, it is responsible for setting up non-conflicting and safe routes of trains, thus defining (safe) limits of movement and transmitting instructions or commands to train drivers.

There are several key elements of railway signaling system. Those are; signals, interlocking, train detection (manual detection, track circuits and axle counters), point machine, level crossing, automatic warning system (AWS) and Train protection warning system (TPWS).

A. Signaling: Signal used to command train operation and shunting homework. Railways are provided with signaling primarily to ensure that there is always enough space between trains to allow one to stop before it hits the one in front. Signal is used to indicate whether the track ahead is clear or occupied and to instruct the train operator to proceed (green), proceed prepared to stop at the next signal (yellow), or to stop (red). There are different ways of displaying a signal;

- Green light: it means all switches on the route have been locked in normal position; allowing the train to pass over the signal under predefined speed.

Figure 1 Green Light

- Yellow light: it means at least one switch is locked in reverse position, allowing the train to pass over the signal under predefined speed.

Figure 2 Yellow Light

- Restrictive signal (Red light or dark): it is forbidden signal, trains are not allowed to pass over the signal.

Figure 3 Red Light

- Red+ yellow light: calling-on signal, trains are allowed to pass the route at no-higher than-specified speed (e.g.10Km/h) and shall be ready to stop at any time. Calling-On is only used in failure conditions and approach axle counter section occupied.

Figure 4 Red and Yellow Light

- White light: it is permitted signal, the train shall run at less than 10km/h speed. N.B. the light is only used in depot.

Figure 5 White Light

B. Interlocking: An interlocking is a computerized system that controls the railway signaling objects in order to allow a safe operation of the train traffic. Each interlocking makes use of particular data, called application data that reflects the track layout of the station under control [2]. Interlocking is an arrangement of signals, points, and appliances, operated from a panel or level frame, interconnected by mechanical locking or electrical locking or both their operation must take place in proper sequence to ensure safety. Interlocking is the part of the signaling system and is the main decision mechanism in a railway signalization. For a complex network with heavy traffic it is important that the signal is taken off only after the ensuring the traffic is clear, points are set, locked and secured for the particular route on which the train is to traverse, interlocked level crossing gate falling in the route of the train including the overlap, are closed and locked against the traffic so as to ensure safety. For a particular track the interlocking enables reservation by changing the conditions of the field equipment to an appropriate position so that no other train can occupy the same track and it assures safety such that no collision could occur [3].

Although different interlocking technologies such as mechanical, electrical (electro-mechanical or relay-based), and electronic/computer-based have been in use for railway operation. The modern computer based interlocking (CBI) is a preferred technology for mass transit service. A Computer Based Interlocking System (CBI) is a control railway station signal devices by use of the computer technology to finish the transportation tasks and providing safe condition for train movements [4]. Computer Based Interlocking (CBI) is Computer hardware (microprocessor, memory, hard drive,etc and input and output cards) and computer software (firmware, operational system and control program) create CBI interlocking. Interlocking functions are defined in a control program, also interlocking inputs and outputs and its association with the hardware are declared in the control program. The control program in the case of CBI is called interlocking logic [5].

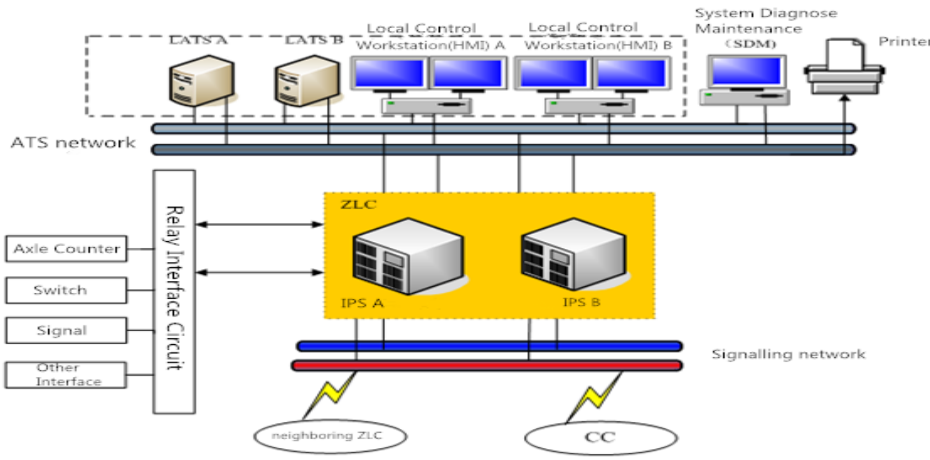

Figure 6 Structure of CBI

C. Point machine: An electric point machine is a device, which can perform the function of unlocking and operating the point switches in the desired position and lock them and detect their correct setting with the aid of an electric motor, similar to that performed by an operator through a lever in a mechanical lever frame.

Figure 7 Point Machine

D. Train detection: its function is to determine if a particular section of track is occupied by a train or not. There are three types of track detection; manual detection, track circuit and axle counter. Manual detection is manual observation by the signaler looking out of the signal box window. Track circuits are electronic components that detect the presence or absence of a train on a railway [6].

Axle counter is a device on a railway that detects the passing of a train b/n two points on a track. A counting head (detection point) is installed at each end of the section and as each train axle passes the counting head at the start of the section, a counter increment. Axle counter do not required insulated rail joints to be installed. And they are particularly useful on electrified railways as they eliminate traction bonding and impedance bonds. But it may forgot how many axles are in a section for various reasons such as a power failure. The system checks whether the zone is free by setting the corresponding axle counter in the section being examined to count the number of axles entering and leaving the zone and also controls the corresponding track relay, to automatically check the section of the idle condition and occupation.

Figure 8 Axle Counter

E. Level Crossing System: A more specialized signaling sub system deals with the management and control of conflicts between road and rail vehicles at level crossings. Equipment includes road lights, barriers, and CCTV monitoring systems.

F. Automatic warning system (AWS): AWS is provided to give train drivers in-cab warnings on the approach to signals, reductions in permissible speed, temporary/ emergency speed restrictions and other locations where the attention of the driver needs to be attracted, such as level crossings. AWS applies the brakes in the event that a driver does not acknowledge the cautionary warnings given by the system**.**

G. Train protection warning system (TPWS): TPWS is designed to intervene and apply the train brakes if the train passes a signal displaying a stop aspect or approaches a stop aspect or a speed restriction at too high a speed. Unlike AWS, TPWS does not provide any warnings to the driver, but activates only when it is necessary to make a brake application.

1.2 Problem Statement

Railway interlocking is a safety, monetary and environmentally critical system because its failure may cause serious consequences such as loss of human life, severe injuries, and large scale of environmental damages or considerable economic penalties. The safety and complexity of this system requires formal modeling. Safe transportation on the railways can be achieved by the use of a reliable interlocking and signalization systems in order to provide safety on the railways so as to avoid fatal accidents. Though there are not any hazards encountered this far; in this investigation there is a reason that can be lead to collision which can cause both human and capital crisis. The reasons is that AALRT uses common stations for both the EW and NS lines that share common track between stations of EW16 and EW20; that are 5 stations. In the common station there are two CBI interlocking systems with their safety check time. If the station is being occupied by a train, the CBI should only check the train while the other wait until the station is cleared, meanwhile it checks the successive train. But in the AALRT case the successive train which enters after the first train was being cleared, was not being checked by the interlocking system. In addition to that, most of the time CBI does not finish the safety check time that allowed to check the safety of the train movement as per requested. Thus this implies that the interlocking system was not being able to check the successive train and the existed interlocking system has a problem functioning asynchronously. Therefore, it is important to investigate the interlocking system of this common section in order to alleviate the problem by modeling a proper interlocking system.

1.3 Objective

1.3.1 General Objective

The main objective of this work is to investigate the Interlocking system in the common section of AALRT, in order to find out the proper remedy for the problem.

1.3.2 Specific Objectives

- To model Interlocking system using Petri net
- Analyze of the physical layout of interlocking system for Common section and the algorithm of train routing system
- To investigate features of AALRT CBI
- To estimate the Interlocking table of the CBI system in provision of greater emphasis to safety
- To analyze Common Interlocking sections utilization using Petri net analyzer

1.4 Methodology

Data has been collected during the investigation of the interlocking system, which leads the indication of the inherent problem of concurrency that makes the trains delay and might leads to danger, in this case, no occurrence of danger has been detected yet, but if the system continues like this there will be apparent probability that will happen, thus Petri net-based model will be designed to alleviate the problem.

In this study, different related research works have been revised. This contains browsing the internet, reading books, publications, and journals related to interlocking system safety and related works. There are many types of research done in the verification, modeling, and simulation of the interlocking system. The interlocking software can be developed or modeled using different kinds of techniques, such as Boolean algebra, State-chart, PLC and SCADA, Matlab and Simulink, VDM, Z notation, Petri nets, and ladder diagram. In this case the research paper deal with a model of the interlocking system using Petri net.

In this paper an investigation is carried out thoroughly to find out the main cause of the restated problem, meanwhile, after the cause of the problem has been addressed sufficient prior works have been gathered and suitable remedy for the problem has been choosing which is modeling of new interlocking system using Petri net. Simulation was done using the Petri net according to the railway safety regulation and safety standard of the international railway system. In modeling the system using Petri net the following aspects were being included; two switches (Normal and Reveres), five stations, and all signals comprised in the common section.

Petri nets are a graphical and mathematical modeling tool applicable to many systems. They are a promising tool for describing and studying information processing systems that are characterized as being concurrent, asynchronous, distributed, parallel, nondeterministic, and/or stochastic. As a graphical tool, Petri nets can be used as a visual-communication aid similar to flow charts, block diagrams, and networks. [7]

Reason for selecting petri net;

- Because of the inherent problem of the investigated interlocking system
- The advantage of Petri net over the rest possible choices to alleviate the problem of the system concurrency by synchronizing the ongoing process.
- The advantage of Petri net inherent characteristics and possibility to be automated using PLC and it is easy to verify the accuracy for the railway station, to reduce the human intervention and to improve the reliability of the system by reducing the chances of errors.
- The main advantages of PNs are easy graphical illustration, easiness in modeling, easy tracking of error and modification. In addition to this, not only PNs can be used for modeling purposes they can also be used for design of supervisory control of interlocking and signalization for different railway operations.

1.5 Scope of the Project

The scope of this work is to investigate the AALRT common section interlocking system and maintain the interlocking safety functions.

1.6 Significance of the research

Innovative solutions and techniques will be develop to increase the capacity of the AALRT railway network. Thus, improved interlocking system will contribute in train safety movement, minimized passengers awaiting time, will increase customer satisfaction, and reduce collision of trains.

1.7 Thesis Organization

The research is organized into six chapters. In the first chapter, the Introduction, background, problem of statement, objectives, scope, significant of the research and, research methodology of the thesis are presented here. In the introduction part about railway interlocking and critical safety and signaling systems are described. In the problem statement, the problem was highlighted.

In the second chapter, types of interlocking systems are presented. Some basic elements of the interlocking system are provided. For a better understanding of the reader principles for safe train movement, fail-safe system, safety standards, components of an interlocking system, interlocking necessity and interlocking principles are discussed. In this chapter different related research works have been revised. This contains browsing the internet, reading books, publications, and journals related to interlocking system safety and related works with their contributions are discussed in here.

Chapter three, contains the modeling of the railway interlocking system, some basic elements of Petri net, properties of Petri net, characteristics of Petri net are discussed. Evaluation of the modeling method, the selected methods to developing the tools, algorithm of railway routing in Ethiopia, Physical layout of the system, and interlocking tables are discussed.

Chapter four contains the results and discussion of the analysis.

In the last chapter, conclusion, recommendation and future works are forwarded.

CHAPTER 2

THEORETICAL BACKGROUND and LITURATURE REVIEW

2.1 Review of Railway Interlocking System

A railway interlocking system is a kind of railway monitor and control system used in railway stations to control traffic safety, for example, to prevent trains from colliding. Railway interlocking system controls signaling system components to achieve safe, expected outcomes of controlling train movement and it must obey the principle of fault safety and equip with necessary redundant. A typical railway definition of interlocking is “an arrangement of signals and signal appliances so interconnected that their movements must succeed each other in proper sequence” [8].

The physical domain of an interlocking system consists of 5 entities, track circuits, points, signal lights, routes, and interlocking table. The tracks circuits are divided into sections, and each section is associated with a circuit for detecting whether it is occupied or not. Track sections are joined by points that can guide trains into different directions depending on the positions of the points. A point can be in position normal or reverse, as well as unlocked to show that the tracks are unconnected at the crossing. Signal lights are placed between track sections and use red or green color to indicate proceed or stop signal respectively. Routes are established for authorizing a train to enter. It is often defined by an interlocking table, which includes the conditions for locking and releasing the train route and for when the entry signals of the route are set to show proceed or stop signal. The railway interlocking system is safety-critical; it must guarantee the safe operations of those signaling apparatus, so its action strictly follows the interlocking logic which is the core of interlocking software [9].

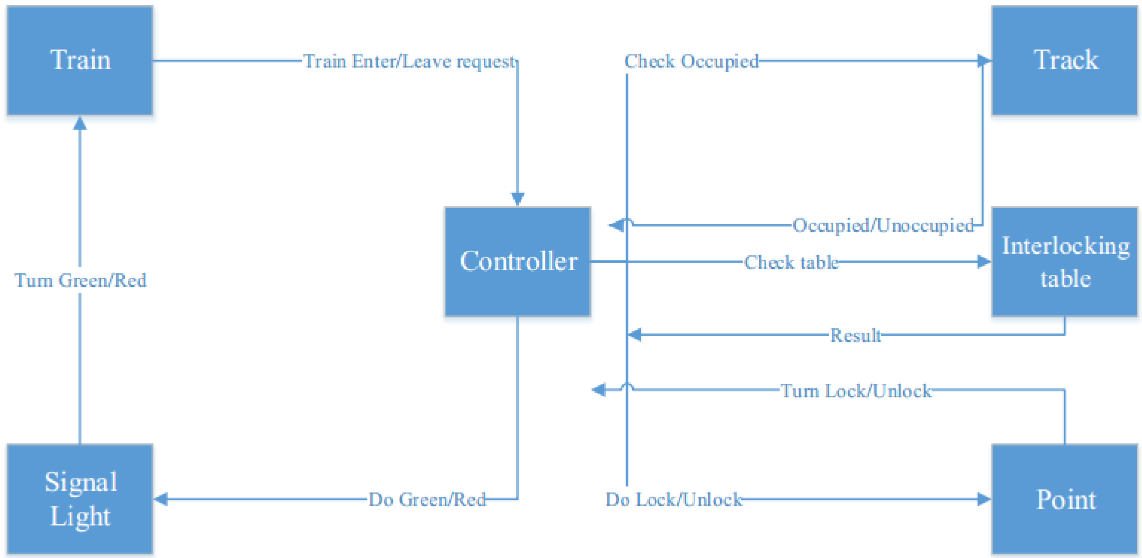

Figure 9 Context diagram of Interlocking system

There are four main types of interlocking systems;

- Mechanical Interlocking system
- Electro-mechanical Interlocking system
- Relay Interlocking system
- Electronic/Computer-based Interlocking System

In a mechanical interlocking system lever frames that operate switches, derails, signals or other appliances are connected to the rod and wire pulls and mechanical levers are used to control elements. A person design the systems can visualize the entire system. Collisions are avoided with the use of mechanical blocks that restrict the actions of elements. This type of interlocking system has benefits for ruler area and minimum traffic flow.

Electro-mechanical interlocking systems consist of a combination of mechanical and relay interlocking system. Wire pulls are replaced by relays which control the movement of elements. In relay interlocking systems, wire pulls are replaced by push buttons on operator panels and track sections enable electrical monitoring [10]. A relay consists of several electrical switches or contacts. Each contact consists of a pair of arms that act as the switch. If the two arms are not in contact the contact remains open and no current can flow through the switch.

However, if the two arms are pushed together by an electric current, the contacts close and current flows through the switch. By interconnecting the relays, the fail-safe logic required by the interlocking can be built into the system. However, railway interlocking systems consist of thousands of relays and require a great deal of space to store all the relays. Besides, the relays are physically wired to the signaling field equipment and cannot be stored far away from the station layout. This significantly limits the size of the area and elements that can be controlled. The copper wires used to connect the relays to the field elements are also a significantly high-cost factor. The relay interlocking influences the need to control trains remotely because interlocking is now centralized for quite extensive area and human actions are limited to requesting route pre-selection. The interlocking logic, in this case, is implemented in circuits that perform specific functions. The interlocking in these circuits is done by relay contacts from relays performing those specific functions. According to Mike Knutton, the average life cycle of an electro-mechanical relay in the UK is 25 years. [11] The relay interlocking allows the capacity of one train every 3-5 minutes again depending on track arrangement. Relays offer the following advantages:

- Low techincal risk regarding safety approval
- Operational performance that can meet all requirements, and
- An economic life long enough to match the capacity of the industry to maintain and renew installations in the long term.

Modern types of interlocking, those installed since the late 1980s, are computer-based interlocking (CBI). They have been implemented in many different configurations always taking into consideration the latest computer developments. The electronic/Computer-based interlocking system is the newest technology system controlled by microprocessors. Instead of an operator panel, the monitoring takes place on a computer screen [10]. CBI shall ensure the safety train-running, and control the routes, signals, and switches under the stipulated interlocking conditions and time sequences to make sure that the interlocking among the signal elements in the route such as track sections, switches, and signals is safe. For the safety operation, shall adopt the security guarantees measure. For the faulty operation of the device, there shall be a valid protective capability.

There are a few reasons why CBI interlocking was introduced to a railway in the space previously occupied by relays. They are the following:

- Interlocking logic previously implemented in circuits (hardware) is done in a computer program (software) that is run in computer hardware
- Computer hardware necessary to implement an interlocking takes much less space than its equivanlent in relays
- Interlocking can be installed remotely and be transmitted to/from the objects (signals, points machine, etc)
- Electronic implementation of interlocking allows digital or software communication with other systems (passenger information system, maintenance system, etc)

Comparing the technology implementation in greater detail, computer-based interlocking is processed sequentially in computing processing. Additionally, conditional checks are also implemented in computing processing. There are many advantages and disadvantages of computer-based. However, signaling experts are not convinced which interlocking implementation gives more benefits or simply which technology suits better current railway needs. According to Mike Knutton, unforeseen delays in the acceptance process for computer-based interlocking (CBI) in Britain have persuaded at least some experts that relay interlocking technology still has a valid and developing future for controlling line-side signaling [11].

The unforseen delays in the acceptance process for CBI can be caused by the following:

- Lack of formal methods to describe behavioural of the interlocking
- Many different applications of CBI interlocking
- Railway expectations to implement more functionality at the same interlocking processing speed and estimated average life of equipment
- Tools to maintain CBI interlocking are not efficient or there is a lack of such tools

On the other hand, some engineers are strongly supporting CBIs. D. Bahr in [12] believes the first types of computer interlocking were more difficult and costly to operate and maintain, however, new types of interlocking based on standard components are to be cheaper, more efficient and flexible.

2.1.1 Components of railway interlocking system

2.1.1.1 Railway Switches

Switches are mechanical devices through which train changes their direction or route from one track to another due to the absence of steering mechanism in railway vehicles. Switches are controlled over switch motors and generally have two states normal and reverse. With the help of sensors, particular data related to the condition of a switch are transmitted to the interlocking systems. [6]

2.1.1.2 Track circuits

Track circuits are electronic components that detect the presence or absence of a train on a railway. They are used to inform signalers and other control equipment. It can be of two types AC or DC track circuits. A logical '1' is sent to the interlocking system when no train is present on track otherwise a logical '0' is sent if a train is present on a track [6].

2.1.1.3 Signal light

Signals are the lights that are placed in front of the switches on railway yards to inform the train driver if the railway yard is occupied or not via the interlocking system and it providing safe and secured train operation [13]. Like on the road signaling, the colors of railway signals have different meanings. Meanings of signal light colors are given in Table 1.

Table 1 Meaning of signal light colors

Colour of the Signal light	Meaning of Colors
Yellow (Y)	The next railway block is free, proceed with a predefined speed
Green (G)	The next two railway blocks are free
Red (R)	The next block is occupied, stop immediately
Yellow-Yellow (YY)	The next block is free, proceed with a track change
Yellow- Green (YG)	The next two block are free, proceed with a track change
Yellow- Red (YR)	A special colour for entering to an occupied railway block
Flashing Yellow (FY)	Flashing signal lights are used while leaving an unsignalled railway block
Flashing Green (FG)	
Flashing Red (FR)	

2.1.1.4 Fail-safe System

A fail-safe system is capable of returning to a predetermined safe state in case there is a failure or malfunction. For railway systems, if switch position indicators shows normal and reverse position at the same time or the position information did not receive even a predefined t time is passed, this means failure and the system have to be lapse into fail situation and have to arrange signal lights and other switches if necessary. Where a signaling system component being in safety-critical fault condition will fail to the right side not causing any dangerous situation for train movement.

2.1.2 Interlocking necessity

The purpose of the railway interlocking system is to control points and signal lights to prevent trains from collisions and derailments while allowing movement. The interlocking system increase high-speed tracks, this arranges points and signals foolproof. Their locking eliminates the possibility of conflicting movement of trains and it helps in proper and safe working of the system.

2.1.3 Interlocking principles

- It must be impossible to take off a signal for approaching train unless the route to which the train taking is properly set, locked and held. At the same time it must be impossible to operate the points while the train is moving on it. This means that points should be set and each facing point is locked.
- It must be impossible to take off position at one and same time for the fixed signals which would lead to conflicting movements. This means points and signals which are locked against such movements.
- It must be impossible for loose wagons to interface with the route for which the points are set and signal has taken off position. This means the levers connecting to points and signals should be interconnected and operated in a particular sequences (pulling/putting back)
- The route for which the points are set and signal taken to off position should be clear of any obstruction (Track circulating)

2.2 Safety Standard

The most important issue in railway systems is to provide safe transportation because no errors can be tolerated in railway systems and errors can sometimes result in fatal accidents. By the development of railways, trains became faster and the density on railways increased. As a result, keeping the trains apart and guaranteeing safety has become more important. A fail-safe design guarantees permanency of the whole system under possible failures and provides required SIL (Safety Integrity Level) levels defined by related safety standards. When a fault occurs, the system either continues safely or moves into a predefined condition known as safe.[14]

Among railway signaling systems, the interlocking systems are responsible of allowing or denying, according to established safety and operational regulations, the routing of the trains through stations or railway yards. Safety and operational regulations are generic for the region or country where the interlocking is located. The high number of complex interlocking rules that guarantee the safe movements of independent trains in a large station makes the verification of such systems a complex task, which needs to be addressed in conformance with EN50128 safety guidelines. [15]

CENELEC EN50128 is the standard that specifies the procedures and the technical requirements for the development of programmable electronic devices to be used in railway control and signaling protection. This standard is part of a family, and it refers only to the software components and to their interaction with the whole system. The basic concept of the standard is the SIL (Safety Integrity Level). Integrity levels characterize software modules and functions according to their criticality, and range is defined from 0 to 4, where 0 is the lowest level, which refers to software functions for which a failure has no safety effects and 4 is the maximum level, for which a software failure can have severe effects on the safety of system, resulting in possible loss of human life.

2.3 Literature Review

Although the Interlocking system was investigated by many researchers their approach to tackling the problems led to a different conclusion, thus, Kahn Et al. [16] [17] modeled software-based automated interlocking system by using timed automata to verify its safety properties using UPPAAL. In their work, they verified the interlocking system and asserted that it was more reliable as compared to the classical system. [18] Studied automated railway signaling and interlocking system design which was a Source of information in order to implement the software in railways. In this paper, they develop the design of an automated railway signaling and interlocking system using a Programmable logic controller (PLC) and SCADA. In the design, the use of sensors and PLC makes the communication and the detection easier than the traditional process. Different methodologies are employed to analyze capacity. In [19], the outer uses real data from the Swedish rail network, train operation and delays to analyze how different factors influence available capacity and train delays. Then the second approach employs the railway simulation tool RailSys in extensive simulation experiments. This methodology is used to analyze the characteristics of double-track operation; and simulation model for strategic capacity evaluation, TigerSim is developed to speed up and improve capacity planning and evaluation of future infrastructure and timetables designs on double-track railway lines. Operating and scheduling railway with safety is the foundation of railway transportation. Analyzing interlocking relationships among turnout junction, signal controller, and track circuit, workers use this method to ensure the safety of train operation [20] elaborate the structure and principle of computer-based railway station Interlocking System based on double 2 out of 2 specifically focusing on computing the security and reliability of this system through factors such as fault coverage, they do the simulation of analysis of security and reliability. The simulation shows that using different redundant structure, different interlocking systems results in incongruity in reliability and security. While in the aspect of security, an interlocking system based on double 2 out of 2 has evident preponderance.

J. LECHNER designed ESA 33, it is a modern, fully electronic world-class interlocking with safety integrity level SIL 4 following European specification EN 50129. Its modular structure allows variable design for different applications to meet the various requirements of a customer [21].

Y. Cao, T. Xu, T. Tang, H. Wang, and L. Zhao [4] developed algorithms, which can be used to automatically generate and verify the interlocking table by inputting the XML file of railway station designed by DSL-CBI. The main advantage of the toolset is to significantly reduce the human errors and improve the efficiency in the generation and verification of interlocking tables. [5] present automating tests used on interlocking systems and show how its use significantly reduces testing time, costs and workload compared to the manual tests used today. Results indicate that automated tests of CBI-systems can bring about a lot of positive changes. The time and resources that are saved can be used to widen the scope of tests performed, and hence speed up system verification and increase safety margins. The automated test was built using Python, although several programming languages could be used. Python presents several benefits that made it seem like the most suitable option. [22][23] Presents an algorithmic approach to interlocking logic Design, followed by an implementation method using programmable devices. The software part of these solutions is often based on the preceding relay system. Regardless of the technology used, every modern railway interlocking system has to conform to the high safety parameters.

A. Bonacchi, A. Fantechi, S. Bacherini, and M. Tempestini [15] suggests to show how the problem has been addressed by a manufacturer at the final validation stage of production interlocking systems, by means of a model extraction procedure that creates a model of the internal behavior, to be exercised with the planned test suites, in order to reduce the high costs of direct validation of the target system. The scope of this work is a modeling of the control tables extracted from the binary files, using a Reverse Engineering process, for the test suites to be simulated on the model by using Matlab and Simulink, using Simulink logic gates to encode Boolean functions extracted from the legacy control tables. Safe transportation on the railways can be achieved by the use of a reliable interlocking and signalization systems to provide safety on the railways to avoid fatal accidents. B. Malakar and B. K. Roy and M. S. Durmuş [6] [13] used automation Petri-Nets (APNs) which is an extension of Petri-nets to model a railway track interlocking and signalization operation systems for safe transportation. The obtained model can be converted into PLC ladder logic program easily to verify the accuracy of the chosen railway yard.

M. Uzam and A. H. Jones (1998) designed a new automation Petri nets (APN) model for the design and implementation of discrete-event control systems (DECS). Moreover, the methodology has been described by considering a discrete event manufacturing problem. To do this, first, an APN model has been designed for the manufacturing system, so that the specifications were met. Then, the APN model has been converted into a token-passing logic (TPL). Finally, the IEC1131- 3 ladder diagram (LD) for implementation on a PLC has been obtained by using a direct mapping from the TPL into LD [24].

S. Ricci and A. Tieri (2008) modeled a software tool based on working criteria and operational rules of interlocking and line signaling systems. The software tool used is a specific software for extended Petri Nets development, validation, and simulation (Faber©), that allows modularity in Petri nets definition and manages variables and types declaration, being endowed with a C language interpreter. [25] The proposed model can be applied in the studies of railway traffic regularity, for example comparing real measured delays with those simulated by the model in the same traffic conditions and finding the causes of specific criticalities. Moreover, the model can be effectively used as a decision support tool both in the phase of planning a new line with new operation timetable and in phase of improvement of existing lines with changed traffic conditions.

H. Xinhong, S. Takahashi, and H. Nakamura (2006) suggest to develop a new concept of distributed interlocking system and new logic of this distributed system and verify its correctness and safety by using Petri net. The result shows that the new distributed interlocking system is feasible and the new logic is safe and correct [26].

P. Sun, S. Collart-Dutilleul, and P. Bon (2015) introduces a colored Petri net model pattern for the French railway interlocking system, which is a parameterized and generalization model framework. [27] This pattern could help people in the planning phase, to validate the correctness of a railway interlocking system in each station along the expected line.

O. Eriş and I. Mutlu (2010) develop a software algorithm for the signal function blocks to satisfy the software requirements, the design and the programming of the interlocking system must be made by formal method. Automaton based method and Petri Nets based method, which are similar to each other in terms of ease of design and applicability, can be chosen as an appropriate method depending on the designer's familiarity and experience. Because of the 20% less usage of work memory, Automaton based method is decided to be the most suitable method for railway signalization systems among other formal methods [2]. To ensure the safety of the railway station interlocking system, Xi Wang, Cheng-tian Ouyang and Pei-Pei Li used the subsystem for route creating as a case study and a formal modeling method based on multiple composite scenarios analysis is provided. In the proposed method, multiple UML sequence diagrams are adopted to specify requirements of the system, and consistent requirements specification are acquired by combining pre-condition and post-condition of object constraint language with domain knowledge to analyze conflicts in multiple UML sequence diagrams. Besides, a model conversion method for transforming behavior sequences to the finite-state process model is proposed, despite these behavior sequences are usually synchronous, asynchronous, concurrency and alternate, which interacted with each other in UML sequence diagram. Finally, an FSP model for the system's formal model is generated by combinatorial operation, it is conformed to the system's functional requirements. The correctness and feasibility of the proposed method have been confirmed by formal model generation for the railway station interlocking system [28]. Petri Nets, including CPNs, have been used extensively to model railway systems. Most researchers focus on train scheduling and performance measures. Without modelling signaling equipment, [29] uses Interval Timed Colored Petri Nets (ITCPN) to model train movement through railway stations and analyses throughput and waiting times of trains using the Modified Transition System Reduction Technique (MTSRT). Similar to [29], Hagalisletto et al. [30] use CPNs to model the Oslo subway and analyze the train schedule but their refined model includes signaling equipment such as track circuits and points. Durmus and Soylemez [31] use an extension of Petri Nets, Automation Petri Nets (APN), to design a simple railway yard. The APN model is then translated into a ladder diagram and Code generated for a programmable logic controller.

Although several papers have been dealt with interlocking using different techniques as mentioned, but there is nothing documented that have been found for AALRT specifically. In this case, a model using the Petri net will be performed for the specified interlocking system, because the inherent problem of the interlocking will be best solved by Petri net and Petri net has an advantage over the other possible choices.

CHAPTER 3

MODELING of INTERLOCKING SYSTEM USING PETRI NET

3.1 Modeling of Interlocking System

Based on the previous discussion and supporting of the literature investigation, the Interlocking model using Petri net software is proposed. Firstly, the application of appropriate Petri net software techniques, properties, characteristics, and analysis of Petri net to the interlocking model is described. The proposed model consists of a physical layout, routing algorithm, control table and simulation of the train route. In the routing algorithm availability of signals, tracks and switch are developed. Thereafter, the route request and point request are implemented for each route.

3.2 Petri net

Petri nets were introduced in 1962 by Dr.Carl AdamPetri (Petri 1962). Petri nets are a powerful modeling formalism in computer science, system engineering and many other disciplines. Petri nets combine a well-defined mathematical theory with a graphical representation of the dynamic behavior of systems. [32] Petri Nets are known as one of the best defined approaches to modeling of discrete and concurrent systems. Petri Nets are a graphical and mathematical modeling tool used to model and analyze information processing systems, communication systems and protocols, real-time systems, multi-processor systems, automatic production systems, flow charts, chemical reactions, ecological systems which may show concurrent, asynchronous, distributed, parallel, nondeterministic and/or stochastic behavior different aspects which have been considered in the research on Petri nets. Petri net is also used in railway application like scheduling rail operation, in supervisory control approach for railway network, modeling train control system for level crossing, and in developing interlocking and signaling system with safety verifications.

A Petri net is a particular kind of bi partite directed graphs populated by three types of objects. These objects are places, transitions, and directed arcs. Directed arcs connect places to transitions or transitions to places. In its simplest form, a Petri net can be represented by a transition together with an input place and an output place In order to study the dynamic behavior of a Petri net modeled system in terms of its states and state changes, each place may potentially hold either none or a positive number of tokens. Tokens are a primitive concept for Petri nets in addition to places and transitions. The tokens are denoted by a solid dot and can be placed inside the place symbol. The presence or absence of a token in a place can indicate whether a condition associated with this place is true or false, for instance. [33] Places can hold any number of tokens or only a limited number (capacitated places).

A Petri net is formally defined as a 5-tuple PN= (P, T, I, O, M_0), where

(1) P= {p1, p2…. pm} is a finite set of places;

(2) T= {t1, t2…. tn} is a finite set of transitions, $P \cup T \neq \emptyset$, and $P \cap T = \emptyset$;

(3) I: $P \times T \rightarrow N$ is an input function that defines directed arcs from places to transitions, where N is a set of nonnegative integers;

(4) O: $T \times P \rightarrow N$ is an output function that defines directed arcs from transitions to places; and

(5) M_0: $P \rightarrow N$ is the initial marking.

The input set (preset) of a transition t, denoted **·t**, is a set of all places for which there are arcs going from these places to the transition t. The output set (post set) of a transition t denoted **t·**, is a set of all places for which there are arcs going from transition t to these places. Similar definitions apply to input and output sets of a place p, denoted by **·p** and **p·** respectively.

A marking in a Petri net is an assignment of tokens to the places of a Petri net. The marking of the net at the beginning of an analysis is called initial marking. Tokens reside in the places of a Petri net. The number and position of tokens may change during the execution of a Petri net. The tokens are used to define the execution of a Petri net. If an arc is drawn from a place to a transition, it indicates that a token in the place is required to enable the transition. The transition is enabled if for all arcs coming to the transition the condition of the required tokens are met. Once a transition is enabled it can fire consuming one token from each input place and putting one token on each output place. A transition can be fired under two circumstance, firstly, number of tokens on a place must be equal to the number of ordinary directed arcs and secondly, transition firing condition X (information coming from sensors that is associated with transition T) must be satisfied. If a place is connected to a transition with an enabling arc, that transition can be fired if and only if the token number on that places is equal or greater than the number of enabling arc. If a place is connected to a transition with an inhibitor arc, that transition can be fired if and only if the token number on that place is lessthan the number of inhibitor arc.

3.2.1 Properties of Petri nets

As a mathematical tool, petri nets possess a number of properties. These properties, when interpreted in the context of the modeled system, allow the system designer to identify the presence or absence of the application domain specific functional properties of the system under design. Two types of properties can be distinguished, behavioral and structural ones. The behavioral properties are these which depend on the initial state or marking of a Petri net. The structural properties, on the other hand, do not depend on the initial marking of a Petri net. They depend on the topology or net structure of a Petri net. Some of the important behavioral properties are: reachability, liveness, safeness (boundedness), and dead lock free. [32,33]

An important issue in designing event-driven systems is whether a system can reach a specific state, or exhibit aparticular functional behavior. In general, the question is whether the system modeled with a Petri net exhibits all desirable properties as specified in the requirement specification, and no undesirable ones [32]. In order to find out whether the modeled system can reach a specific state as a result of a required functional behavior, it is necessary to find such a transition firing sequence which would transform a marking M_0 to Mi, where Mi represents the specific state, and the firing sequence represents the required functional behavior. It should be noted that a real system may reach a given state as a result of exhibiting different permissible patterns of functional behavior, which would transform M_0 to the required Mi. The existence in the Petri net model of additional sequences of transition firings which transform M_0 to Mi indicates that the Petri net model may not exactly reflect the structure and dynamics of the underlying system. This may also indicate the presence of un anticipated facets of the functional behaviorof the real system, provided that the Petri net model accurately reflects the underlying system requirement specification. A marking Mi is said to be reachable from a marking M_0 if there exists asequence of transitions firings which transforms a marking M_0 to Mi. A marking M1 is said to be immediately reachable from M_0 if firing an enabled transition in M_0 results in M1.

In a Petri net, places are often used to represent information storage areas in communication and computer systems, product and tool storage areas in manufacturing systems, etc. It is important to be able to determine whether proposed control strategies prevent from the overflows of these storage areas. The petri net property which helps the existence of overflows in the modeled system is the concept of boundedness. A place p is said to be k-bounded if the number of tokens in p is always less than or equal to k (k is a non negative integer number) for every marking M reachable from the initial marking M_0, i.e., $M \in R(M_0)$. It is safe if it is 1-bounded. A Petri net N= (P, T, I, O, M_0) is k-bounded (safe) if each place in P is k-bounded (safe). A petri net is structurally (inherently) bounded if all its initial marking are bounded. In other words, no reachable state can at any place contain more than k tokens. If k equals one, the marking is said to be safe. This property is used for modelling limited (bounded) resources. [33]

Liveness is a marking Mx of network is live if, for any transition t and for every reachability marking My there exists a firing sequence from My that includes t, in other words, every transition of the net can fire an infinite number of times. A petrinet PN is structurally live, if any initial marking of PN is live. Liveness maybe used to model the occurrences of deadlocks.

3.2.2 Characteristics of Petri net

The typical characteristics exhibited by the activities in a dynamic event-driven system, such as concurrency, decision making, synchronization and priorities, can be modeled effectively by Petri nets.[8]

1. Sequential Execution: In Figure (10), transition t_2 can fire only after the firing of t_1. This imposes the precedence constraint "t_2 after t_1." Such precedence constraints are typical of the execution of the parts in a dynamic system. Also, this Petri net construct models the causal relationship among activities.

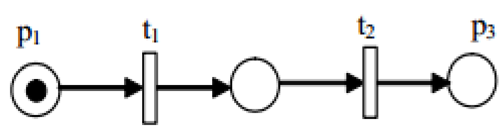

Figure 10 Sequential Execution

2. Conflict: Transitions t_1 and t_2 are in conflict in Figure (11) both are enabled but the firing of any transition leads to the disabling of the other transition. Such a situation will arise, for example, when a machine has to choose among part types or a part has to choose among several machines. The resulting conflict may be resolved in a purely non-deterministic way or in a probabilistic way, by assigning appropriate probabilities to the conflicting transitions.

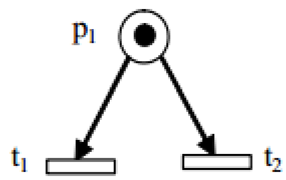

Figure 11 Conflict Transition

3. Concurrency: In Figure (12), the transitions t_1, and t_2 are concurrent. Concurrency is an important attribute of system interactions. Note that a necessary condition for transitions to be concurrent is the existence of a forking transition that deposits a token in two or more output places.

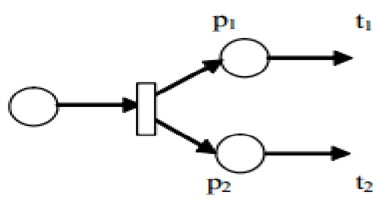

Figure 12 Concurrency

4. Synchronization: It is quite normal in a dynamic system that an event requires multiple resources. The resulting synchronization of resources can be captured by transitions of the type shown in Figure (13). Here, t1is enabled only when each of p_1 and p_2 receives a token. The arrival of a token into each of the two places could be the result a possibly complex sequence of operations elsewhere in the rest of the Petri net model. Essentially, transition t1 models the joining operation.

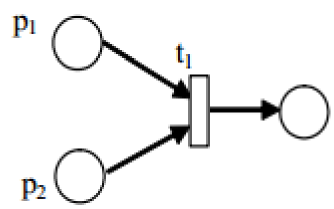

Figure 13 Synchronization

5. Mutually exclusive: Two processes are mutually exclusive if they cannot be performed at the same time due to constraints on the usage of shared resources. Figure (14) shows this structure. For example, a robot maybe shared by two machines for loading and unloading. Two such structures are parallel mutual exclusion and sequential mutual exclusion.

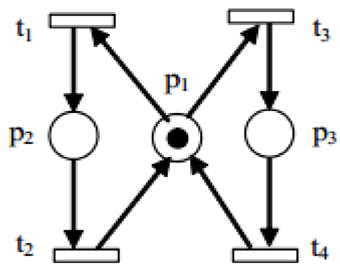

Figure 14 Mutual Exclusive

6. Priorities: A Petri net with an inhibitor arc is shown in Figure (15) t_1 is enabled if p1contains a token, while t_2 is enabled if p_2 contains a token and p_1 has no token. This gives priority to t_1 over t_2.

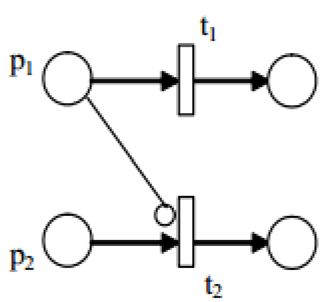

Figure 15 Priority

3.2.3 Petri net Analysis

There are three common approaches to Petri net analysis: 1) reachability analysis, 2) the matrix equation approach, and 3) simulation. The first approach involves the enumeration of all reachable markings, but it suffers from the state-space explosion issue. The matrix equations technique is powerful but in many cases it is applicable only to special subclasses of Petri nets or special situations. For complex Petri net models, discrete-event simulation is an option to check the system properties.

3.2.3.1 Reachability Analysis

Reachability set $R(M_0)$ is a set of petri net of all marking reachable from initial marking $M(t_0)$. If a marking is in the rechability set $R(M_0)$, it means that there exists a firing sequence transforming M_0 into M. Rechability can be analysed by building a rechability graph. Rechability graph is a directed graph where nodes represents marking and edges or transtions between two markings. The graph is constructed by finding all possible transtions from the initial marking , this gives a set of marking reachable from the initial one, then all possible transitions from the previously discovered markings.

Reachability analysis is conducted through the construction of reachability tree (also called coverability tree due to the use of ω markings). Given a Perti net N, from its initial marking M_0, we can obtain as many "new" markings as the number of the enabled transitions. From each new marking, we can again reach more markings. Repeating the procedure over and over results in a tree representation of the markings. Nodes represent markings generated from M_0 and its successors, and each arc represents a transition firing, which transforms one marking to another.

The tree representation, however, will grow infinitely large if the net is unbounded. To keep the tree finite, introduce a special symbol ω, which can be thought of as "infinity". It has the properties that for each integer n, $\omega > n$, $\omega + n = \omega$ and $\omega \geq \omega$.

The reachability tree for a Petri net N is constructed by the following algorithm.

1. Label the initial marking M_0 as the root and tag it "new"
2. For every new marking M:
   2.1 If M is identical to a marking already appeared in the tree, then tag M "old" and go to another new marking.
   2.2 If no transitions are enabled at M, tag M "dead-end" and go to another new marking.
   2.3 While there exist enabled transitions at M, do the following for each enabled transtions t at M:
      2.3.1 Obtain the marking M′ that results from firing t at M.
      2.3.2 On the path from the root to M if there exists a marking M″ such that M′ (p) ≥ M″ (p) for each place p and M′ ≠ M″ i.e. M″ is coverable, then replace M′ (p) by ω for each place p such that M′ (p) > M″ (p).
      2.3.3 Introduce M′ as a node, draw an arc with lable t from M to M′, and tag M′ "new"
3. Merging the same node in a rechabillity results in a rechability graph.

3.2.3.2 Matrix equation

An alternative approach to the representation and analysis of Petri nets is based on matrix equations. In this approach matrix equations are used to represent dynamic behavior of Petri nets. The fundamental to this approach is the incidence matrix which defines all possible inter connections between places and transitions in a Petri net. The incidence matrix of a pure net is an integer n × m matrix A, where n is the number of transitions and m is the number of places. The entries of the incidence matrix are defined as follows: $a_{ij} = a_{ij}^{+} - a_{ij}^{-}$ where, $a_{ij}^{+} = O(t_i, p_j)$ is the weight of the arc from transtion i to its output place j and $a_{ij}^{-} = I(t_i, p_j)$ is the weight of the arc to transtion i from its input place j. It is easy to see from the transtion firing rule that a_{ij}^{+}, a_{ij}^{-}, and aij represents the number of tokens removed, added, and changed in place pj when transtion ti fires once, respectively. Transtion ti enabled at a marking M if and only if $a_{ij}^{-} \leq M(p_j)$, j = 1, 2,..,m [33].

In writing matrix equations, we write a marking M as an m×1 column vector. The j-th entry of mk denotes the number of tokens in place j immediately after the k-th firing sequence. The k-th firing or control vector uk is an n×1 column vector of n – 1 0′s and one nonzeros entry, a 1 in the i-th position indicating that transtion I fires at the k-th firing. Since the i-th row of the incidence matrix A denotes the change of the marrking as the result of firing transtion i, we can write the following state equation for a petri net: $M_k = M_{k-1} + A^T u_k$ k = 1, 2, …. Suppose that a destination marking M_d is reachable from M_0 through a firing sequence $\{u_1, u_2,\ldots,u_d\}$. Writing the state equation for k = 1, 2, …,d and summing them, we obtain $M_d = M_0 + A^T = \sum_{k=1}^{d}$ uk

3.2.3.3 Simulation

For complex Petri net models, simulation is another way to check the system properties. The idea is simple, that is, using the execution algorithm to run the net. Simulation is an expensive and time-consuming technique. It can show the presence of undesirable properties but cannot prove the correctness of the model in general case. Despite this, Petri net simulation is indeed a convenient and straight forward yet effective approach for engineers to validate the desired properties of a discrete event system. The algorithm is given as follows:

1. Initialization: decide the initial marking and the set of all enabled transitions in the marking;
2. If the number of preset simulation steps or certain stopping criteria is met, stop. Otherwise, if there is no transition enabled, report a deadlock marking and either stop or go to Step (1).
3. Randomly pick a transition to fire. Remove the same number of tokens from each of its input places as the number of arcs from that place to the transition and deposit the same number of tokens to each of its output places as the number of arcs from the transition to that place.
4. Remove enabled transitions which are modified at the new marking by checking the output transitions of the input places used in Step (3). If the output transitions of the output places in Step (3) become enabled, add those enabled ones. Go to Step (2).

3.3 Railway Routing in AALRT

Different Interlocking systems from different manufacturers may have different control methods. In AALRT CBI is combined with the ATS system to control the train route automatically. Through ATS network, the interlocking devices provide the signal status information to ATS equipment, and receive the route control command from ATS system. When a fault occurs in ATS, the train route shall be set through the fleet route mode or cycle route mode and the automatic control mode shall not be changed until there is manual intervention. Train route shall be setup, established, and unlocked in accordance with correct interlocking relationship, and comply with the principle of fault-safety, and may have certain function of automatic route setting.

3.3.1 Route Set

The correct route shall be set according to the operation intention. The routes cannot be set at the same time because it would open the scenario for a train crash. Therefore, they have to be interlocked within each other allowing just one route at a time. The system also will to have an option to independently request individual point movement in a case where for example some maintenance work has to be conducted.

3.3.2 Route Locking

Route setting involves a collection of adjacent track circuits, points and signals. A route can be set and reserved for a passage of a train along this route. To ensure the safety, firstly the interlocking system verifies that the route does not conflict with other routes previously set. Secondly, the points along the route are locked in the correct positions. If the related points are not in the correct position, the controller will attempt to set and lock them in the correct positions. Thirdly, the track circuits along the required route are all clear or unoccupied so that nothing obstructs the passage of the train. Then the entry signal can be cleared (showing yellow or green).

Route locking shall be divided into advance locking and approaching locking.

- Advanced locking: is constituted when the route is established and interlocking conditions are provided.
- Approaching locking: is constituted, when the approaching section is occupied after the

signal is clear. If there is no approaching section, approaching locking shall be constituted immediately after the signal is clear.

3.3.3 Route Release

After the passage of the train, the reserved route is released automatically. There are different types of route release in AALRT. Those are;

- Normal Release: after the protective signal is closed, each track section shall be released automatically along with train normal running.
- Route Cancel: when a route is not in the approach lock status is to be cancelled, it should be unlocked immediately after confirming the signal is closed and the route is unoccupied.
- Manual Release: if then route is in the approaching locked, cancel the route and the route is only released with delay to ensure the safety of the running. If the train moved into the route, the route cannot be cancelled or released. The route will be released after a while, and the operation of manual route release shall be recorded automatically.
- Section release Manually(section fault release): when the track section is power-on, recovery and locked for faults, it shall be released manually by “Section Fault Released’’ and recorded automatically after confirming it is unoccupied and doesn’t be set as a part of the route, release this section.
- Call-on Route Release: after manually confirming the safety of running, the call-on route shall be released via “Route release manually” operation.

3.3.4 Route protection

Except for protecting the normal train route, the CBI shall set the appropriate overlap to protect the train route according to the need.

3.3.5 Fleet Route

The operator shall set parts or all of the signals to automatic status on HMI to set the fleet route mode. Before the fleet route mode is set, the route shall remain unchanged if the route has been set. When cancelling the fleet route, it shall cancel the fleet mode of the route without cancelling the route. The route shall be released by train running.

3.3.6 Cycle Route

The cycle route is a sequence of route triggered automatically by CBI and used to turn back a train. According to the ground signal, the driver controls the train running.

3.4 Physical Layout

The physical layout illustrates the geographical arrangement of signaling filed elements, switch and, track circuits in a railway system. Railway layouts have been modeled using AutoCAD to develop a basic physical layout show in the figure below. These components are built according to CBI system that the current AALRT used.

In AALRT, there are 8 main stations on the East-West line and the North-South line, (EW1, EW7, EW16, EW20, EW22, NS27, NS10 and NS6) controlling the signals, switches and routes on mainline through the CBI subsystem installed in 8 stations. This paper basically focuses in EW16 - EW20, which comprises five stations.

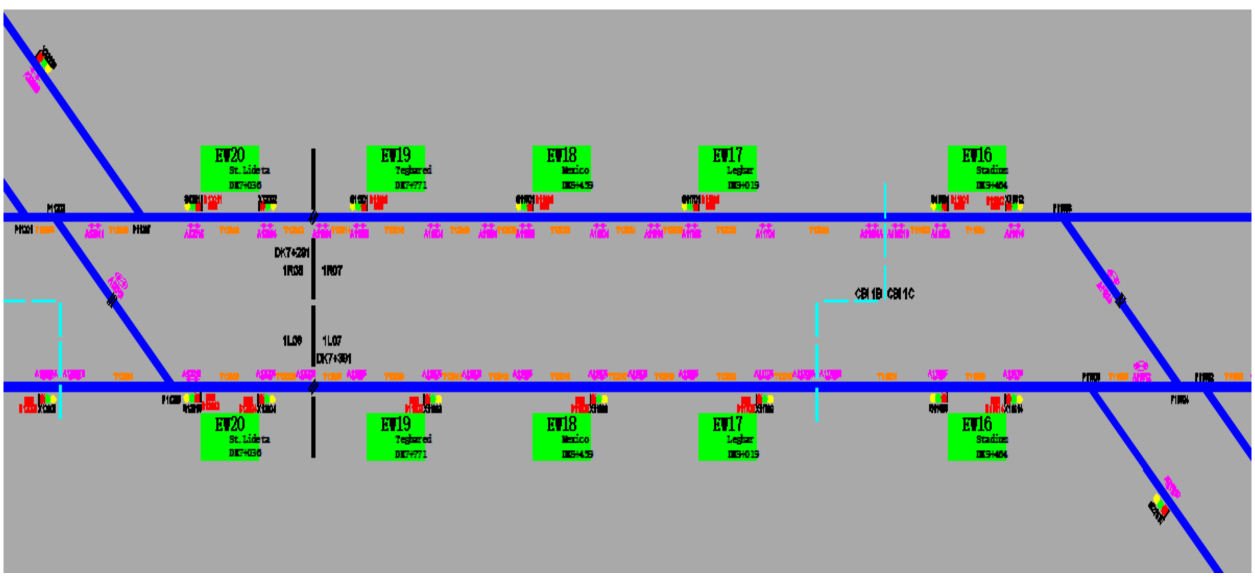

Figure 16 AALRT common section

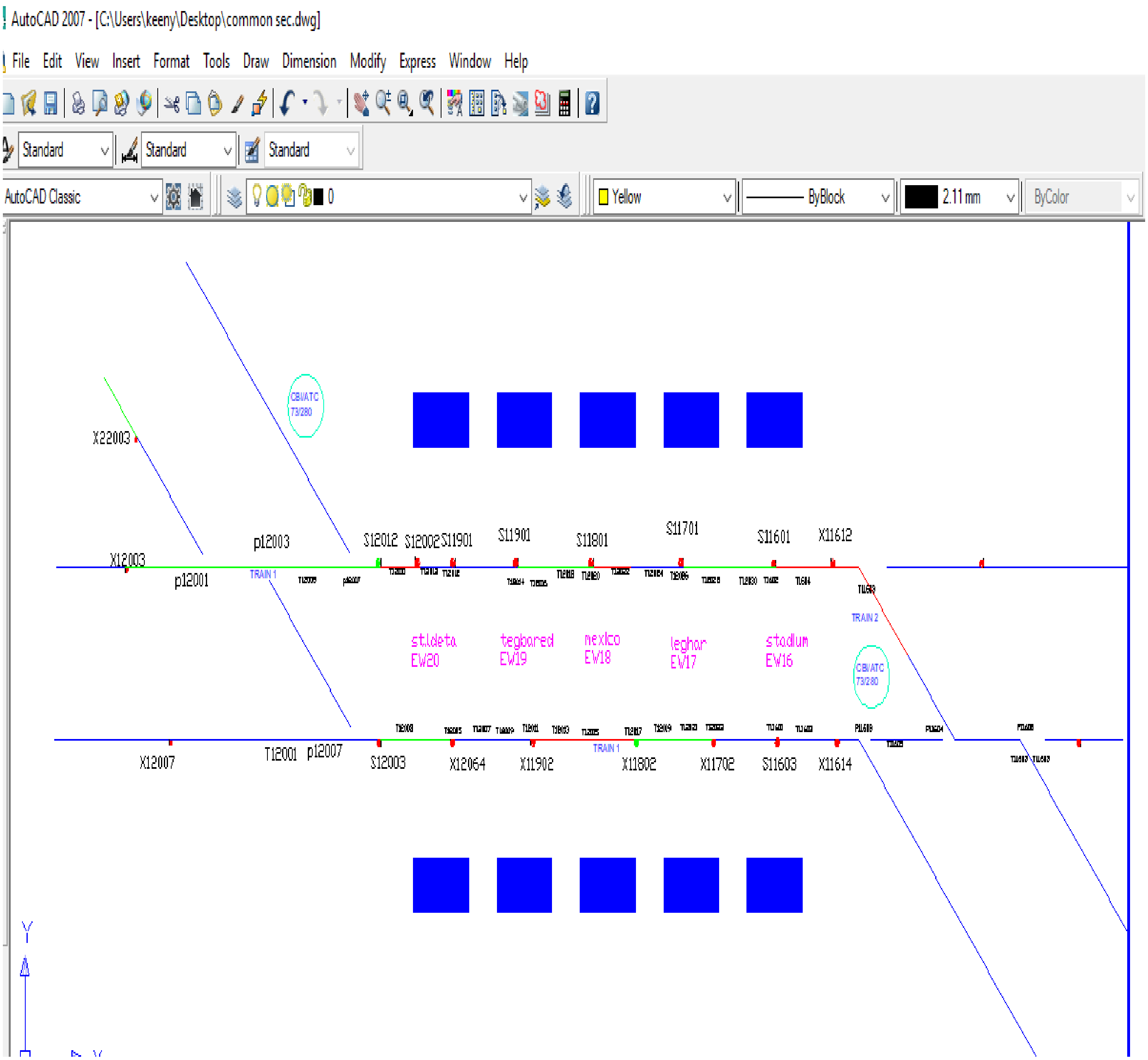

Figure Physical layout of common section using AutoCAD

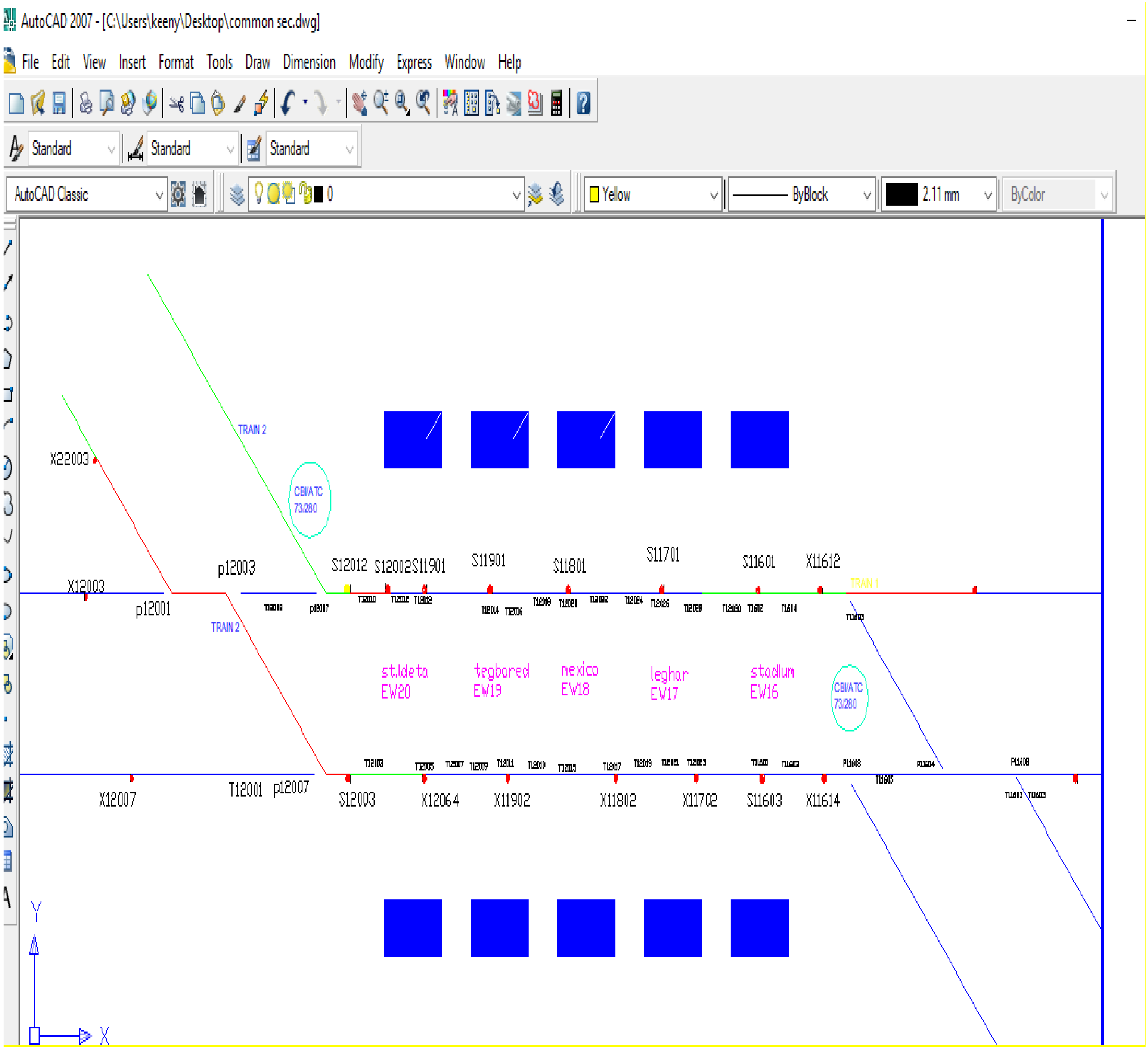

Figure 17 Physical layout of common section using AutoCAD

3.5 Routing Algorithm in Common Section of AALRT

The first step in the interlocking algorithm is to check for any operator request (Route request and Point request) and detect its kind, then detect which exact situation is being requested. Before allowing the passage of a train in a zone that includes turnouts, it is necessary to be sure that: if the route is free (trains in sense of permissive block), if switches are properly moved and locked and if the route is protected against any converging, cutting, or running in the opposite direction.

There are 8 possible route request for a train in these common section of AALRT.

- From signal S21513 (Meshalokya) toward signal S11601 (Stadium) through Reverse position of point P11604 and P11606, the route will be symbolized M → R
- From signal S12011 (St.Lideta) toward signal S22101 (Darmar) through Reverse position of point P11207, the route will be symbolized L → R
- From signal S11501 (St.Estifanos) toward signal S11601 (Stadium) through Normal position of point P11606, the route will be symbolized E → N
- From signal S12011 (St.Lideta) toward signal S12101 (Coca Cola) through Normal position of point P11207 and P11201, the route will be symbolized L → N
- From signal X22110 (Darmar) toward signal X12004 (St.Lideta) through Reverse position of point P11203 and P11205, the route will be symbolized D→ R
- From signal X11614 (Stadium) toward signal X21504 (Meshalokya) through Reverse position of point P11608, the route will be symbolized S→ R
- From signal X12102 (Coca Cola) toward signal X12004 (St.Lideta) through Normal position of point P11205, the route will be symbolized C → N
- From signal X11614 (Stadium) toward signal X11510 (St.Estifanos) through Normal position of point P11608 and P11602, the route will be symbolized S → N

The route cannot be set at the same time because it would open the scenario for a train crash. Therefore, they have to be interlocked within each other allowing just one route at a time. The system also will need to have an option to independently request individual point movement in a case where for example some maintenance work has to be conducted.

Route request

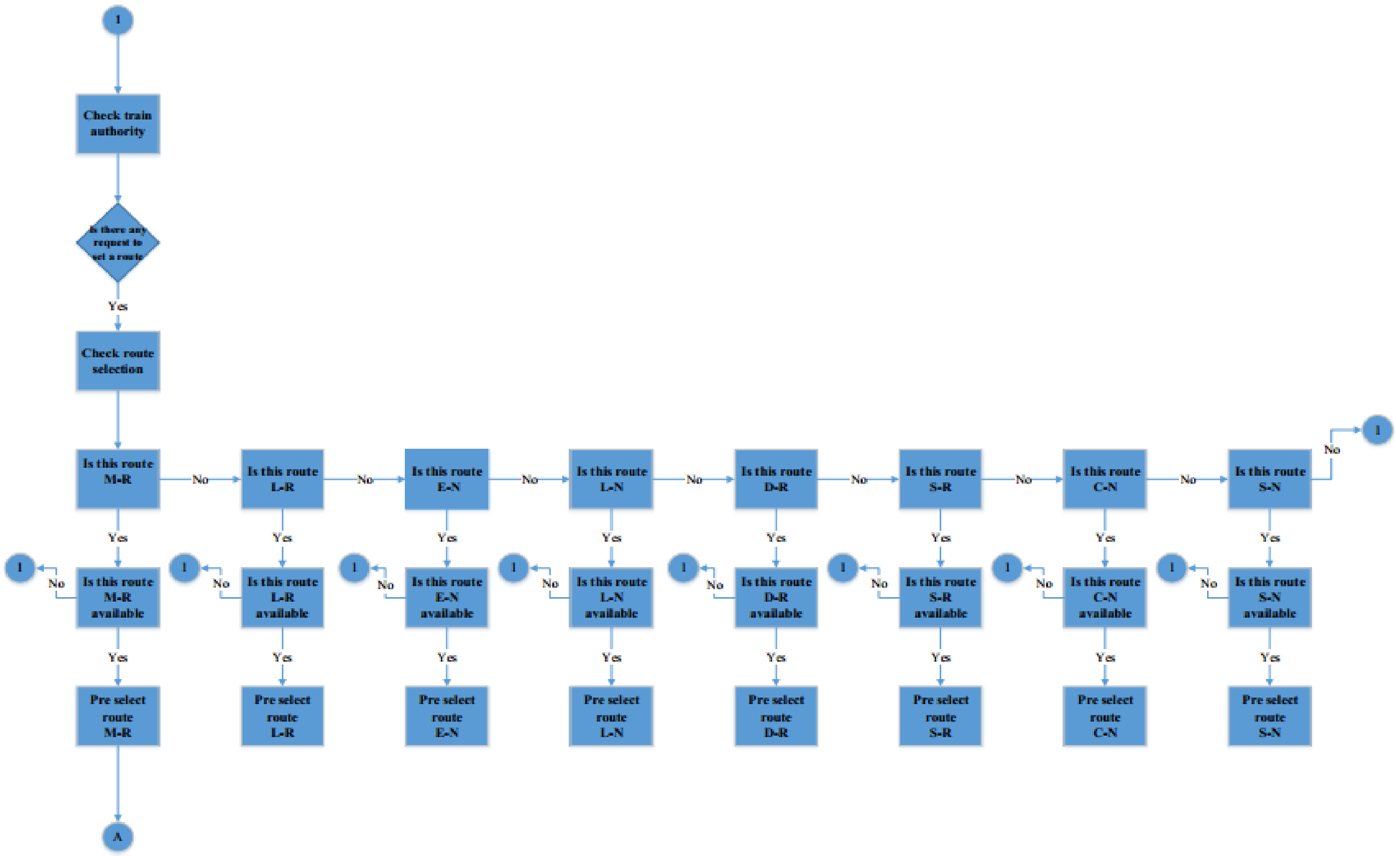

Figure 18 Route request for CBI Algorithm

Route Availability

1. Check train authority
2. Is there any request to set a route?

    Yes then, check route selection go to step 3

    Else, go to step 1

2.1 Are the signal available?

    No, then signal unavailable go to step 1

    Else, signal is available go to step 2.2

2.2 Are the switch available?

No, then switch unavailable go to step 1

Else, switch is available go to step 3

3. Are there are conflicting routes?

Yes, then the route is unavailable go to step 1

Else, route is available go to step 4

4. Is this route M-R?

Yes, then go to step 4.1

Else, go to step 5

4.1 Is this route M-R available?

Yes, then preselect route M-R

Else, go to step 1

5. Is this route L-R?

Yes, then go to step 5.1

Else, go to step 6

5.1 Is this route L-R available?

Yes, then preselect route L-R

Else, go to step 1

6. Is this route E-N?

Yes, then go to step 6.1

Else, go to step 7

6.1 Is this route E-N available?

Yes, then preselect route E-N

Else, go to step 1

7. Is this route L-N?

Yes, then go to step 7.1

Else, go to step 8

7.1 Is this route L-N available?

Yes, then preselect route L-N

Else, go to step 1

8. Is this route D-R?

   Yes, then go to step 8.1

   Else, go to step 9

8.1 Is this route D-R available?

   Yes, then preselect route D-R?

   Else, go to step 1

9. Is this route S-R?

   Yes, then go to step 9.1

   Else, go to step 10

9.1 Is this route S-R available?

   Yes, then preselect route S-R

   Else, go to step 1

10. Is this route C-N?

   Yes, then go to step 10.1

   Else, go to step 11

10.1 Is this route C-N available?

   Yes, then preselect route C-N

   Else, go to step 1

11. Is this route S-N?

   Yes, then go to step 11.1

   Else, go to step 1

11.1 Is this route S-N available?

   Yes, then preselect S-N

   Else, go to step 1

Point Request

1. Check train authority
2. Is there any normal point request (R-N)?
   Yes, Initialize point request R-N and go to step 3
   Else, go to step 1
3. Is there any point request cancellation?
   Yes, then cancel point request and go to step 1
   Else, go to step 4
4. Is there any route preselected or locked?
   Yes, then initialize point request R-N
   Else, go to step 5
5. Are the points detected reverse?
   Yes, then control points normal (R-N) and go to step 8
   Else, cancel point request (R-N) and go to step 6
6. Is there any technical problem?
   Yes, then point system fault and go to step 7
   Else, go to step 1
7. Is point movement system fault removed?
   Yes, then perform all check again and go to step 1
   Else, points movement fault
8. Are the points locked and detected in normal position?
   Yes, then go to step 1
   Else, go to step 9
9. Is there any technical problem?
   Yes, then point movement R-N system fault and go to step 10
10. Is point movement system fault removed?
    No, then point movement R-N system fault
    Else, perform all checks again and go to step 1

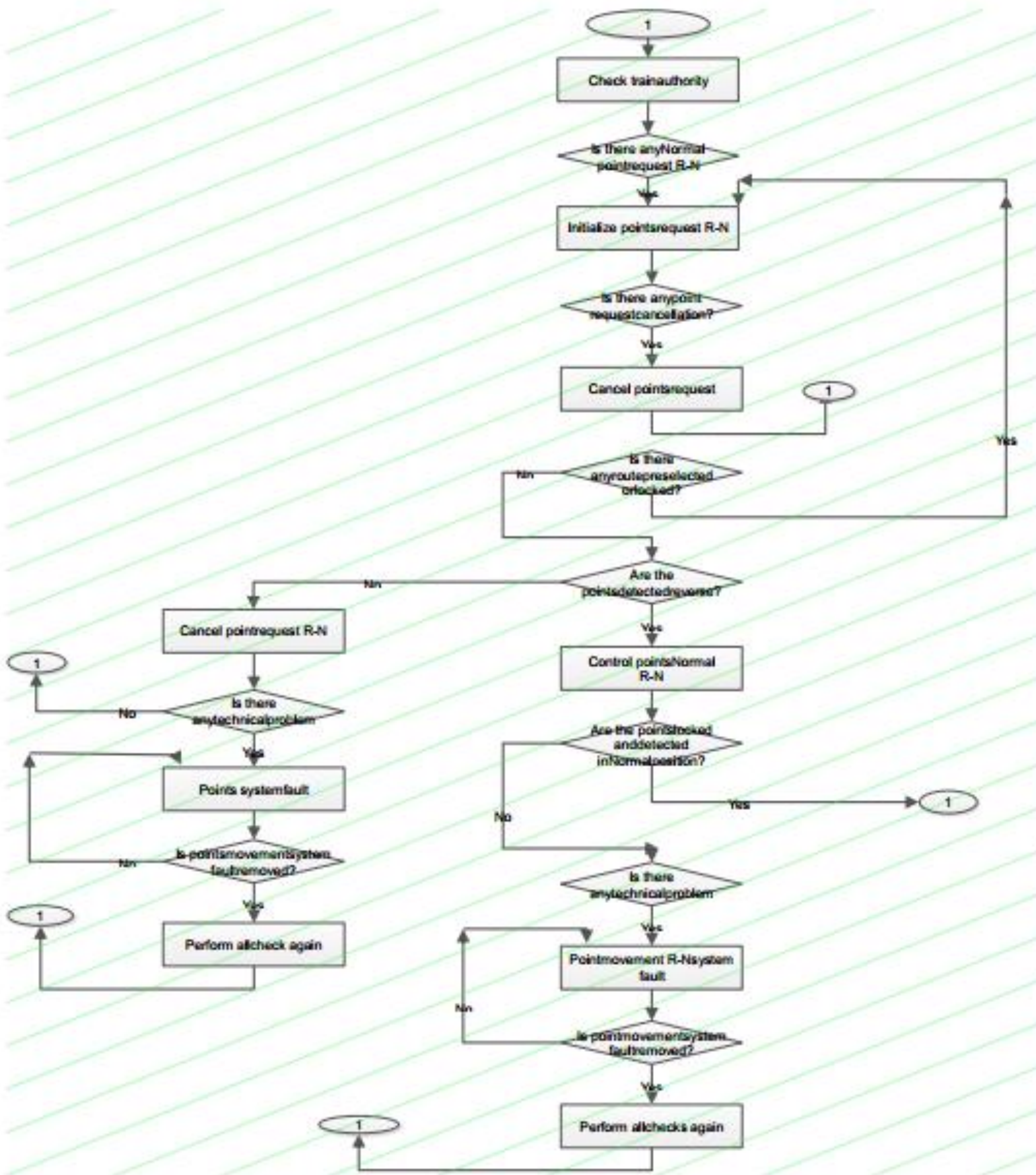

Figure 19 Point request for CBI Algorithm

3.6 Interlocking Table

The Interlocking table is a tabular representation specifying how the trains move together with the required states and actions of all related equipment. An entry signal shall be clear to let the train enter the route. Although the request to clear the entry signal is issued by the signal man, the route entry permission is decided by the interlocking system using safety rules and control methods specified in the agreed control tables. From the above routing algorithm of AALRT we have interlocking table of Signals, Track sections, and Point (switches).

Table 2 Interlocking table of Signals

Route No	Route		Signals					
	From	To	A	B	F	G	H	I
1	Meshalokya (H)	Stadium (B)	Red	Red			Green	
2	St.Lideta (F)	Darmar (I)			Green			Red
3	St.Estifanos (A)	Stadium (B)	Green	Red			Red	
4	St.Lideta (F)	Coca Cola (G)			Green	Red		Red
5	Darmar (I)	St.Lideta (F)			Red	Red		Green
6	Stadium (B)	Meshalokya (H)		Green			Red	
7	Coca Cola (G)	St.Lideta (F)				Green		Red
8	Stadium (B)	St.Estifanos (A)		Green			Red	

Table 3 Interlocking table of Track

Route No	Route		Track Sections					
	From	To	T11606 (A)	T11604 (B)	T12010 (F)	T12006 (G)	T21602 (H)	T22211 (I)
1	Meshalokya (H)	Stadium (B)	0	↑	↑	0	↑	↑
2	St.Lideta (F)	Darmar (I)	0	0	↑	0	0	↑
3	St.Estifanos (A)	Stadium (B)	↑	↑	↑	↑	0	0
4	St.Lideta (F)	Coca Cola (G)	↑	↑	↑	↑	0	0
5	Darmar (I)	St.Lideta (F)	0	↑	↑	0	↑	↑
6	Stadium (B)	Meshalokya (H)	0	↑	0	0	↑	0
7	Coca Cola (G)	St.Lideta (F)	↑	↑	↑	↑	0	0
8	Stadium (B)	St.Estifanos (A)	↑	↑	0	0	0	0

Table 4 Interlocking table of Points

Route No	Route		Points		Stop	Route Release	
	From	To	Normal	Reverse		Initial	Final
1	Meshalokya (H)	Stadium (B)		✓	H:T21602	↓T21602, T11604↑	↓T11604, T21602↑
2	St.Lideta (F)	Darmar (I)		✓	F:T12010	↓T12010, T22211↑	↓ T22211, T12010↑
3	St.Estifanos (A)	Stadium (B)	✓		A:T11606	↓T11606, T11604↑	↓ T11604, T11606↑
4	St.Lideta (F)	Coca Cola (G)	✓		F:T12010	↓T12010, T12006↑	↓ T12006, T12010↑
5	Darmar (I)	St.Lideta (F)		✓	I:T22211	↓T22211, T12010↑	↓ T12010, T22211↑
6	Stadium (B)	Meshalokya (H)		✓	B:T11604	↓T11604, T21602↑	↓T21602, T11604↑
7	Coca Cola (G)	St.Lideta (F)	✓		G:T12006	↓T12006, T12010↑	↓T12010, T12006↑
8	Stadium (B)	St.Estifanos (A)	✓		B:T11604	↓T11604, T11606↑	↓T11606, T11604↑

The above tables shows a simplified interlocking table for common section of AALRT. The interlocking table has one row for each train route. For each route

- The route sub columns contain basic information about the train route such as its route number
- The Signals sub-columns state (1) which signals (the entry signal and any distant signal for this) should be set to a proceed aspect when the conditions for entering the route are met, and (2) which signals must be set to a stop aspect (to provide flank or front protection) before the entry signal can be set to proceed (green light (indicating proceed) and red light (indicating stop))
- The Points sub-columns state required positions of points (Normal/Reverse) for the route to be connected
- The Track sections columns state with an ↑ which track sections must be unoccupied for the route and its safety distance to be empty

- The Stop column specifies that a certain signal (the entry signal of the route) should be switched to a stop aspect when a certain track section (the first section of the route) becomes occupied
- The Route release columns define conditions for when the train route can be released (a condition expressing that ↓ which the track section is occupied, and ↑ which the last track section is unoccupied)

3.7 Modeling of Interlocking System using Petri net Software

Railway blocks, position of switches and colors of signal lights are modeled as places (PXXX) and trains are modeled as tokens. PN model of the OCC, Switches and Signal lights are given in figure below. These models are obtained by using the interlocking table given on Table 2, Table 3, and Table 4. This model is used for monitoring movement of the train on the railway station. These events are labeled with different numbers because switches can change manually from OCC when necessary. Likewise, for the signal lights, all conditions have to be satisfied in order to change the color of the signal lights. All signal lights are on red and switches are on normal position when there is no train or reservation.

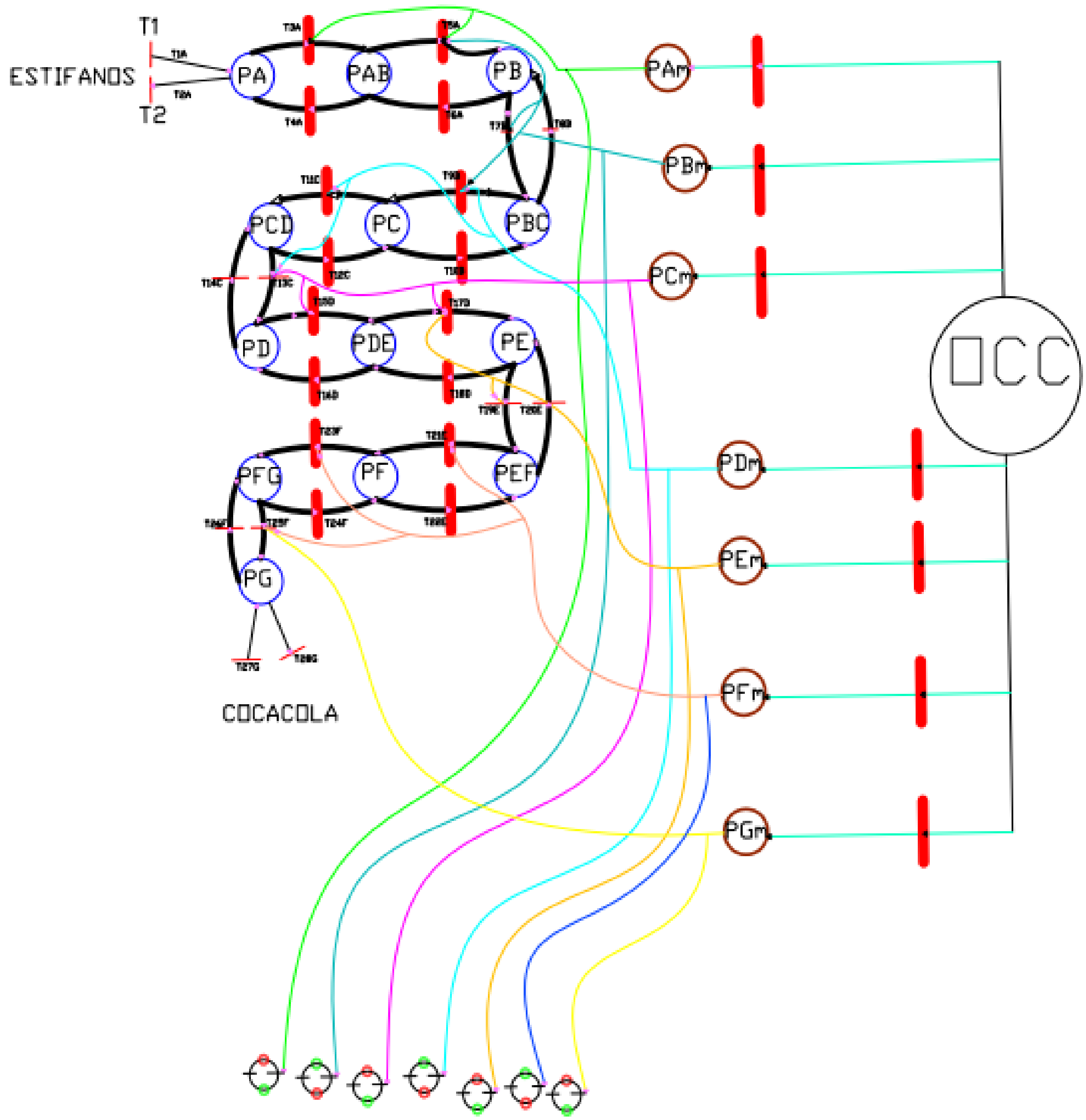

Figure 20 PN model of AALRT Common section

CHAPTER 4

RESULT and DISCUSSION

4.1 Result

The software simulation considers fundamental interlocking functions and main components that form part of an interlocking system, such as requesting, setting and locking a route that has been successfully evaluated by simulating these functions and comparing the output to the process defined in routing algorithm and to the interlocking table.

The train moves sequentially along the route asynchronously to avoid conflict during the checking time by not occurring concurrently at the same time (which in this time skips checking the second train as mentioned in the problem statement); thus avoids this problem by firing the trains asynchronously as seen in the simulation results.

AALRT common station has many track circuits, switches, and signals. When analyzing the route and the chance of the combination of the interlocking elements: acceptable and prohibit combinations can occur. Permitted means the route is safe when the interlocking system work properly. Prohibit means it has a combination state of the interlocking elements but the path has unsafe. The safety requirement is to ensure collision-free operation of trains in the Common station. The task of an interlocking system is to control points and signals such that train collisions and derailments are avoided. The interlocking systems we are considering use a train route based approach to achieve that. The following safety properties consider for the common station in the interaction between the Interlocking and the train.

- ✓ Trains should drive on predefined routes through the network
- ✓ Each route is covered by an entry signal that indicates whether it is allowed for a train to enter the route or not. Trains are assumed to respect the signals.
- ✓ Trains never collides: Two trains must never be allowed to drive on conflicting (e.g. overlapping) routes at the same time.

- ✓ Before a train is allowed to enter a route, the points in the route must be locked in positions making the route connected (i.e. it is physically possible to go from one end of the route to the other end without derailing), and the route must be empty (i.e. there are no trains on the route). (To prevent derailments and collisions, respectively.)
- ✓ The points of a route must not be switched while a train is driving on the route. (To prevent derailments.) A switch is not allowed to move when the track is occupied by a train
- ✓ Conflict routes are never enabled at the same time
- ✓ Routes in opposite directions never locked at the same time

4.2 Test cases and Results

The physical layout of common section given in figure 16 is modeled by using PN, in this modeling trains coming from East West (EW) line is considered and it is the same scenario for North South (NS) line. From the above Petri net modeling, we have reachable state analysis, reachability tree, reachability graph, Markov, Table and Incidence matrix.

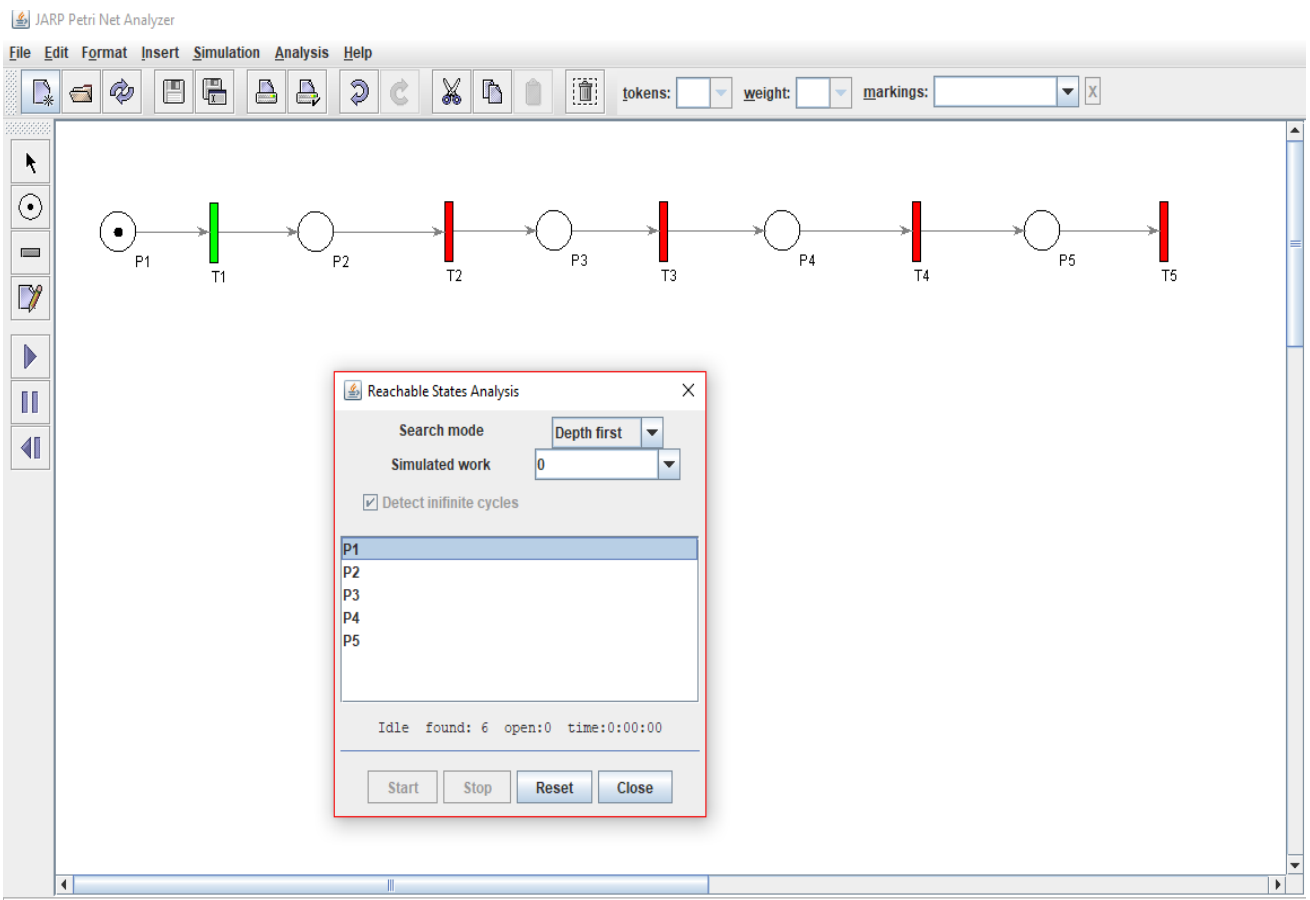

Figure 21 PN software Analyzer shows when T1 enabled

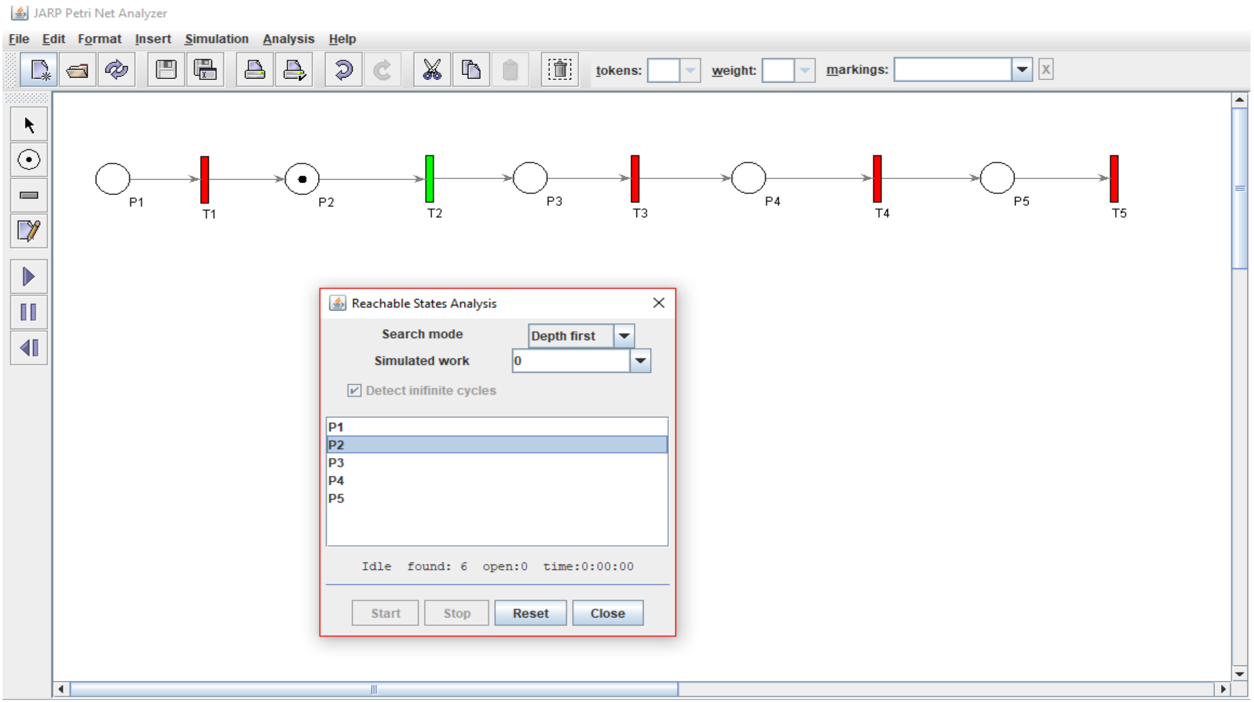

Figure 22 PN software analyzer shows when T2 enabled

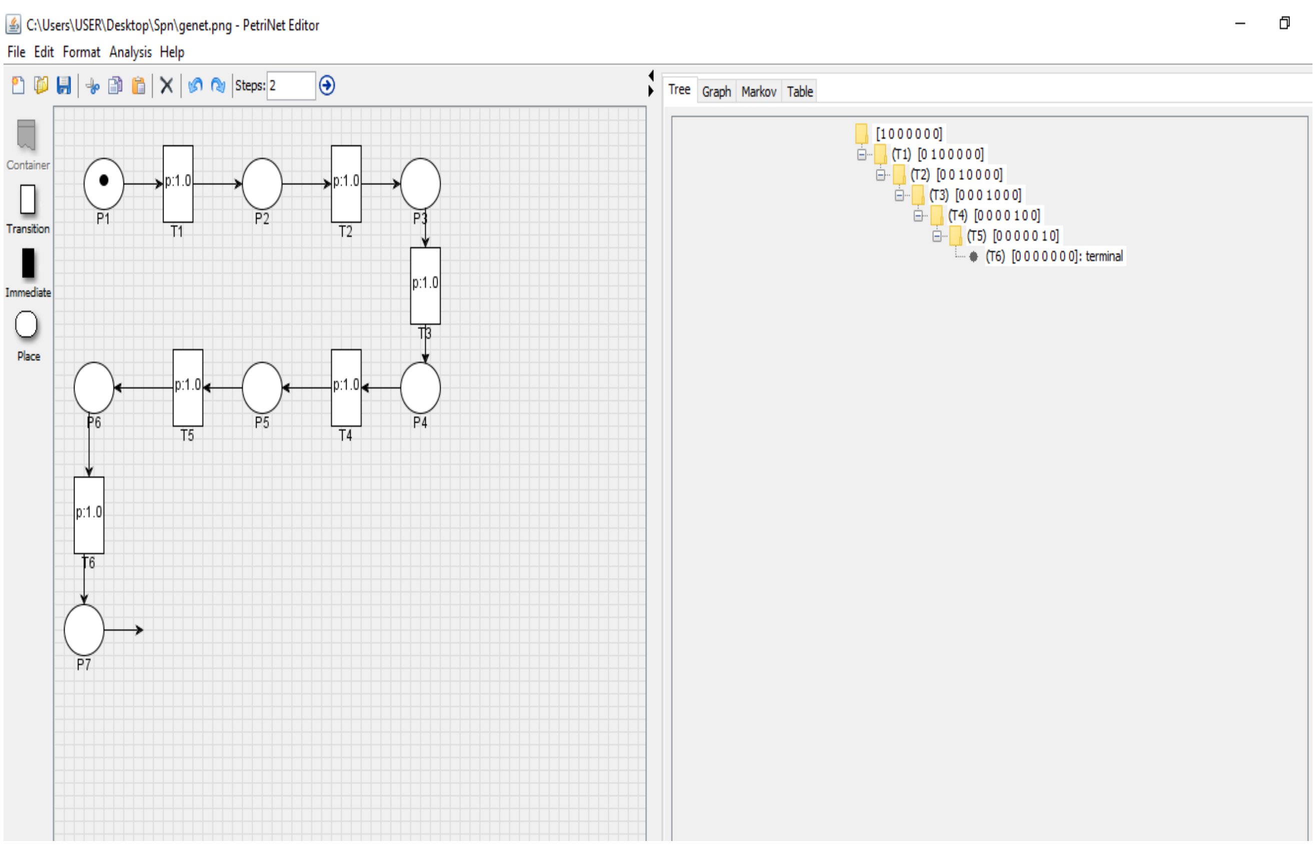

Figure 23 Reachability Tree

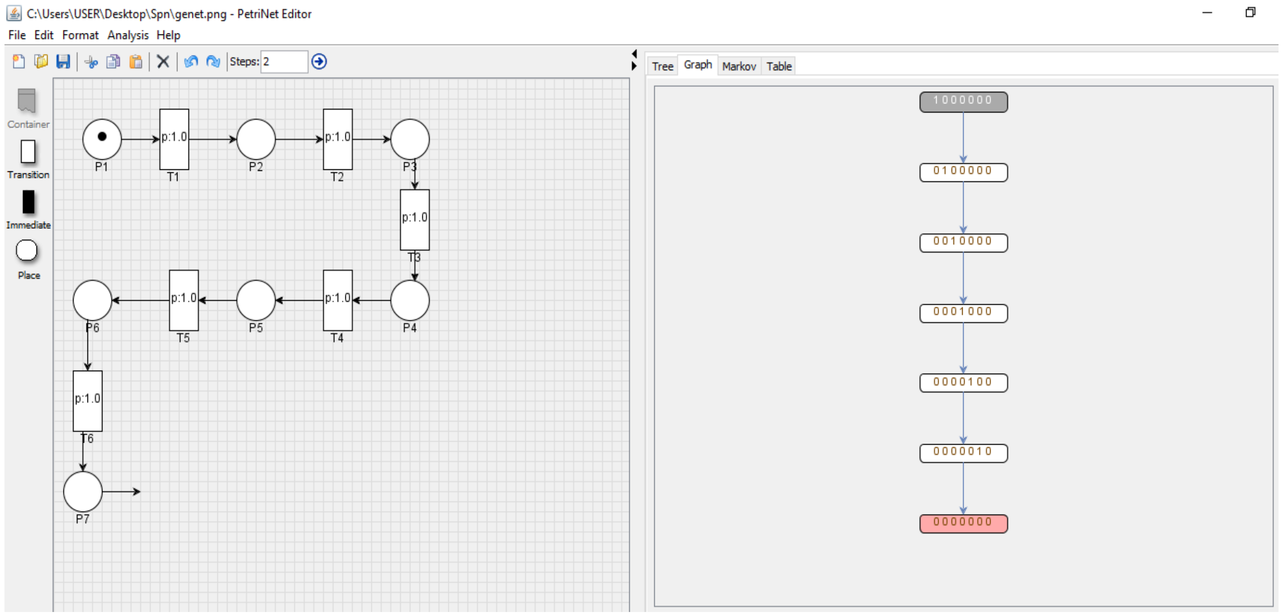

Figure 24 Reachability Graph

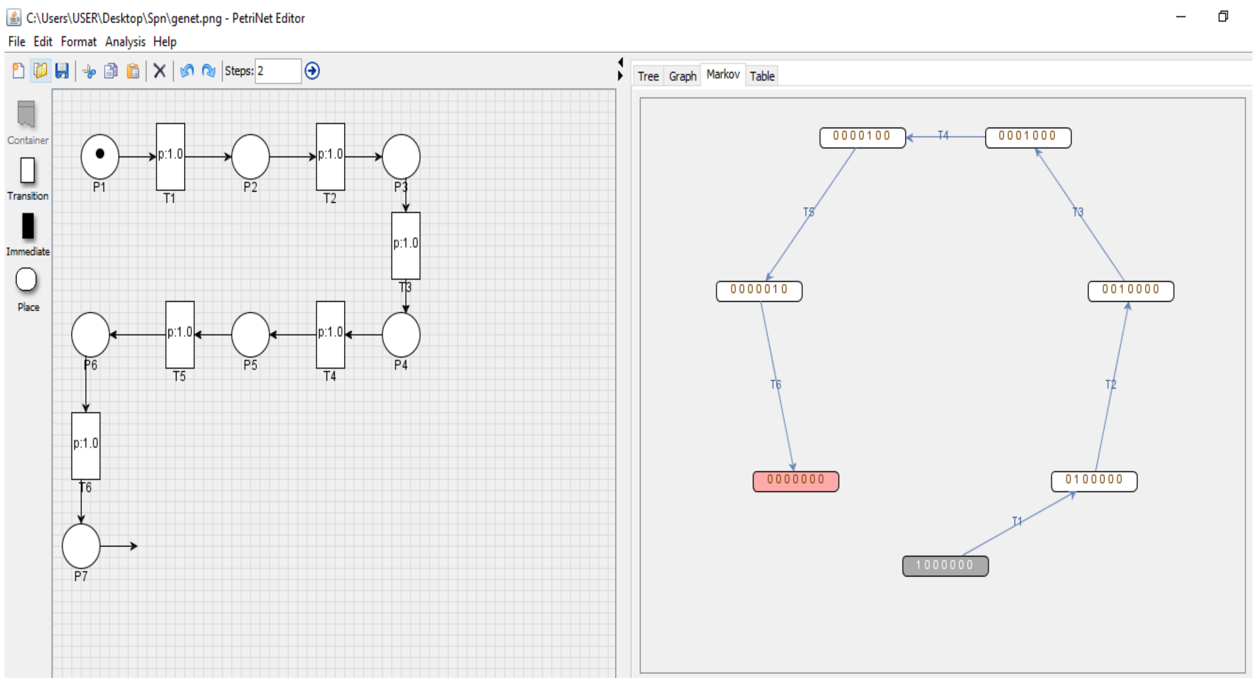

Figure 25 Reachability Markov

Tree Graph Markov Table

Level	Start	Path	End	Description
0	root		1 0 0 0 0 0 0	
1	1 0 0 0 0 0 0	T1	0 1 0 0 0 0 0	
2	0 1 0 0 0 0 0	T2	0 0 1 0 0 0 0	
3	0 0 1 0 0 0 0	T3	0 0 0 1 0 0 0	
4	0 0 0 1 0 0 0	T4	0 0 0 0 1 0 0	
5	0 0 0 0 1 0 0	T5	0 0 0 0 0 1 0	
6	0 0 0 0 0 1 0	T6	0 0 0 0 0 0 0	terminal

Figure 26 Reachability Table

From the above test case we have different results, in the reachability states analysis we have 5 possible results that regulates the movement of the train by finding all possible transtions from the initial marking, this gives a set of marking reachable from the initial one, then all possible transitions from the previously discovered markings. For example if T1 fires the train goes from P1 to P2 and if T2 fires the train should move from P2 to P3, this indicates that the train moves from one place to another place with out any conflict, because the transtions can enabled asynchronously.

4.2.1 Incidence matrix using Matrix analysis

From the above Petri net network we can construct incidence matrix which defines all possible inter connections between places and transitions in a Petri net. The entries of the incidence matrix are defined as follows:

$A_{ij} = A_{ij}^{+} - A_{ij}^{-}$ where, $A_{ij}^{+} = O(t_i, p_j)$ matrix of output

$A_{ij}^{-} = I(t_i, p_j)$ matrix of input

$A_{ij}^{+} = O(t_i, p_j)$ matrix of output (From Transtion to Place)

	P1	P2	P3	P4	P5	P6	P7
T1	0	1	0	0	0	0	0
T2	0	0	1	0	0	0	0
T3	0	0	0	1	0	0	0
T4	0	0	0	0	1	0	0
T5	0	0	0	0	0	1	0
T6	0	0	0	0	0	0	1

A_{ij}^{-} = I (t_i, p_j) matrix of input (From Place to Transtion)

	P1	P2	P3	P4	P5	P6	P7
T1	1	0	0	0	0	0	0
T2	0	1	0	0	0	0	0
T3	0	0	1	0	0	0	0
T4	0	0	0	1	0	0	0
T5	0	0	0	0	1	0	0
T6	0	0	0	0	0	1	0

$A_{ij} = A_{ij}^{+} - A_{ij}^{-}$ (Incidence matrix)

	P1	P2	P3	P4	P5	P6	P7
T1	-1	1	0	0	0	0	0
T2	0	-1	1	0	0	0	0
T3	0	0	-1	1	0	0	0
T4	0	0	0	-1	1	0	0
T5	0	0	0	0	-1	1	0
T6	0	0	0	0	0	-1	1

A given Petri net matrix has one incidence matrix and that incidence matrix can represent many networks. The above incidence matrix represents the number of tokens removed, added, and changed in place pj when transtion ti fires once, respectively. For example when T1 fires the token removed from P1 and added 1 token to P2. From the above interlocking tables, routing algorithm and, Petri net analysis the following conditions are generated for AALRT Common section.

Table 5 Testing case results

Testing Cases	Routes							
	One	Two	Three	Four	Five	Six	Seven	Eight
Switch Availability	✓	✓	✓	✓	✓	✓	✓	✓
Switch Position	✓	✓	✓	✓	✓	✓	✓	✓
Switch set correctly while locking	✓	✓	✓	✓	✓	✓	✓	✓
Route Set	✓	✓	✓	✓	✓	✓	✓	✓
Route Locking	✓	✓	✓	✓	✓	✓	✓	✓
Route Release	✓	✓	✓	✓	✓	✓	✓	✓
No locking of Conflicting Routes	✓	✓	✓	✓	✓	✓	✓	✓
Only green Signal when allowed	✓	✓	✓	✓	✓	✓	✓	✓
Keep red signal until release	✓	✓	✓	✓	✓	✓	✓	✓
Track locking	✓	✓	✓	✓	✓	✓	✓	✓

CHAPTER 5

CONCLUSION, RECOMMENDATION and FUTURE WORK

5.1 Conclusion

This paper dealt with an investigation of common sections interlocking system which ensured system a synchronization and concurrency by modeling suitable interlocking systems with the help of Petri net. PN based models have been widely used due to their ease of understanding, logic based and modular modeling principles, and finally because they can be represented graphically. At first, the five stations of AALRT are being drawn using AutoCAD with its full components, such as signals, switches, and track circuits. After that, a proper model of interlocking system is being modeled with the help of Petri net software and the model alleviates the problem which has been encountered in the interlocking system by allowing the interlocking to check the trains asynchronously without any conflict.

This modeling of interlocking systems includes a physical layout, routing algorithm, control table and Petri net models of this model done according to safety standard. In this thesis, a typical railway interlocking layout encompassing key signaling elements have been developed. The algorithms in the form of flow charts have been definitely for key interlocking functions and can be applied to any route configuration. From the simulation part using the Petri net, we have reachability analysis such as (reachability tree, reachability graph, reachability table), and incidence matrix and automation Petri net model of AALRT common section. This result shows the interlocking system is safe and the system is working asynchronously without any collision.

5.2 Recommendation

Petri nets have been proven to be a powerful modeling tool for various types of dynamic event-driven systems. Since Petri nets were introduced in 1962, numerous research papers have been published, but there is nothing documented that have been found for AALRT specifically. In this case, a model using the Petri net will be performed for the specified interlocking system, this modeling basically focuses stations between EW16 - EW20, which comprises five stations but we can apply this system to all AALRT Interlocking system. Because of Petri net is new in this country, it is hard to cover all the features of petri nets or to choose the extended Petri nets in this thesis paper. The software tools of the interlocking model are flexible and can easily be adapted to suit any interlocking with a minimum modification. You can add, delete and edit the interlocking element such that signal, switch and track. Although certain elements of the interlocking system require the knowledge of skilled signal engineers to interpret the station layout, control tables and the Petri net analyzer.

5.3 Future work

- The future work includes extended Petri nets.
- Convert the given model to PLC, FBD code or SCADA.
- It includes, APN model and PLC code for real systems which have more safety specifications considering time-delays like the commands and actualizing the commands will be develop in order to broaden availability of this method.

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