Modeling of a Railroad Worker Protection System Architecture in PFS

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***Abstract*—The metro system is an important transportation mode for urban cities. This system has had a long operation time since its construction, is still operating, and will not be replaced easily. Hence, it can be classified as a legacy system. Moreover, the metro system requires preventive or corrective maintenance, because there are still situations and occurrences that cannot be properly predicted. During the corrective maintenance, the metro line is still running while the railroad worker is also on the railway. In this situation, the operator, from the Operations Control Center (OCC), must create a safe area for the railroad worker to carry out the maintenance. Although the metro line has safety procedures, training, and rules for this situation, a miscommunication or leak of the operator's attention might make the railroad worker vulnerable to accidents. Based on that, this paper focuses on providing an architecture in which the railroad worker is considered protected automatically. The railroad worker protection system architecture is modeled using the Production Flow Schema (PFS), as well as the metro one, to present the architectures` operation and the interaction between the two architectures.**

Keywords: metro system; legacy system; protection system architecture; production flow schema.

I. INTRODUCTION

The metro system is a transportation mode characterized by being capable of transporting people or goods, at high velocity and with a high level of safety [1]. In a big city, such as São Paulo (Brazil) for instance, approximately 81 million people used metro lines 1, 2, and 3 in January 2020. Beyond that, the metro system is the most efficient option to be implemented in urban areas based on the space occupied compared to the other types of transportation [1].

Another characteristic of the metro system is the long operating time. In some cases, the metro system in London (England) has been working since 1890, in Chicago (USA) since 1897 [2], and in São Paulo (Brazil) since 1974 [3]. Considering this operating time and the old technology used on these systems, they can be regarded as legacy systems. Legacy systems are running systems that do not comply with the emerging architectural standards but still meet some functional business needs [4]. Moreover, legacy systems cannot be easily stopped because of the critical information in their operational code and database. Lastly, legacy systems demand frequent and complex maintenance [5].

The metro system comprises different equipment responsible for controlling energy consumption, passenger flow, managing rail devices, and supporting operating the line. Equipment or devices in general need maintenance, mainly when they have a long operating time, such as the ones that belong to the metro system. When maintenance of railway equipment is required during metro line operation, such as a broken rail, for example, some safety actions are required to allow local safe maintenance while the remaining line continues to run. The operator, who is monitoring and controlling the line, takes these actions manually. If these actions are not taken properly, the railroad worker, carrying out the field maintenance, is unsafe.

According to the company responsible for managing the metro lines in São Paulo, there were 57 accidents between 2017 and 2021 on the railway in São Paulo. These accidents are related to inadequate management of the tools, same-level fall, not following the internal procedure, and bumping on objects or equipment. Although none of the accidents reported by the company were fatal, fatal ones were found in the São Paulo metro history.

A 30-year experienced railroad worker was run over by a metro car. He was wearing Personal Protection Equipment (PPE). The accident's cause was the lack of communication between the operator and the railroad worker [6]. In another case, the railroad worker was electrocuted, while he was executing maintenance on a circuit breaker that was badly signalized. In addition, the railroad worker reported communication issues between him and the operator. Although the railroad worker was wearing PPE, he was aware of the safety rules, and had years of experience, these were not enough to protect him [7].

Some similar cases were found outside Brazil. In New York (USA), for instance, a railroad worker was taken to a hospital with severe injuries [8]. According to the news, he had five years of experience and there were lights and signals to avoid accidents. However, this was not enough to stop the train on time. In London (England), an inspector was run over by the train during his work routines [9]. In this case, there was a system to alert the inspector about the train arriving, but this was also not enough to protect him. It was described by the local news that this system was only able to alert the inspector, not to take action to guarantee the inspector's protection.

 ISBN: 978-1-68558-037-7

The common reason for these accidents is the miscommunication between the railroad worker, who is executing the maintenance on the field, and the operator, who is the Operations Control Center (OCC) monitoring not only the maintenance activities, but the whole metro line. This issue is also highlighted in [10] as the main reason that keeps the railway insecure in London. Hence, a system focused on automatically protecting the railroad workers during their activities shall create a new layer of protection for them and avoid miscommunication-related accidents, such as touching an energized power rail, being hit by a train or energized switch rail, and not being quickly notified about a fire detection on the railway.

Although a new system needs to be added to the metro architecture, the metro system is a legacy system, and as such, cannot be changed easily. Hence, the new system architecture shall run separately of the metro architecture. Furthermore, the interface points between the two architectures shall be mapped to reduce the changes needed in the metro architecture. In summary, the contribution of this paper is the presentation of a railroad worker protection architecture that protects the railroad worker and can communicate with the metro architecture with minimum interference. Beyond that, this paper shows a railroad worker protection system architecture and metro system architecture modeled using the Production Flow Schema (PFS).

The remainder of this paper is divided into five sections. Section II presents the projects and papers related to worker protection in railway/metro systems. Section III describes the metro system architecture. Section IV focuses on PFS. After this, Section V models the metro and railroad worker protection system architecture in PFS. Finally, Section VI is the conclusion.

II. Related Work

The section lists projects/papers that highlight solutions to improve the railroad worker safety during his tasks on field.

The authors of [11] propose a system to detect if the rail vehicle is next to the railroad worker location. This system uses fiber optic interferometers as vibration sensors to detect the rail vehicle next to him. Once a rail vehicle is detected, the authors suggest optical or acoustical signal to alert the railroad worker.

The authors of [12] present a wearable Global Navigation Satellite System (GNSS) sensor to track the railroad worker in rail worksites. His position is used to verify if the railroad worker is in any dangerous area. Although this paper focuses on protecting the railroad worker, it does not clarify how to protect him, only how to detect if he is in a dangerous area.

The Litum company developed a safety system that monitors in real-time the construction workers during the construction of the Paris subway expansion [13]. This project used Ultra-Wideband Radio-Frequency Identification (UWB RFID) attached to the 400 construction workers' helmets. Beyond that, the tunnel where the construction workers were is 33km long in total and they received alarms by e-mail through Wi-Fi. The goal of this system was to ensure that only authorized construction workers were in the restricted areas, the number of construction workers in specific areas were not exceeded, confirmed that all workers followed the directions, and the system was capable to react quickly in potential cases of emergency.

The author of [14] suggests a safety mechanism that uses image analyses to verify whether a track segment is damaged or not. The author focuses on the SkyTran track, but this solution can be applied to other rail tracks. Although this solution can prevent derailing, and consequently damage to the railroad worker, this paper does not present how this system will be integrated to any railway system.

Lastly, the authors of [15] propose a solution in which the railroad worker is alerted when the train arrival time to his position is 30 seconds or less. In this solution, the railroad worker wears wearable device that contains a Global Position System (GPS) sensor, radio receptor device and actuators to create tactile, visual, and sound alerts. Moreover, a GPS sensor and radio transmitter, signaling on broadcasting mode, are attached to the train.

Although the solutions presented in this section focus on the railroad worker safety, gathering more data from him and keeping him updated, most of them require that he or any other operator react to guarantee the railroad worker safety. The goal of this paper is beyond that; it is to monitor and protect the railroad worker automatically, not depending on anyone's reaction, once activated.

III. Metro System

The São Paulo's metro system can be divided into two main systems: Signaling and Control System (SCS) and Central Control System (CCS). The SCS is responsible for rail equipment management, metro position and protection, and passenger safety on the metro. The CCS is responsible for station management, equipment monitoring and control, and passenger safety in the station. These systems interchange information, such as train position, fire detection, power consumption, etc. These systems can be seen in Figure 1.

According to [16], the SCS follows the IEEE 1474.1-2004 [17], which described the requirements to execute the Communications-Based Train Control (CBTC). In other words, it describes the system requirement to allow the train to run safely and automatically. The SCS is divided into three subsystems: Automatic Train Protection (ATP), which certifies that the train has a speed-maximal threshold for the metro car in each section of the railway to ensure a safe road, protecting the train from collisions; Automatic Train Operation (ATO), that shall define the metro road, metro velocity (following the maximum speed established by

ATP), and the waiting time in each station; and Automatic Train Supervision (ATS), that is the SCS supervisory, presenting the position and status of the metro and rail devices on operator's screen. The ATP and the ATO are usually defined by regions. Hence, they are presented as Regional ATP (RATP) and Regional ATO (RATO).

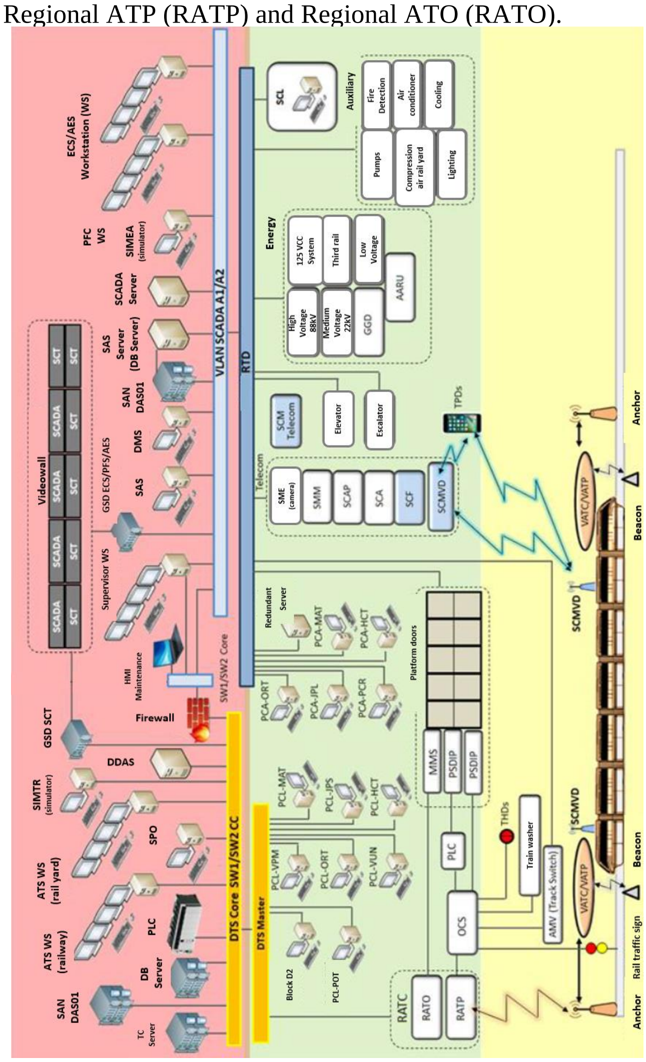

Figure 1. São Paulo's metro system architecture translated into English [18].

The CCS has a central Supervisory Control and Data Acquisition (SCADA) component that monitors and controls the equipment in the metro line. The CCS is also divided into three subsystems: Electric Control System (ECS), Passengers Flow Control system (PFC), and Auxiliary Equipment System (AES). For instance, the ECS monitors and controls electric devices, such as feeders, third rail, and circuit breakers. Beyond that, the ECS monitor the demand and power consumption. The PFC controls the passenger flow. Therefore, this subsystem monitors and controls cameras, elevators, escalators, etc. Finally, all other devices, such as fire detectors, cooling devices, pumps, tanks, networks, and multimedia devices are included in the AES.

The metro system has an OCC where the workstations, SCADA server, ATS server, videowall, and others are located. From the OCC, the operator can monitor and control the metro line. Furthermore, the operator can communicate remotely with the railroad worker through Walkie-Talkie.

It is important to highlight that, besides the metro system being a legacy system, the metro architecture also follows the automation pyramid proposed by International Society of Automation (ISA) in ISA-95 [19], as can be seen in Figure 1. This means the three bottom layers of ISA-95 (field, control, supervisory) are present in this architecture, from bottom to top: field layer is indicated in yellow; control layer is shown in green; and supervisory layer in red. Lasty, due to a huge number of devices present in each system, this paper will focus on two of them from each system:

- **CCS:** we present the behavior of the feeder, a circuit breaker used in middle voltage to feed the power rail, because the power rail is not directly controllable, and the fire detector. The feeder status is opened or closed, and can be commanded to open or close. The fire detector status is activated or not activated. Note that there is no command for the fire detector;
- **SCS:** we present the behavior of the rail switch and the metro car. The rail switch status is like the CCS equipment. In other words, the device status is energized or de-energized, and can be commanded to energize and de-energize. Whereas the train can be understood in a different way, the train behavior is based on the speed thresholds in a specific area. The ATP defines this and can be controlled by the ATS. If the speed threshold is 0, the area is blocked for the train. If it is not 0, the train can pass through that area.

IV. PRODUCTION FLOW SCHEMA

Production Flow Schema (PFS) is an interpreted graph from Petri Net (PN) to model Discrete Events Systems (DES) in an abstract level [20]. The PFS was designed to systematize and facilitate the modeling process, because system modeling processes are done in a natural language, and the mathematical formalism is guaranteed due to the net structure.

The PFS allows abstract model improvement using a top-down approach exploring the macro events [21]. Furthermore, this graph does not have a token, different from the PN, because the PFS focuses on the structural description of the items flow and system data. However, when reaching the appropriate level of detail for the study, a PN or Colored Petri Net (CPN) model can be directly generated to carry out analysis through simulation.

The PFS is also considered a bipartite graph compound of activity elements (action, execution), distributing elements (collect, accumulate and/or store items), and

 ISBN: 978-1-68558-037-7

oriented arcs to connect the elements [22]. These elements and the different structures allowed in PFS can be seen in Figure 2.

It is important to highlight that the communication flow between different modules can only be used, if the data/item used in each net is different and if this arc represents the data flow between the activity elements.

According to [23], EN 50128, which defines software development requirements for railway applications, highly recommend the use of semi-formal methods (like PN, and consequently PFS and CPN) for developing safety related software for railway application to satisfy the safety requirements. In addition, [24] presents the advantage of the PN comparing it to other safety analysis tools, such as expanded Failure Mode & Effects Analysis (FMEA), and Hazard and Operability (HAZOP). Based on that, PN, PFS and CPN are applicable for safety applications. Lasty, there are several applications of the PN and CPN in railway applications, for instance [25] and [26], but they do not focus on protecting the railroad worker.

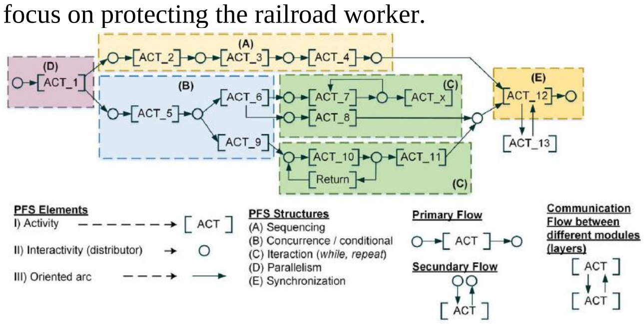

Figure 2. Elements, structures and flows in PFS [21].

The conversion from the PFS to the PN was used in [20], and can be explain through an example in Figure 3. In this picture, the PFS model can be seen in the left side, and the equivalent of this PN model in the right side. Note that the activities can be replaced by one or more places in the PN model, and the brackets by transitions. If there is an arc entering or leaving the activity in the middle, a transition shall be added. Moreover, the communication flow between different modules is represented by a transition fusion in the PN, as can be seen by the transition **{t1}**. The mark position should be decided at the end of the modeling process.

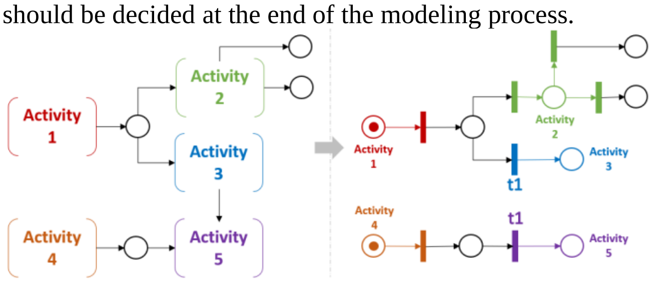

Figure 3. Example of conversion from PFS to PN.

Since the PFS focuses on the architecture structure, the model of the metro system architecture, more specifically São Paulo's one, and railroad worker protection system architecture in the PFS are presented in the next sections. Thus, the architecture structure, through the architecture models and interaction between each other, must be defined, before executing simulation analysis. If the architecture structure is wrong, it will be useless, even though the results of the simulations are positives. Moreover, this paper will present only PFS due to space available.

V. ARCHITECTURES MODELING

The railroad worker protection architecture shall follow the same division in three macro activities, and color, as shown in Figure 4. The goal is a system that works automatically. Hence, it needs to acquire railroad worker positions in real-time to know which equipment and area shall be interlocked. Beyond that, it needs a real-time channel to inform the railroad worker of alarms. These two requirements are related to **[Railroad Worker Protection Field]**.

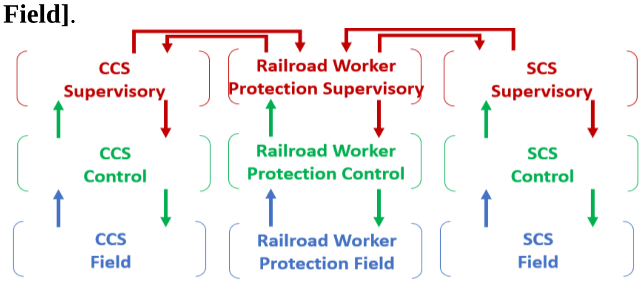

Figure 4. Main activities of the metro and rail worker protection system architecture.

[Railroad Worker Protection Control] shall start and stop the railroad worker position request if there is any on the railway. Moreover, this layer shall also prepare a database of pre-recorded voice message to be sent to railroad workers based on the alarm message.

Finally, **[Railroad Worker Protection Supervisory]** shall monitor and manage the protection of the railroad worker. Moreover, it shall interface with the other systems.

Since all equipment data in a metro architecture are in **[CCS Supervisory]** and **[SCS Supervisory]**, this system architecture will interface with the existing metro architecture through the supervisory layer. In addition, the equipment commands shall be executed initially by **[CCS Supervisory]** and **[SCS Supervisory]**. Finally, **[Railroad Worker Protection Supervisory]** shall be responsible for identifying the equipment to be interlocked in each system.

Although CCS and SCS supervisory are interchanging information as reported in Section III, this information does not affect the railroad worker protection system architecture. Hence, this connection is not presented in PFS model.

A. *Metro System Architecture*

[CCS Supervisory] and **[SCS Supervisory]** can be modeled as represented in Figure 5 and Figure 6. First, they receive equipment status from the control activity **{1} {5}**. The equipment status can be transferred to other systems **{A} {C}**. From the CCS or SCS to other systems, such as the railroad worker protection system. Subsequently, data from the other systems is received **{B} {D},** and then, the equipment command to the control activity can be sent. For instance, when the equipment command to interlock from the railroad worker system architecture is received, the command shall be sent to the control layer in this step **{2}{6}**. Finally, restart the loop.

[CCS Control] and **[SCS Control]** have two main tasks: (1) Receive the command from the supervisory **{2}{6}** and deliver to the field equipment **{3} {7}**; (2) Receive the equipment data from the field **{4} {8}** and deliver to the supervisory **{1}{5}**.

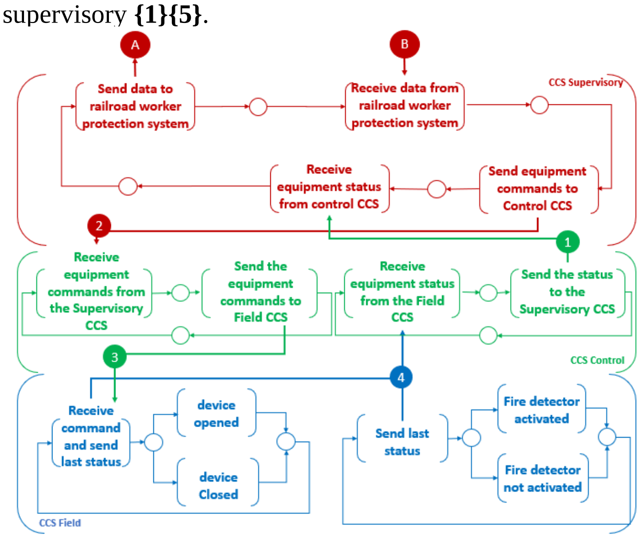

Figure 5. CCS architecture modeled in PFS. “A” and “B” continues in Figure 7.

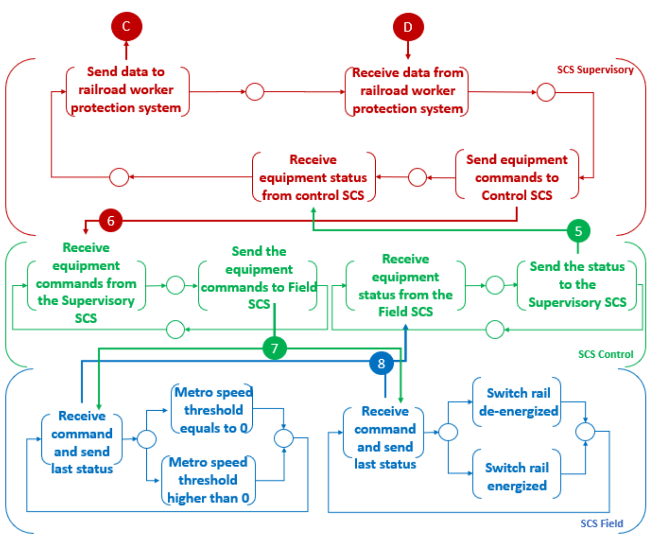

Figure 6. SCS architecture modeled in PFS. “C” and “D” continues in Figure 7.

[CCS Field] and **[SCS Field]** have the same structure, but equipment used in each model are different. Therefore, to each loop, the last equipment data acquired is sent to the control layer **{4} {8}**, and the command, received from control activity **{3} {7}**, is executed. If the equipment does not have command, this layer shall only send the equipment status. Finally, as discussed in Section III, the behavior of the Feeder and fire detector is highlighted and modeled for the CCS Field. The behavior of the rail switch and the metro car is highlighted and modeled for the SCS Field.

B. Railroad Worker Protection Architecture

The railroad worker protection architecture requires tracking the railroad worker in real-time, and according to [15] can be used a wearable device for this task, represented in **[Railroad Worker Protection Field]**. Beyond that, the railroad worker can be updated automatically through audio messages on Walkie-Talkie **[Messages received via Walkie-Talkie]**, such as fire alarm messages. In this case, the railroad worker can also manage his safety once he is well-informed.

[Railroad worker Protection Control] shall acquire the railroad worker position **[Railroad worker data request]**. This data shall be shared to **[Calculate railroad worker protection area]**. In addition, this layer prepares the message to be sent via Walkie Talkie **[Send audio messages to railroad worker]**.

On **[Railroad worker Protection Supervisory]**, there are six main requirements that this macro activity shall accomplish:

1) **[Calculate railroad worker protection area]:** calculates based on the railroad worker position and position lost alarm;

2) **[Recognize the equipment to be interlocked]:** compares the railroad worker position with the equipment status, and train location to select the equipment that shall be interlocked to guarantee the railroad worker safety. This information is sent to the **[Middleware]** to forward to metro system;

3) **[Show on screen the railroad worker data]:** indicates on screen the railroad worker position and his status in real-time;

4) **[Alarm management to keep railroad worker updated]:** gathers alarms from the **[Middleware]**, for example fire detection to update the railway worker;

5) **[Middleware]:** allows the communication between the metro and railroad worker system. This activity shall send the device list and commands to the metro system, gather the device status from there and filter the status that are alarmed;

6) **[Railroad worker registration management]:** the operator shall insert the railroad worker in the system, to trigger the logics, and remove it, in case the maintenance is over.

Each activity listed above can be detailed in Figure 7 and each activity will be explained hereinafter.

The operator, knowing the necessary maintenance, shall insert the railroad worker into the system through **[Railroad worker registration management] {1}**. This triggers the

 ISBN: 978-1-68558-037-7

other activities to run **{15}**. The activities shall continue until the operator removes the railroad worker from the system **{2}**.

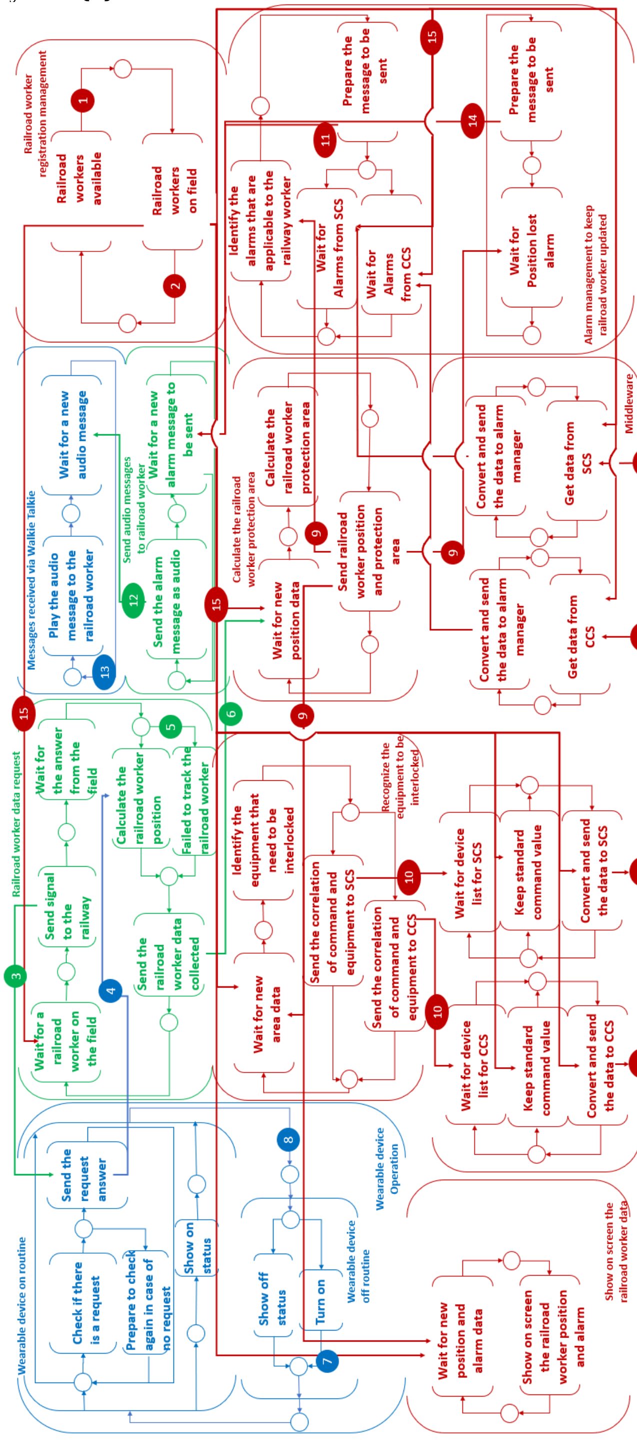

Figure 7. Refined railroad worker protection architecture modeled in PFS. "A", "B", "C" and "D" continues in Figure 5 and Figure 6.

After receiving the data that the railroad worker is on the railway, **[Railroad worker data request]** starts looking for him. First, the signals are sent to the railway, looking for the railroad worker **{3}**. If he is found, his position is calculated **{4}**. If he is not found, a flag is set to alarm the operator **{5}**. This data will be used to calculate his protection area in **[Calculate railroad worker protection area] {6}**.

The **[Wearable Device Operation]** starts off **{7}**. The railroad worker shall turn on the wearable device to be found. In case of success, the wearable device is on and ready to be found. Once a request signal for data is received **{3}**, the reply signal is sent back **{4}**. The wearable device keeps in this loop until the railroad worker turned the wearable device off **{8}**.

The railroad worker position and position lost alarm are used to calculate a protection area around him in **[Calculate railroad worker protection area] {6}**. The area value are variation of x and y position called delta X and delta Y. In case of position lost, the railway worker protection area results in a bigger area than the last calculation to protect him, if he is nearby. After calculating the delta X and Y, these values with the railroad worker position (x and y values) are sent to other activities **{9}**.

[Recognize the equipment to be interlocked] uses the protection area **{9}** to match the devices position and identify the devices in that area. After that, the list of the SCS and CSS equipment that shall be interlocked is sent to **[Middleware] {10}**.

[Alarm management to keep railroad worker updated] uses the protection area **{9}** to match the alarms activated on SCS and CSS **{11}**. Once the alarms that apply to the railroad worker area are recognized, the messages are converted to the voice message in **[Send audio messages to railroad worker] {12}** and then sent to railroad workers via Walkie Talkie in **[Message received via Walkie-Talkie] {13}**. In addition, the railroad worker shall be also informed through Walkie-Talkie in case of losing his position **{14}**.

[Show on screen the railroad worker data] uses the position and area of the railroad worker to show his position on the screen. The screens are maps of the railway with alarm banner. Therefore, the operator can see the railroad worker position, his protection area, and any alarm related to him, such as loss of his position.

Lasty, the railroad worker protection system architecture must interface with metro one, considering it as a legacy system, through **[Middleware]**. Therefore, the devices and command devices shall be sent to metro system in a way that it can process this information **{B} {D}**. Furthermore, this architecture shall be capable of collecting device data to inform him properly **{A} {C}**.

VI. Conclusion

The metro system has been demonstrated to be essential to urban cities, mainly because of its capability of transporting, occupying less space in comparison to other transport modes. This legacy system, compounded of many devices, requires repair. Once a maintenance is needed, the railroad workers are sent to the railway to fix the issue. The accident reports during maintenance have shown that current safety actions are insufficient to protect the railway worker. Hence, a railroad worker protection system architecture is needed to protect him automatically.

It was concluded that the interface between the metro and railroad protection system architecture shall be done through the supervisory layer, because metro's SCADA gathers the metro line data. The metro system architecture shall command the equipment to an interlock status. The PFS can be used to generate the model of the railroad worker protection system architecture.

Finally, the contribution of this paper is the presentation and modeling of an architecture that focuses on protecting the railroad workers automatically since activated, taking in consideration that metro system is legacy system, in other words, reducing changes on the metro system; and on simplifying the supervision procedures in OCC. Although it was applied the architecture to São Paulo's metro system, this architecture shall be applicable for any metro system. It has only to understand the system that the railroad worker protection system architecture is being applied to and where this architecture can communicate with the metro one. Furthermore, its construction in PFS allow the uses of formal method as PFS to convert into PN [20] or CPN, and subsequently into programming languages [27].

A. *Further work*

The PFS model presented will be used to generate the CPN model of the railroad worker protection system architecture, metro system architecture and their interaction. Finally, the CPN model will be simulated to verify and validate the proposed architecture. It will be verify if all states reachable are safe and there is no deadlock or live lock in the modeled system, as done in [25] and [26].

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 ISBN: 978-1-68558-037-7