QUANTITATIVE AND QUALITATIVE ANALYSIS OF SPAD

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Summary

This paper presents a methodology designed to address safety issues in the railway domain. The aim of the methodology is the analysis of SPADs (Signal Passed At Danger), which consist in the passing of red signals by the train drivers, without injuries or bad consequences for people and technologies. Following the organizational model of accidents by James Reason , the methodology investigates the SPADs as near misses and aims at identifying preventive safety actions addressed to reduce real accidents [12]. It is based on the integration of two types of analysis: qualitative analysis resulting from the investigation on the field and quantitative analysis of databases, containing historical data about SPADs. The qualitative analysis explores the critical interactions among the different components of the productive processes, via a strong involvement of railway workers. Instead the quantitative analysis helps in developing and validating hypotheses about the possible common causes of SPAD events. Examples of the integration between the two level of analyses are provided, together with the results coming from the experiment run on the field.

Context and methodology

The methodology presented on this paper was developed for the Italian Railways organization (FS) with the main objective of promoting actions that can eliminate latent failures, reducing the probability of future accidents. According to the organizational model of accidents by James Reason, latent failures are the results of events that happened in the past, creating conditions that have not yet been discovered or completely realized by the people working inside the organization [13]. Latent failures are decisions or actions, the damaging consequences of which may lie dormant for a long time (i.e. wrong design decisions concerning a human machine interface, wrong management decisions, ineffective procedures). They become evident when they combine with local triggering factors such as technical faults, or atypical system conditions. Their defining characteristic is that they were present within the system well before the onset of a recognizable accident sequence [6].
SPADs are relatively frequent events. The report of the UK Railway Inspectorate concerning 1998 [10] describes, for that year, over 630 signals passed at danger for a variety of reasons including drivers failing to observe the red signal and the previous warning yellow signal. The vast majority of SPAD involve trains passing the signal by just a few meters, with no danger for the train or its occupants. Only in a few cases consequences are extremely severe. For that reason SPAD can be very useful in order to detect potential latent failures. As they don’t lead to bad consequences in most of the cases, they can help in capturing essential knowledge and insights concerning the quality and safety of the productive processes. Instead of focusing on individual responsibilities, the SPAD analysis can be directed to the understanding of causes and critical conditions, which take part of the normal life of the system.
The methodology that we developed can be used either reactively or proactively. The reactive modality serves to identify the causes of SPAD once the event has occurred. The proactive modality helps in identifying the possible action to prevent the SPAD events. Both modalities are supported by two different kinds of analyses. The first one is the qualitative analysis, studying each single case by an investigation on the field. The second one is the quantitative analysis, which explores causes and critical conditions in the historical databases concerning the SPAD events.
During the reactive application of the methodology the qualitative analysis provides preliminary hypothesis about the causes of the SPAD, these hypothesis can then be reinforced by the analysis of events with similar conditions recorded in the historical database. For example one of the investigation raised some doubts about the effectiveness of the Signal Repetition System (SRS) in preventing the SPAD under certain operating conditions[1], then the quantitative analysis investigated the passed events involving train equipped with the SRS operated under the same conditions.
During the proactive application of the methodology the quantitative analysis can help to develop hypotheses about the possible common causes of past SPAD events, through predictive statistic. These hypotheses can then be validated and refined through the retrospective qualitative analysis of the events concerned.

Qualitative analisys

The method we adopted for qualitative analysis is based on a systemic model, named SHEL, which considers the human role in a productive process and represents its relationship with the other process components (Edwards, 1972). We elaborated it on the basis of the Distributed Cognition Theory (Norman, 1993) and used it as a conceptual framework for developing the different steps of the methodology.
SHEL is the acronym for Software, Hardware, Environment and Liveware:

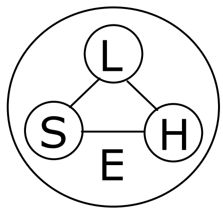

Fig.1 – The SHEL model

Software represents any components such as policies, rules, computational codes and practices that define the way in which the different components of the system interact with each other and with the external environment.
Hardware represents any physical and non-human component of the system, such as equipment, vehicles, tools, manuals and signs.
Liveware represents any human components in their relational and communicational aspects.

[1] This is an Italian equipment (similar to the English Automatic Warning System) that supports the train driver providing anticipated information about the status of the coming signal (whether red, yellow or green)

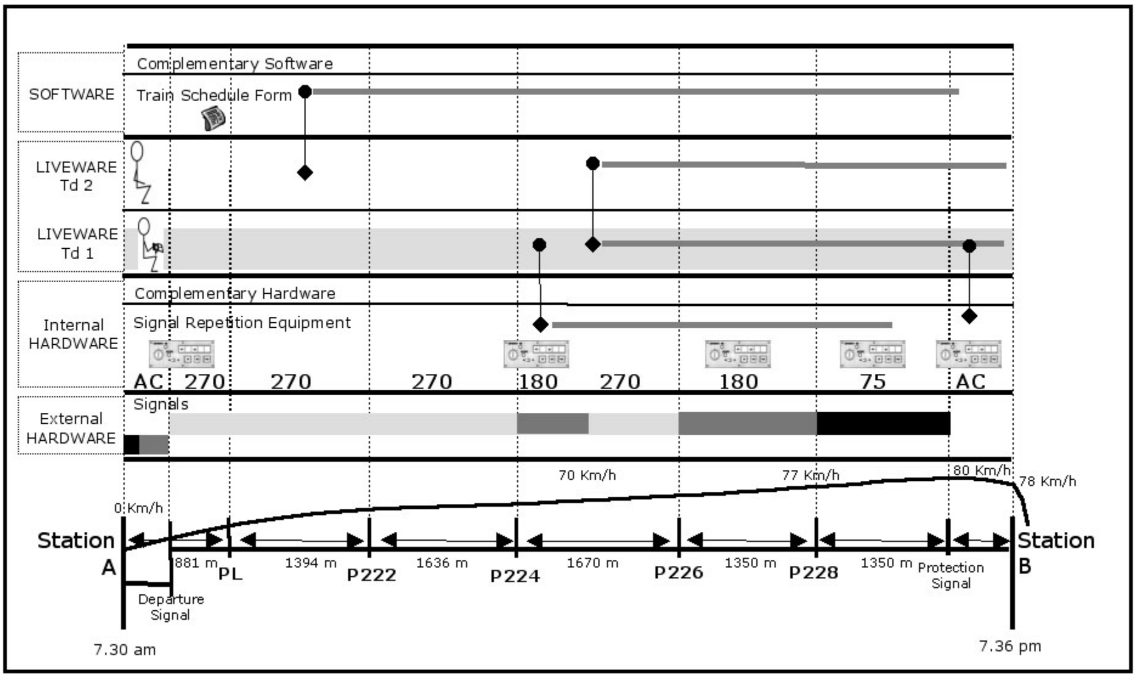

Fig. 2 – A simplified example of timeline based on SHEL model

Environment represents the socio-political and economic environment in which the different components of a process interact as shown in Figure 1.

SHEL offers a system view where humans cannot be seen as isolated from other system components and where the safety issues inside the productive processes are studied as breakdowns in the interactions between components. This view is consistent with a long-lasting and empirically well-grounded theory of human cognition: the cultural historical theory of Vigotsky, Lurja and Leontev [1]. Recently many authors have elaborated it along the main ideas of Vygotsky's approach, e.g. Engeström [3], Hutchins [7] and Norman [9]. The recent elaborations of cultural historical theory share the assumption that any productive process is always defined by a specific combination of Hardware, Software and Liveware resources that mediate the execution of human activity. There are no processes that can be carried out by one of these components alone. And, there are no exclusive combinations of the three components to shape a specific process.

The qualitative method has been developed adopting a user-centered approach and directly involving the personnel of the railway organization in the study. A few members of the companies, representing different roles in the productive processes composed the working group, together with the human factors researchers. The data source for the experimentation came from internal reports of the railway organization documenting three cases of SPAD that had happened in the years 1997 and 1998. These reports were principally aimed at identifying individual responsibilities of the operators involved in the critical event. Instead we used them only to extract objective data and information about the system resources taking part in the productive process (such as the hardware equipment, the infrastructure, the related procedures and the train crew).

After the first cycle of experimentation we divided the methodology in six steps: 1) resource identification, 2) identification of critical interaction, 3) timeline analysis, 4) field study 5) SPAD report and redesign proposals. All the steps relate to the identification of the critical interactions among the system resources, as defined by SHEL. As our main interest is in human factors issues, the attention is focused only on the interactions that include the liveware component: these are the L-H interaction, the L-S interaction and the L-L interaction. We do not consider any interaction with the Environment, as we focus only on those components that can be manipulated by the operators and the system designers.

In the following, we provide a brief description of the six steps.

Resources identification

The aim of the first phase is to identify all the resources involved in the sequence of events leading to the SPAD and the respective roles of these resources. These can include procedures, forms, signals, safety equipment, automated systems and, obviously, the involved people such as train drivers, station managers, etc.

The railway experts identify the resources and their roles using the available databases and documents. Moreover they classify the resources according to the SHEL model, taking into account the specific role the resource is playing in the process. For example a procedure is normally considered Software, but it can also be Hardware when it is embodied in a rulebook.

Identification of critical interactions

In the second phase the railway experts detect the potential critical interactions among the resources supposed to be influential in the SPAD event. An investigation checklist, which includes 8 sources of critical interaction based on the SHEL model, lets the experts cope with the complexity of the process and elicit the most critical issues [14]. The resource interactions for the specific case under investigation are derived from the objective documentation and recording concerning the events leading to the SPAD. This documentation can include: the map of the rail line of the zone, the train tachograph recording, the train course form, the interviews with the involved people and so on.

Timeline analysis

The timeline analysis is a graphic representation of the event showing the changing of state of the most critical S-H-L resources and their relative interactions. These are represented in a diagram with the resources on the vertical axis and the time-space on the horizontal axis.

In Figure 2 we present a simplified example. It concerns a train that entered a station passing a red signal and braking just in time to avoid the collision with another train.

The arrows below represent different blocks of rail line. Each one ends with a signal protecting the following block. The row external hardware shows the status of the signal that is placed at the end of the corresponding block. The signal status is represented using gray shades: black stands for red signal, medium gray means yellow and light gray means green. Then, a light gray box means that the signal at the end of the associated block was green.

A box with two colors, for example medium gray and light gray, means that the signal was yellow when the train entered the block and then switched to green while the train was running through the block. The row Internal Hardware shows the status of the Signal Repetition Equipment, a computer machine installed inside the train cockpit to help the driver detect the correct status of the external signals. Each numeric code displayed by the equipment corresponds to a different status of the external signals. 270 states for a green signal, 180 for a yellow signal and 75 for a red signal. Then there is the AC condition, which means that the equipment doesn't detect any signal at all.
Above the internal hardware, there are two rows representing the role of the two drivers (liveware components). Instead in the last row there is the software component, with the Train Schedule Form, concerning a special procedure the driver has to accomplish during the train conduction. Finally, at the bottom side of the figure, it is possible to understand the time progression and the train's speed. In the example the train started from station A at 7:29, passed several signals, including the red protection signal at the entrance of station B, and stopped with an emergency break at 7:36.
Building a graphic representation of the main interactions is very important as a support for the focus group meeting, described in the following. In the example the vertical segments represents only four of the critical interactions we analyzed. The one between Train Driver 1 and Signal Repetition Equipment. The one between the two train drivers. The one between Train Driver 2 and the Train Schedule Form. Finally the one between the first train driver and the Signal Repetition Equipment after having passed the red signal.

Field study

At this stage at least one person among the human factors researchers and one person among the railway expert go on the train to study a productive process similar to the one that fell in a case of SPAD. Ethnographic observations and conversations either with the train drivers and with the other roles involved in the process lead to better understand the critical interactions explored in the previous steps. Some critical interactions are completely understood in this phase, other will need to be discussed in the following focus group (next step), others come up only in this phase as they were not considered in the previous definition of resources. What it is very important of this phase is the possibility to collect a rich documentation concerning the critical interactions, with the essential contribution of the railway experts.
The documentation is provided in different forms. The most important one is the video recording of the productive process. This is very helpful in understanding and reviewing the activity with operators having the same role of the workers who were involved in the event. Other important forms of documentation are the excerpts from the rule books of the railway organization which are relevant for the specific process. Such as, the norms stating the competencies of the two drivers or the manuals concerning the use of the Signal Repetition Equipment. In addition, other interesting indications could come from stories and scenarios told by the railway experts and by the first line operators. The whole documentation will be useful also in a better definition and enrichment of the timeline previously defined.

Focus Group Meeting

Critical issues, together with the approaches to manage and control them, are then analyzed and discussed in a focus group. The focus group is a moderated and stimulated discussion between selected participants. It involves at least one representative for each of the professional roles involved in the SPAD, because they are the stakeholders of the knowledge required for the related processes. There is no need to have the same persons who were directly involved in the SPAD under investigation, on the contrary this is counter-effective because of the related strong emotional bias. Examples of typical roles are: train drivers, station managers, rail traffic controllers, maintenance operators, managers in charge of the development and maintenance of rules and procedures. Additional evidence about the critical issues can be obtained iterating between this phase and the previous ones, especially to verify the exact role of the resources and their interactions.

SPAD report and redesign proposals

The last phase of the methodology concerns the identification of remedial actions. This is done after the focus group where proposal to remove or mitigate the critical issues where discussed. It consists in the production of a report and of a multimedia timeline to be presented and discussed with the railways decision-makers. The previous graphic representation is enriched with all the documentation collected during the field study and during the focus group, in order to put in evidence the context and the specific aspects of the critical interactions. Each vertical segment becomes a link to display the different kinds of documentation collected during the experiment on the specific issue (video-recordings, norms' excerpts, stories, etc.).
The output of this phase is the definition of possible remedial actions to apply on the S-H-L resources. This would consist in actions concerning with the training program of the operators, with the design of new technologies to support the process or even with modifications of the organizational rules.
The application of qualitative analysis to the three mentioned cases of SPAD was very successful in revealing critical interactions and in collecting proposal for possible remedial actions. At least 12 critical interactions were fully analyzed and discussed both with the first line operators and with the railway organization managers [15]. Two interesting examples were the proposal for redesigning the SRE control panel and the study of critical interactions between first and second driver, both coming from the SPAD represented in figure 2. The proposal for redesigning the SRE control panel came from the observation of many problems of interaction with the train drivers, which can lead to a misinterpretation of the real state of the signal in changing conditions. Instead the study of the problems of interaction between the two drivers emerged from the lack of definition of the second driver's role. For example, even if he is responsible for the monitoring of signal like the first driver, he is frequently occupied in activities that do not allow him in helping the first driver (figure 3).

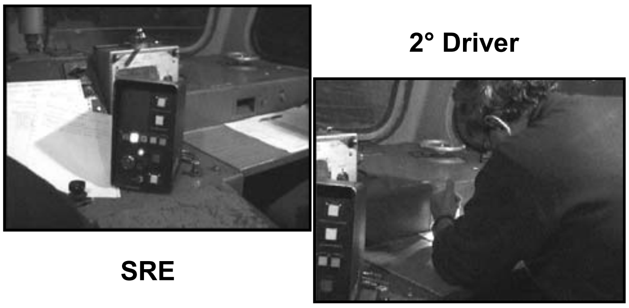

Fig. 3 – Examples from the field study

Quantitative analisys

The quantitative analysis has two main goals in the context of SPAD analysis. Firstly it provides a statistical support to the qualitative analysis. It enables the passage from the results of qualitative analysis on a specific SPAD event to more generalized results on a wide sample of cases (reactive modality). Secondly it provides proactive indications by formulation of hypotheses and hypothesis testing on the available data (proactive modality). Furthermore quantitative analysis would be useful in cost-benefit evaluation of some of the possible measures that can be adopted to improve the quality and safety of railway productive processes.
The potential impact of these measures should be assessed predicting the effect not only on the specific SPAD event, but also on the whole sample of cases defined by the SPAD itself. In the case under investigation only the reactive and proactive modality were developed. Further investigations and improvements in the data collecting system of the railway organization will be needed in order to assess the efficiency of the methodology in supporting the cost benefit analysis. Figure 4 shows the adopted procedure for proactive and reactive modalities.

Proactive Modality

The proactive modality of the analysis begins from the observation and study of databases available inside the organization. In this modality single cases are not considered. Databases entries are analyzed in order to find common causes for the SPAD event to be removed. It is important to understand whether the cause for a certain number of events is just a random superimposition of independent events in time and space or if it is possible to find real links and correlation among them.

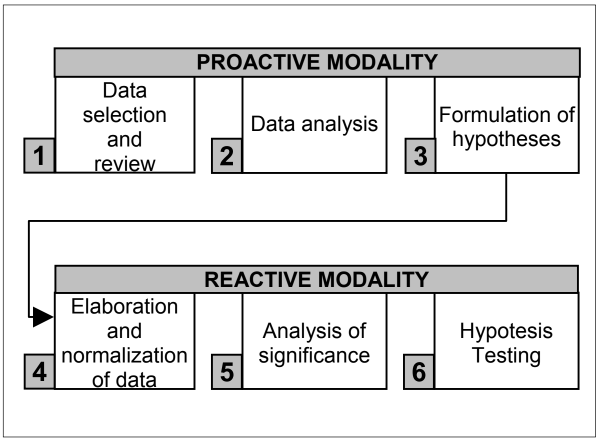

Fig. 4 – Procedure for quantitative analysis

In our case study two different databases were used. The first was concerning 68 cases of SPAD happening between 1995 and 1996, with an elaborate description of every single SPAD [5]. The second was an historical database from FS concerning all kind of anomalies between 1995 and 1999. In this case there was no distinction between SPAD and real accidents and the descriptions of the events were too concise to be easily used.
The *first step* of the proactive analysis is the selection and validation of data. Data are analyzed to asses if they are correct and consistent. In our investigation, for example, some cases were deleted, as they couldn't be classified as real SPAD or they were duplicates inside the database. Another example was the deletion of a particular database field concerning the railway anomalies. That field reported "human error" as a cause for the anomaly in most of the cases and was not considered significant for the goals of our study.
The *second step* is a preliminary descriptive analysis. Here only the summary statistics techniques are adopted, in order to have a better understanding of the distribution of data. These are the summary measures like means, standard variety, variance, etc. Hence data are analyzed as such, without any formulation of hypotheses. An example of descriptive analysis is presented in figure 5. Here, 68 SPAD events happened between 1995 and 1996 and were classified taking into account the kind of engine pulling the train. The analysis shows a high frequency of SPAD for a certain kind of engines: 656 and 636, for example, were considerably more subject to SPAD events. That observation led to the hypothesis that some characteristics of the locomotive could have an influence on the occurrence of SPADs.
In the following some work hypotheses were formulated, entering in the *third step* of the methodology. Among them there was the hypothesis that the whole ergonomics of the engine could have an influence on the SPAD rate. In order to test this hypothesis we run the last part of the methodology, which shares the same steps with the reactive modality (steps 4, 5 and 6 in figure 4).
First of all the hypothesis testing involves a further normalization and elaboration of data, in order to have an adequate data grouping and to prevent an high spread of values as regards the dimension of the sample. Then some predictive statistic techniques are applied, such as *Chi Squared* and *Student t* tests, in order to validate the formulated hypothesis.

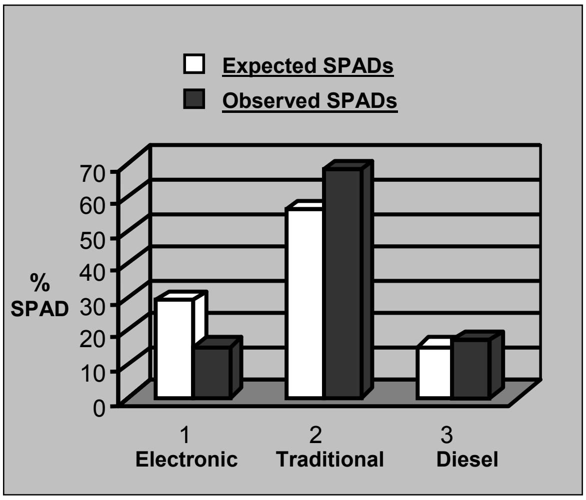

Fig. 6 – Different distribution of SPAD among the 3 categories

In the case study we decided to group the train engines in three categories: electronic engines, diesel engines and traditional engines. Recently improved ergonomic equipment characterized the first category. The second category, instead, had medium level ergonomic equipment. Finally the third category had less satisfying ergonomic devices. Then, in order to normalize data,

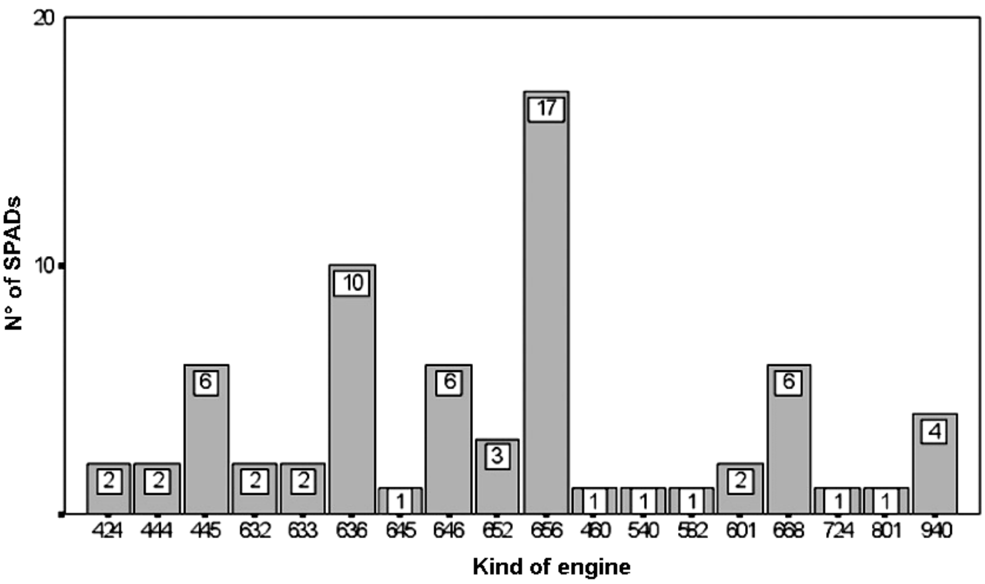

Fig. 5 - N° of SPADs of the different kind of engine

the number of kilometers run by each category of engine in a year was considered. It was logically expected that there would be a direct proportion between the run kilometers and the number of SPAD. Through that assumption it was possible to derive the expected percentage of SPAD for each category (the light gray columns in figure 6). As the graph illustrates there is a considerable difference between the expected SPAD and the observed SPAD, which are indicated by the dark gray columns.
At this stage the analysis should asses if the difference between the two distributions is just random (the *null hypothesis*) or if the work hypothesis is verified (the difference between the two distributions is not only due to chance). In the case study the hypothesis testing was run via a Chi Squared test. The probability to reject the null hypothesis with an *error 1 type* was less than 1%. This meant that it was possible to assume a certain role of engine ergonomic level, with less than 1% of possibility to be in error.
The last phase of the analysis should be the reinforcement of the hypothesis by further statistic analyses or by comparison with similar studies. In the case study, for example, there was a comparison with an investigation conducted for Canadian railways, which put in evidence of a significant role of ergonomic and comfort factors in the occurrence of SPAD [8].

Reactive Modality

Pursuing different goals, the proactive modality of the analysis follows the steps 4, 5 and 6 previously analyzed for the proactive modality (figure 4). It is put in place to verify observed phenomena from a quantitative point of view and to validate hypothesis formulated by the qualitative analysis.
During one of our qualitative analysis, for example, doubts came out about the efficiency of SRE (see qualitative analysis) in preventing SPADs. Hence a request to verify past occurrence of SPAD events in trains equipped with SRE was formulated. In addition, always after a qualitative analysis, there was a request to evaluate from a statistical point of view the role-played by the kind of service provided by the railway organization. It was asked to understand if there was a significant difference in SPAD occurrence among three categories of train: Long Distance trains, Local Trains and Cargo Trains.
Testing of the two hypotheses was run following the same steps described in the previous section. Unfortunately it was possible to normalize only the data concerning the kind of service provided by the railway organization. Because of the incompleteness of the anomalies database, it was not possible to normalize the data concerning the SRE.

	N° SPADs on DS	N° SPADs on PS
SRE installed	5	5
SRE not installed	25	25
RSE out of work	3	2

Table 1 – Inpact of SRE on the number of SPADs.

Table 1 shows the provisional results of the first analysis. SPADs are grouped taking into account the kind of signal passed: DS for Departure Signal and PS for protection Signal. Then there are three different conditions: SRE not installed, SRE installed and SRE not working. Data indicate a considerable presence of SPAD also for trains with SRE installed, but the lack of information showing the number of kilometers and the number of signals met by trains in different rail lines do not allow understanding if there is a significant difference between the two distributions.
Instead, concerning the kind of service (long distance, local, cargo), normalization was done taking into account the number of kilometers run in the three different modalities. In this case the outcome of the hypothesis testing resulted in the acceptance of the null hypothesis. No significant difference was found in the distribution of SPAD events among the three categories (figure 7).
A comparison with a similar investigation run by Railtrack and concerning the SPAD events between 1990 and 1997 confirmed a low impact of the kind of service on the occurrence of SPADs [Gibson].

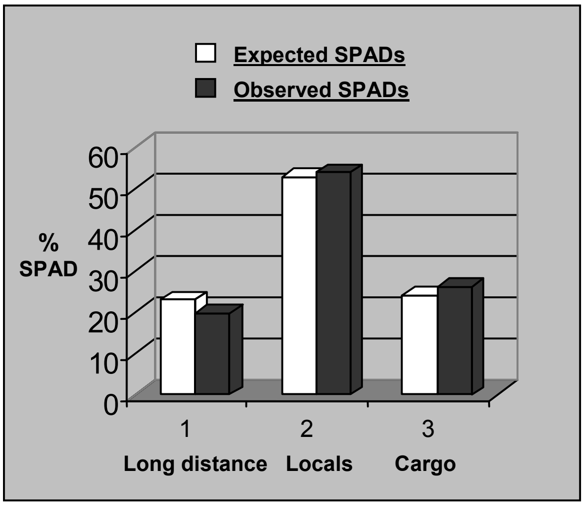

Fig 7 – Different distributions according to the kind of service

Integration of quantitative and qualitative

As we observed in the previous sections it is possible to integrate qualitative and quantitative analysis of SPADs in the identification of remedial actions to prevent real accidents and to improve the quality and safety of railway productive processes. That integration is useful either at a proactive or reactive level of intervention. We now consider in more detail the different role of the two levels of analysis.

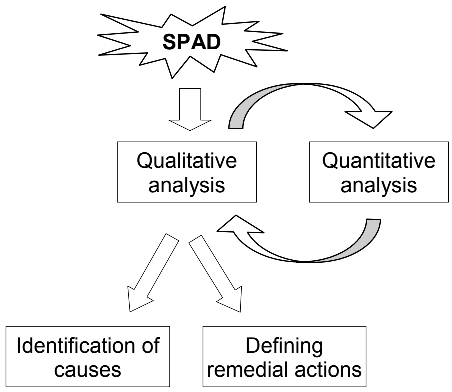

Fig.8 – From qualitative to quantitative

In the first case (figure 8) we move from an event that has already occurred and we analyze it from a qualitative point of view, in order to understand enabling causes and conditions. Here the contribution of quantitative analysis is the validation and reinforcement of hypotheses concerning the causes of SPAD through predictive statistics techniques. A further role of quantitative analysis should also be the predictions of the impact of remedial actions at a wide level inside the railway productive processes. In other terms it should be useful in understanding if a specific solution will be efficient only limited to a specific case observed or if it will be useful in a wide range of cases. That aspect of quantitative analysis was not explored in the paper, because of the strong limitation of available data.
In the second case (figure 9) we start from preliminary results of quantitative analysis in order to find common causes for the SPAD events. Through that procedure different hypotheses are tested. Then, it is possible to better specify the hypothesis adopting concrete examples and using results coming from qualitative analysis.
Quantitative analysis should provide indications concerning the remedial actions at a global level. Instead qualitative analysis

allows a better specification of the remedial actions, at least at the specific level of the case under investigation.

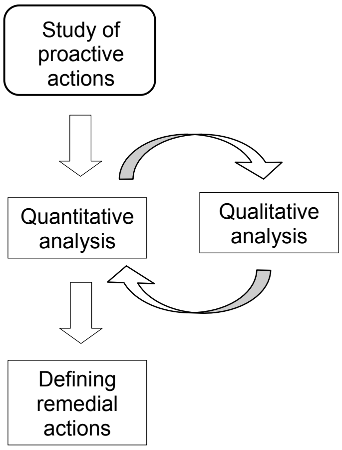

Fig.9 – From qualitative to quantitative

Conclusion

The paper presented a methodology for SPAD analysis and some examples of application carried out during an experiment with the railway organization. The integration of qualitative and quantitative analysis was successful in discovering latent failures inside the productive processes and in providing redesign proposals with a direct involvement of railway operators. The qualitative part of the method was particularly effective in detecting weak interactions among the system components, as defined at the light of SHEL model. Thanks to the strong involvement of railway operators, it was also possible to define in detail a solution to most of the 12 critical interactions analyzed during the study. Instead, the quantitative part of the method was useful in evaluating the incidence of some causal factors explored during the qualitative analysis, such as the impact of the kind of service on the number of SPADs. Furthermore, it helped in formulating other work hypothesis, like in the evaluation of the incidence of ergonomic equipment. Nevertheless, limitations were found in the possibility to use historical databases and to retrieve reliable information concerning most of the SPAD events occurred in the past. Therefore cost-benefit analysis of possible remedial actions was not accomplished.

Although the methodology is still in the form of a prototype, suggestions and requirements were provided to run an engineering process of the method inside the railway organization. Future research directions will be the design of specific tools to support the different methodological steps, such as an historical database for the repository of critical interactions, and the application of the methodology to new cases of SPAD.

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