Identification of safety relevant activities of train crews using the Functional Resonance Analysis Method (FRAM)

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Abstract: During the classical training process of train crews are used real vehicles. There are two disadvantages of this approach. The first, vehicles are out of order to perform commercial tasks. This factor cerates high costs and, to minimize them, the training time is kept as short as possible. Secondly, there is no possibility to trainee dangerous situations, as for example fire on board of a train. Thus, using of Virtual Reality in the training process is a key undertaking to improve safety and efficiency of railway operation processes. The problem occurs how to choose safety relevant situations for implementation as scenarios in the Virtual Reality environment. The paper proposes a method for determining train crew activities based on a combined PHA and FRAM approach. The variability of activity execution is characterized by precision and timeliness. The accuracy and timeliness of train crew activity performance were estimated mainly based on a survey of train crews, as well operation data from the Polish Railway Network Manager. The research problem is focused on selection of the most important activities and scenarios that can be carried out by train crews. The structure of typical and atypical train crew activities and their interactions is modelled using the Functional Resonance Analysis Method (FRAM). Functions of the FRAM model represent activities of the train crews under their duty. For individual functions, the variability is determined taking into account precision, and time correctness of execution. Activities and scenarios requiring training are selected from the activities with the highest variability and the activities with the highest variability chains. The typical FRAM variability is exchanged into a risk measure got from staff survey and PHA analysis. Finally, the selected sequences of activities were highlighted on the built FRAM model. The presented approach allows to identify the most important scenarios to be trained in Virtual Reality environment.

1. INTRODUCTION

The rail transportation system safety is influenced by: environmental, technical, human, and organizational issues. In training rail personnel, it is important to select the activities assigned to be performed within the job and the scenarios to be trained. A train is manned by a train crew consisting of a traction crew and additionally conductors. Passenger trains should be manned by a conductor consisting at least of a train manager unless his operational tasks are performed by another employee or technical equipment. Passenger trains may run without a train manager if closing and opening of doors is provided by an automatic system and this is signaled to the driver. The train manager is an employee responsible for operating a train in a designated section of a route and is subordinated to all employees operating the train except for supervisory and control bodies. The conductor performs commercial and transport duties (ticket sales and control, activities related to taking over and returning the train, watching over the maintenance of order and order on the train). [1]

In complex sociotechnical systems, humans and the organization are essential sources of variability. On the one hand, man is the cause of undesirable events as well as a factor leading to the robustness of the system through his adaptability. Classical methods of reliability or safety analysis of complex

sociotechnical systems are not sufficient in the construction of train manager training programs (Fault Tree Analysis, Event Tree Analysis, Failure Mode and Effect Analysis, Hazard and Operability Study or Swiss Reasons Cheese Method). Alternatives in hazard prediction and risk estimation are developing systems-based safety approaches such as System-Theoretic Accident Model and Process (STAMP) [2], Functional Resonance Analysis Method (FRAM) [3], AcciMap [4]. The STAMP approach is more strongly oriented towards the structure of the system, while FRAM is more oriented towards the behavior (operation of functions and interactions between them). Application areas of the FRAM method are aviation [5] and medical care [3], construction [6], and marine transportation [7]. In the FRAM method, the focus is on the variability of the performance of the component functions by the system components: people, organization and technical equipment. This paper focuses on the train manager as one of the elements responsible for the quality of transportation. A method of selecting train managers activities in the training process based on the analysis of conducted interviews in the community of train managers was proposed.

Employees serving passengers must follow strict procedures to ensure high levels of service, safety and punctuality of trains. Human factors research is crucial to understand the aspects that affect safety and work culture. The authors of [8] conducted an experience study among train crews and built people models to describe how train crews perceive their responsibilities and the implementation of new technologies at work. The article [9] presented the results of a study to test train driving skills in a modern (display-based) and traditional way. The article [10] noted that about 70-90% of accidents in transportation are, directly or indirectly, the result of human error. A methodological approach to human error in rail transport was proposed. The presented methodology is based on Failure Modes, Effects and Criticality Analysis (FMECA) and Human Reliability Analysis (HRA). In [11, 12], a railroad accident was analyzed that was influenced by a human factor related to the train crew. The phenomenological analyses conducted showed that proper training among workers plays a key role in preventing such incidents. The authors of [13] developed a simulation model of the workload associated with on-board ticket sales by train conductors. This was used to ensure a high level of service by adjusting the number of staff to the needs of the passengers on the train. In publications [14, 15, 16, 17, 18], one of the indicators for evaluating the quality of service provided by railroad operators was the level of passenger service provided by on-board staff. Additionally, punctuality, cleanliness and safety were indicated by travelers as important parameters.

2. TRAIN MANAGER'S WORK

A train manager is a railroad employee who is responsible for a train in service, under operation on a given section. He is a part of the conductor's team. All employees operating the train, except internal control employees, are subject to the supervision and instructions of the train manager. Based on available documentation [19, 20, 21, 1], the duties of the employee in this job position have been identified:

- activity on demand of the train driver in exceptional cases,
- being in the driver's cab in auxiliary vehicles, provided that the speed of the vehicle does not exceed 60 km/h,
- performing coupling and uncoupling of railcars,
- performing combined brake tests (simplified and detailed),
- determining the length, the total weight of the train, the actual and the required brake weight, calculating the maximum permissible speed of the train (when the actual brake weight is lower than the required brake weight),
- use of timetable, knowledge of the railroad network,
- protecting rolling stock against derailment,
- visually checking the technical condition of switches, the phase of shifting a manually set switch, checking the setting locking,
- filling in the documentation kept by the train manager regarding the operation of the train and conductor team,

- operating railcar devices and equipment,
- performing technical inspection of the train,
- informing the traffic controller of the nearest station about a damage to the train's braking devices, its type, method of proceeding and possible request for help,
- receiving and returning keys for derailleur, siding and protective switch,
- putting switches and derailleurs in their basic position after operating the siding and closing them, making sure that no car is left on the track,
- in a technical train managing traffic of this train on a track, being responsible for traffic safety and giving movement orders to a technical train staff,
- supervising groups of detached railroad vehicles from a work train on the trail or appointing a qualified employee,
- after completing work on the trail the manager of the technical train is obliged to personally check if there are no obstacles on the track or next to the track for the train movement,
- receiving and accepting written orders, including giving their first copy to the driver,
- communicating signaling information to the train driver when semaphores are out of the driver's range of vision,
- informing the traffic controller of the passing of a train out of bounds,
- stopping a train in case of emergency or dangerous situations
- notifying the traffic controller of the nearest station about open barriers and lack of the crossing guard on the serviced level crossing,
- if necessary, and also in case of train stopping on the track, observing the track ahead of the train and if another train is approaching on that track, run against it and give "Stop" signal,
- notifying the traffic controller by available means of communication about unplanned stopping of a train on the route and determining the reason of its stopping,
- requesting from the traffic controller to switch on the warning on the level crossing or on the crossing for the time of technical train passage,
- indicating to the driver that he is in readiness to depart,
- supervising the work of conductors and to a limited extent the traction crew,
- performing conductor activities:
    - ➢ performing accounting and reporting of tickets sold,
    - ➢ shipment / delivery of the shipment,
    - ➢ handing over left items to the lost and found office,
    - ➢ passenger service: checking documents and documents confirming the right to concessions, issuing and selling tickets, dealing with passengers who do not have a valid ticket, dealing with disabled people, taking care of the comfort of travelling, dealing with stress, building a positive image of the company.

A model of the structure of train managers activities in typical situations expressed in the language of the Functional Resonance Analysis Method (FRAM) was developed. It enabled the identification of links between the activities indicated in the interviews and other activities.

3. FUNCTIONAL RESONANCE ANALYSIS METHOD

In this method, the focus is on the behaviour of the system as an effect of the various functions and interactions between functions, rather than on the decomposition of the system into structural components. The FRAM model consists of functions and interactions between them. The graphical image of the functions with the meaning associated with the aspects are shown in Figure 1.

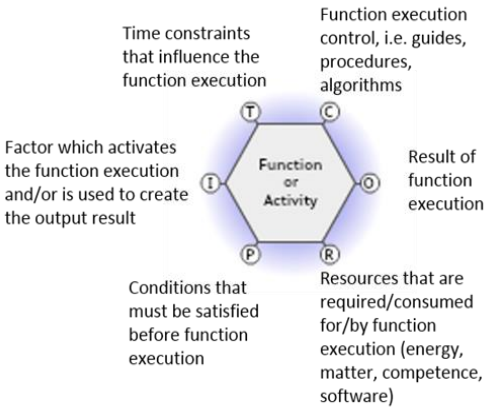

Fig. 1. Function of FRAM model with its six aspects: Input, Control, Time, Precondition, Re-sources, Output. source: own elaboration

Examples of functions may include: determination of readiness for departure, Checking the safety brake seals, Reacting to a passenger's inappropriate behavior. In order to obtain a FRAM model of a slice of reality, the functions of the FRAM model are combined by connections from the O (output) aspects of the functions to the following aspects of other functions:

- I - Factor which activates the function execution and/or is used to create the output result,
- C - Function execution control, i.e. guides, procedures, algorithms,
- T - Time constraints that influence the function execution,
- P - Conditions that must be satisfied before function execution,
- R - Resources that are required/consumed for/by function execution (energy, matter, competence, software).

4. PROBLEM AND METHOD

The research problem is to select the activities among those assigned to the position of train manager and the scenarios on which the training process should be focused. The research method is as follows: the structure of train driver activities and the interactions between them are modeled using the functional resonance analysis method. The activities are represented by FRAM functions. Based on the interviews conducted in the train manager community, the key activities during the work were determined and the relationships between them were investigated using the FRAM model. It was assumed that training should be focused on them.

5. INTERVIEWS WITH TRAIN MANAGERS

Interviews were conducted with 10 train crew members. Questions were asked about a nominal workday and the most important activities. In terms of the most important activities, employees could list an unlimited number of activities. Figure 2. summarizes the activities considered important by the employees.

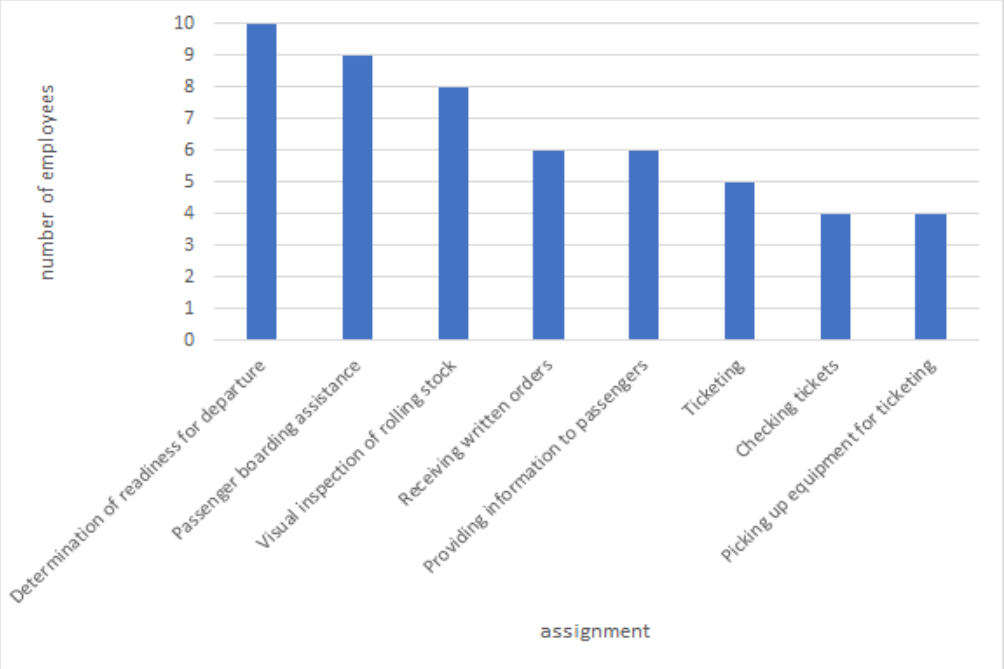

Fig. 2. Activity defined as important in relation to number of employees
source: own elaboration

The most important activities for employees were determination of readiness for departure (10 people), then passenger boarding assistance (people with reduced mobility) (9 people), visual inspection of rolling stock (8 people), receiving written orders (6 people), providing information to passengers (6 people), ticketing (5 people), checking tickets (4 people), picking up equipment for ticketing (4 people). The indicated activities are related to safety and passenger service. It means that not only for passengers a high level of service is important, but also for members of trains crews.

Based on the interviews, the flow of a typical employee's shift was described and used in conjunction with the documents [19, 20, 21, 1] to build the FRAM model: The duty scheduled by the scheduler begins with a report to the dispatcher at the home station. This is the administrative time for retrieving the duty equipment, i.e., the cashier to check tickets and secure receipts. Later, the employee signs the attendance list in the dispatcher. In the meantime, there is free time to check all the news. Then the train manager goes to the train, where he collects the relevant documents from the traffic controller and the train driver and goes to his service compartment in the car. Then after filling all the documents related to the train movement and giving the departure signal from the station, the train departs. The conductor makes announcements after departing from each station. After all these steps are done, he proceeds to inspect the tickets. He checks if the travelers are comfortable, if the temperature is right, if the air conditioning is working properly. After the train arrives at the final station, it is the conductor's duty to check if the passengers have disembarked from the train, if all the passengers' belongings have been taken and after checking, the doors are locked and the driver is informed that the train is ready to depart to the stabling tracks. Later, the employee goes to the dispatcher, there gives back all the documents and equipment that were taken at the beginning of the service, accounts for the receipts and closes the work shift.

6. TRAIN MANAGER'S ACTIVITY FRAM MODEL

The constructed FRAM model (Figure 3) consists of 20 functions related to the activities performed by the train manager. In addition, 21 functions were identified that are in addition to other parameter functions:

- internal timetable,
- train departure on time,

- train departure ahead of time or behind time,
- financial loss,
- time card errors,
- observing train line environment and train speed,
- closing car doors,
- receiving/releasing shipment,
- arrival of service,
- handing over left items to office,
- problem in locating the train by the service,
- retrieving duty equipment,
- reducing the comfort of the trip,
- inspecting rolling stock,
- observing the road with the driver,
- train accident/catastrophe,
- death or accident,
- train delay,
- derailment,
- instruction/procedures,
- receiving written schedules.

Therefore, they only have parameters related to the function result or activating factor. All other functions have more parameters related to: timing aspects, control of function execution, function results, conditions that must be met before the function is executed, factors that activate functions.

The first function included in the FRAM model is passenger handling. This function is activated by picking up equipment for ticketing, the result of which is to prepare the equipment for passenger service. This function has a number of results:

- the first outcome of passenger handling is accounting from tickets sold, which activates the documentation writing function, which results in irregularities in cash register billing and discrepancies in time records, which in turn activate new functions related to financial losses and time card errors,
- the second result is that the passenger wants to pick up / drop off the shipment, which activates shipment / delivery of the shipment function,
- another result of the passenger handling function is a non-compliant passenger behavior, activating the function of responding to the passenger's inappropriate behavior, the result of which is checking the train location, activating the train location information, the result of which is providing incorrect train location information to the services which activates the function of the problem in locating the train by guard service. The second result is a correct train position information for the service activating the function of arrival of guard service. The control factor of this function is the internal timetable. The passenger misbehaviour function has also a second result, the information about the need to call for help, which activates the informing the traffic controller about undesirable events function. The result of this function is failure to inform the traffic controller about an unscheduled train stop on the route activating the wireless communication service function,
- the next result is the finding of a left behind item activating the function handing over left items to the lost and found office,
- its fifth result is a passenger remark that activates the response to passenger attention function. Its first result is a passenger comment on the heating / air conditioning activating the

verification of the operation of the air conditioning / heating resulting in a report of a faulty air conditioning / heating and activating the reduction of the passenger's travel comfort,
- the sixth result is a passenger asking for the train location / giving a message via radio. Its effect is the activation of the providing train location information. The control factor of this function is the internal timetable. In case of giving incorrect information, the function of misleading the passenger is activated, which results in longer traveler location, activating train delay,
- the next result is a lack of control of credentials for relief that activates financial losses,
- the last outcome is the lack of ability to handle people with limited mobility when boarding the train, which activates the train delay or death or accident function.

The next function is determination of readiness for departuret. It is activated by the check of readiness for train departure caused by closing the wagon doors. The control factor of this function is the internal timetable. After correct or incorrect check of the departure time, the function of wireless communication is activated, where the result is train information activating the function of train departure at time or train departure after time depending on the correctness of information read from the internal timetable.

The handling wireless communications function also has other results. The first one is giving the wrong train number in communication with the signal box activating the function of train delay and accident / train crash. The second result is the difficulty to understand messages containing names of operating stations when talking to train dispatchers activating the function train delay and accident / train crash. The third result is a train in the gauge of another track activating an accident / train crash. Fourth: an unscheduled stop on the track activating train delay, and fifth: giving the readiness for departure signal when a person gets on the car or is next to the car activating an accident / train crash.

The next function is a visual inspection of rolling stock, which results in the inspection of equipment / components or the inspection of other equipment (windows, seats, sound system, toilets, etc.). New functions are activated:

- checking the condition of the wagon equipment, the first result of which is the non-noticing of defective non-safety elements activating the reducing journey comfort function. The second result is the failure to detect a defective safety feature, activating the death or accident function,
- verification of lighting performance, resulting in a report of faulty lighting that activates the reducing journey comfort function,
- checking the seals of the emergency brake, resulting in a report of a missing seal on the brake, activating the reducing journey comfort function,
- checking the presence of fire extinguishers in cars, the first result of which is a report on the lack of fire extinguishers activating the function of reducing journey comfort. The second result is the inability to extinguish a fire activating the death or accident function,
- verification of door operation, which results in a report of a defective door that activates the function of reducing journey comfort or delaying the train,
- verification of the operation of the air conditioning/heating system resulting in a report of a faulty air conditioning/heating system activating the reducing journey comfort function.

The train coupling function is controlled by the car coupling instruction. The result of the function can be:

- failure to turn the main line valve, which activates the accident / train crash function,
- correcting an incorrectly executed coupling, which activates the train delay function,

- standing between cars during coupling which activates the death or accident function.

The brake test function is controlled by the brake test instruction. The result of the function is that the procedures are skipped and the test is abandoned, which activates the accident / train crash function.

The function of determining the train length and braking weight is controlled by the instruction for calculating the length and braking weight of a train set. It results in errors in length and weight calculations activating the function of a different braking distance than in reality. This function has two results. The first one is that the train does not stop in a certain place which activates the function of accident / train crash and train delay. The second result is exceeding the speed limit activating the train derailment function.

The securing rolling stock against uncontrolled runs function is controlled by the rolling stock anti-runaway instruction. It results in rolling stock runaway, which activates an accident / train crash or a train derailment.

The function receiving written orders has two results. The first is failure to transmit a written command to the driver / overspeed activating train derailment, and the second is failure to transmit a written command to the driver activating train delay.

The function of observing the road with the train driver has a result related to missing the "Stop!" signal, activating an accident / train crash.

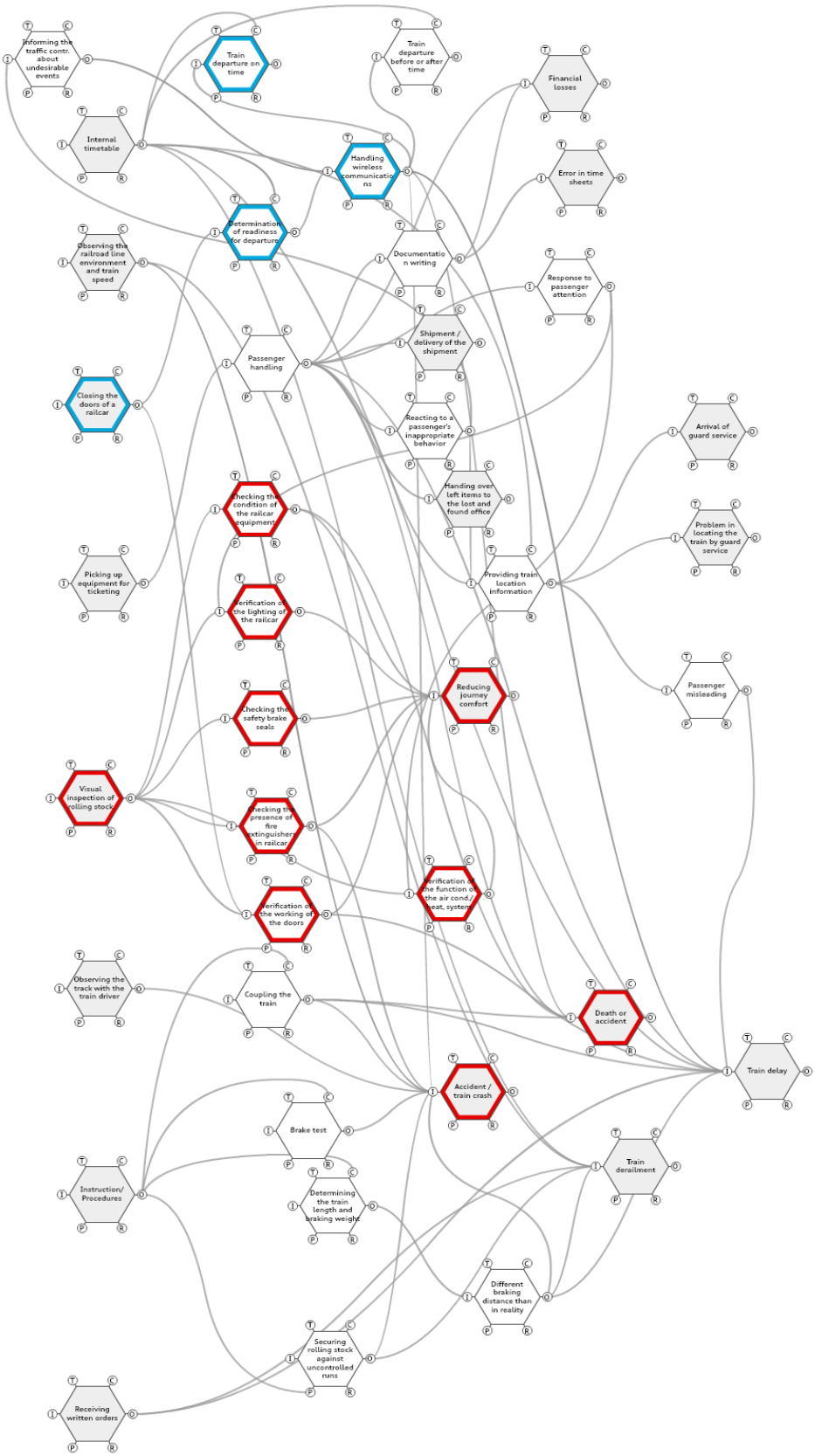

Fig. 3. FRAM model of train crews activities
source: own elaboration

The sequences of activities with the highest probability of occurrence and consequences marked with the same colors in the PHA analysis (tab. 1) were color-coded in the FRAM model (fig. 3). The blue

color is the sequence of activities associated with determining readiness for train departure, and the red color is the activities associated with visual inspection of rolling stock.

7. SELECTION OF TRAIN MANAGER ACTIVITIES IN THE TRAINING PROCESS

A detailed preliminary hazard analysis (PHA) was performed, where each function was assigned 1 to 5 undesirable situations and the one with the worst rate was selected. We then extracted strings of functions from the FRAM model from the beginning to the end, assigned indicator values to the functions, and then counted moving averages for always three consecutive functions. Then we ranked the worst threes that overlapped at most with one extreme function. From these, 8 was selected for the purpose of building training scenarios.

Table 1: PHA analysis of train crews activities

activity 1	consequences	probability		activity 2	consequences	probability	RPN index	activity 3	consequences	probability	RPN index	moving average	ranking of the worst threes
Closing the doors of a railcar	3	3	9	Determination of readiness for departure	4	3	12	Handling wireless communications	2	3	6	9,00	8,50
Determination of readiness for departure	4	3	12	Handling wireless communications	2	3	6	Train departure on time	2	3	6	8,00	
Picking up equipment for ticketing	1	1	1	Passenger handling	3	2	6	Documentation writing	3	2	6	4,33	5,50
Passenger handling	3	2	6	Documentation writing	3	2	6	Financial losses	4	2	8	6,67	
Passenger handling	3	2	6	Documentation writing	3	2	6	Error in time sheets	4	2	8	6,67	6,67
Picking up equipment for ticketing	1	1	1	Passenger handling	3	2	6	Shipment / delivery of the shipment	2	1	2	3,00	3,00
Picking up equipment for ticketing	1	1	1	Passenger handling	3	2	6	Reacting to a passenger's inappropriate behavior	4	3	12	6,33	6,93
Passenger handling	3	2	6	Reacting to a passenger's inappropriate behavior	4	3	12	Informing the traffic controller about undesirable events	3	2	6	8,00	
Reacting to a passenger's inappropriate behavior	4	3	12	Informing the traffic controller about undesirable events	3	2	6	Handling wireless communications	2	2	4	7,33	
Informing the traffic controller about undesirable events	3	2	6	Handling wireless communications	2	2	4	Providing train location information	4	2	8	6,00	
Handling wireless communications	2	2	4	Providing train location information	4	2	8	Arrival of guard service	3	3	9	7,00	
Picking up equipment for ticketing	1	1	1	Passenger handling	3	2	6	Handing over left items to the lost and found office	2	2	4	3,67	3,67
Picking up equipment for ticketing	1	1	1	Passenger handling	3	2	6	Providing train location information	2	1	2	3,00	4,11
Passenger handling	3	2	6	Providing train location information	2	1	2	Passenger misleading	3	2	6	4,67	
Providing train location information	2	1	2	Passenger misleading	3	2	6	Train delay	3	2	6	4,67	
Picking up equipment for ticketing	1	1	1	Passenger handling	3	2	6	Response to passenger attention	1	2	2	3,00	3,22
Passenger handling	3	2	6	Response to passenger attention	1	2	2	Verification of the lighting of the railcar	1	2	2	3,33	
Response to passenger attention	1	2	2	Verification of the lighting of the railcar	1	2	2	Reducing journey comfort	3	2	6	3,33	
Picking up equipment for ticketing	1	1	1	Passenger handling	3	2	6	Response to passenger attention	1	2	2	3,00	3,00
Passenger handling	3	2	6	Response to passenger attention	1	2	2	Verification of the function of the air conditioning/heating system	1	2	2	3,33	
Response to passenger attention	1	2	2	Verification of the function of the air conditioning/heating system	1	2	2	Reducing journey comfort	2	2	4	2,67	
Visual inspection of rolling stock	5	3	15	Checking the condition of the railcar equipment	3	3	9	Reducing journey comfort	2	2	4	9,33	9,33
Visual inspection of rolling stock	5	3	15	Checking the condition of the railcar equipment	3	3	9	Death or accident	6	3	18	14,00	14,00
Visual inspection of rolling stock	5	3	15	Verification of the lighting of the railcar	1	2	2	Reducing journey comfort	3	2	6	7,67	7,67
Visual inspection of rolling stock	5	3	15	Checking the safety brake seals	2	3	6	Reducing journey comfort	3	3	9	10,00	10,00
Visual inspection of rolling stock	5	3	15	Checking the presence of fire extinguishers in railcar	4	2	8	Reducing journey comfort	4	2	8	10,33	10,33
Visual inspection of rolling stock	5	3	15	Verification of the working of the doors	2	3	6	Reducing journey comfort	4	3	12	11,00	11,00
Visual inspection of rolling stock	5	3	15	Verification of the working of the doors	4	2	8	Death or accident	6	3	18	13,67	13,67

source: own elaboration

Based on the analysis, a set of potential misbehaviors of train crews was identified:

- loss of attentiveness,
- misreading the train departure time,
- giving the wrong train number,
- incorrect securing of rolling stock,
- skipping of procedures and careless rolling stock inspection
- not checking that the doors are locked before departure

8. CONCLUSION

For train crew members, safety and professional service to travelers are important aspects. This coincides with the passenger requirements detailed in the literature review. Using the performed staff interviews, the PHA analysis and the FRAM model, an approach was presented to find the most important scenarios for training of staff in Virtual Reality. For the FRAM model of train manager timing and precision description has been implemented by the risk number resulting from the PHA analysis. Thus, variabilities of activities in terms of timing and precision have been estimated in form of a risk measure. Finally we are able to rank the most important scenarios in terms of risk, that we can in the next step implement to the elaborated VR environment to teach the staff.

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