Building critical infrastructure resilience –
Cross-sectoral comparison of vital operational tasks and practices

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Abstract: Resilience describes the ability of critical infrastructures (CIs) to mitigate hazards, minimize disruption, facilitate recovery and alleviate the effects of future hazards. CIs are to a great degree coupled, mutually dependent and interconnected, while their actors contribute with their planning, decisions and actions towards building (or not) resilience. To design resilient CIs the dependencies among the systems and corresponding human contribution shall therefore be investigated. First, to identify dependencies of different tasks within a sector and between sectors and demonstrate whether such dependencies may affect resilience. Second, to define the tasks that affect resilience during a system's different operational states. This study focuses on critical tasks during normal and disrupted operations in the energy (electricity) and transportation (railways) sectors. Retrospective analysis of accident data determines the critical tasks based on their importance to the operation. Hierarchical task analysis provides insights about the tasks complexity, differences and similarities. The factors that affect human operators' performance while conducting their tasks are also ascertained. Findings confirm that tasks with similar attributes across sectors result in different resilient performances in recovery time and service loss terms. Kendall's tau correlations show various relationships between tasks, factors, consequences upon disruption, recovery time and service loss.

Keywords: Resilience, Critical Infrastructure, Critical tasks, Cross-sectoral comparison, Kendall's tau correlations.

1. INTRODUCTION

The welfare and security of modern societies depend heavily on the undisturbed flow of goods and services produced and distributed by a variety of critical infrastructures (CIs), such as energy, transportation or healthcare [1]. The unavailability of one or more of these infrastructures, or the loss/degradation of its continuous service may lead to significant economic or other losses, while potential cascades across sectorial boundaries could result in multi-infrastructural collapse and severe consequences [1, 2]. To this end, the notion of resilience has substantially developed over the last decade [3] and it is broadly used to describe the *ability of a CI to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions* [4]. Resilience has also been associated with a system's loss of service and its corresponding recovery subsequent to a disruption [5, 6].

CIs are to a great extent coupled, mutually dependent and highly interconnected [7], while their relevant actors, e.g., operators, contribute with their planning, decisions and actions to building (or not) resilience [8]. Consequently, when designing/building resilient CIs not only shall the equipment and physical dependencies among the systems be investigated but also the corresponding human contribution thoroughly be examined. For the former, it is essential to identify how different tasks within a sector and between sectors may be dependent, and how such dependencies may affect resilience. For the latter, it is important to define the critical tasks and behaviours that affect a system's resilience during normal and maintenance operational states, as well as under abnormal and emergency conditions. This study focuses on identifying, comparing and analysing critical tasks

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during normal and disrupted operations in interdependent sectors. The highly interconnected energy and transportation networks are investigated, in particular the electricity and railway systems [9, 10]. Retrospective analysis of accident data is used to determine the most critical tasks based on their importance to the operation. For those tasks, hierarchical task analysis provides detailed insights about the tasks' complexity, differences and similarities. Comparison of the tasks with similar attributes in the two sectors of interest is performed to establish whether different resilient performances may have achieved across sectors, in terms of recovery time and loss of service (preparedness).

In addition, the factors, also known as Performance Shaping Factors (PSFs), which may affect the performance of human operators while conducting their duties are determined. The PSFs are generally described as *all these factors such as age, working conditions, team collaboration, mental and physical health, work experience or training which enhance or degrade human performance* [11]. They express the various situational, organisational, systemic, personal and environmental factors that may influence the performance of an individual (or group) while executing their tasks. Here, the retrospective analysis of accident data is again exercised to define the relevant PSFs, that is, the most common and important factors that have an impact on the operators' performance.

Kendall's tau correlations are finally employed to determine potential correlations between the tasks, the identified PSFs, severity of consequences upon disruption, recovery time and loss of service. Future work will investigate tasks in other sectors, including emergency (evacuation), communication and healthcare to provide a more comprehensive list of critical tasks and best practices towards building more resilient infrastructures.

The remainder of the paper is organised as follows. Section 2 discusses the aspects of interdependency between critical infrastructures and presents a case relevant to the context of this paper. Section 3 describes the data sources used to define the relevant critical tasks and associated PSFs in the electricity and railway sectors. The findings are then demonstrated in Section 4. Section 5 presents the statistical findings. Finally, Section 6 summarises the findings, addresses the areas of concerns and charts the future research directions.

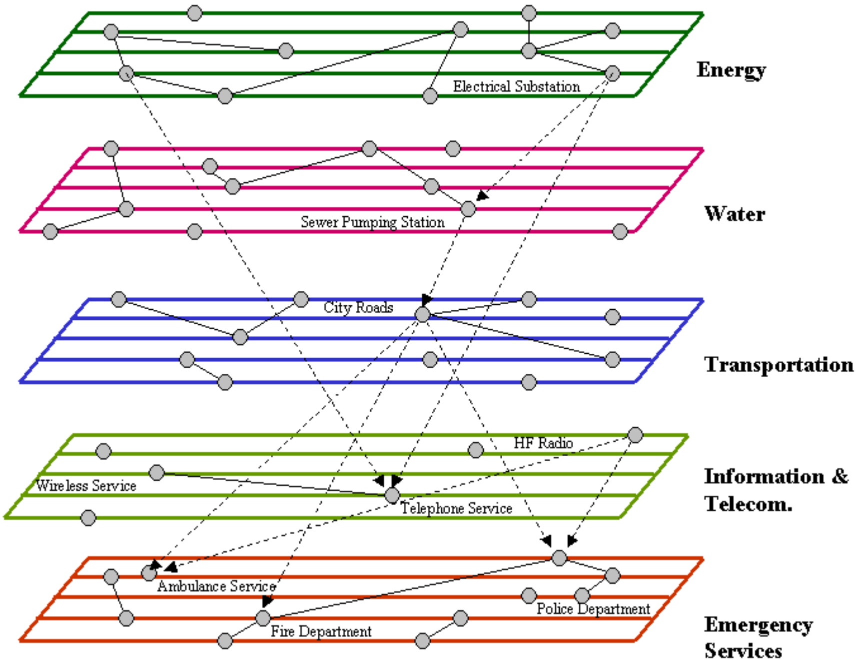
2. CRITICAL INFRASTRUCTURE INTERDEPENDENCIES

The (inter)dependencies among critical infrastructure are variously described in the literature. Rinaldi et al. [7], for instance, define and examine four principal classes of CIs interdependencies: physical, cyber, geographical, and logical. In the same vein, Pederson et al. [2] adopt a more extended list comprising physical, informational, geospatial, policy/procedural and societal interdependencies, while the NIST [12] identify four types, that is internal and external, time, space, and source interdependencies.

All classifications are built upon common grounds and underscore the complexity, strong relationships and linkages among the different types of infrastructure. Figure 1 presents an example of CI system interdependencies showing the possible dependencies among the numerous services and premises at the emergency services level with the other infrastructure systems [2]. As it can be seen in Figure 1, understanding the dependencies and potential cascading effects among the different infrastructure could result in effective response and coordination for recovery, and restoration subsequent to a shock event [12].

Due to the strong linkages between the infrastructures it can be expected that the impact of a shock event on one system could be transmitted across multiple systems. To this direction, this paper investigates interdependencies between the electricity and railway systems and potential cascade effects.

Figure 1: Infrastructure Interdependencies [2]



The 2005 blackout in the Swiss railway electric supply system is an example of such (inter)dependency [13]. Due to maintenance work on the network three generators and one frequency converter were out of service. Further, one of the system's transmission lines was also undergoing maintenance work and hence was not operational. The latter led to the overload of an adjacent line and subsequently to the split of the SBB electrical system into two parts, namely the northern and southern. The frequency in the northern part decreased while it increased in the southern. The power surplus in the southern part resulted in an over-frequency, which caused the trip of most of the system's generators. Consequently, no power supply was provided to the southern part of the railway system and the train traffic came to a complete standstill. The disruption occurred during rush-hour and affected approximately 2,000 passenger trains and 200,000 passengers. Restoration was initiated 90 minutes after the blackout. The passenger train traffic returned to a normal level about four hours after the loss of power, while the freight trains service was back to normal operation the next day.

In addition to the poor data update in the documentation used in the control centre, one of the causes of the blackout that highlights the interdependency between the two systems stems from the trains routing. Modern electric locomotives operating on the Swiss network have the ability to recuperate energy, that is, they feed the grid with power when traveling downhill or decreasing speed. At the moment of the blackout, many trains in the southern part of the railway network were traveling downhill at the same time. Consequently, instead of consuming, they were feeding the grid with power, which contributed to the overload of the line in a reduced-capacity power system. Had the scheduling of trains considered how they may collectively impact the power system, namely some of the trains traveling uphill, the line overload and subsequently the blackout would probably have been avoided [13].

3. DATA SOURCES

Two sources of publically available data were used in this study: the first comprises several reports that describe worldwide blackout events in the electricity sector, for instance the 2003 blackout in the US and Canada [14, 15]. The second includes reports that analyse serious worldwide railway accidents, as defined in [16]. The selected data contain detailed information about the tasks that the human operators are expected to perform, as well as the factors that influence human performance in a risk-significant accident in either of the sectors. Although the list of events is not exhaustive, the selected reports provide an illustrative sample of human involvement in events that have affected the electricity and railway sectors in the past 15 years.

All of the reports consist of four main parts: (i) executive summary, (ii) factual information of the event, (iii) detailed analysis and (iv) conclusions and recommendations. The executive summary describes briefly the sequence of events that led to the event, while it also indicates the immediate causes, the causal and contributory factors and any underlying causes. However, if the analysis is based only on the facts provided in the executive summary, information regarding the performed operational tasks, state of the relevant PSFs, as well as any additional insights that may have contributed to the event could be overlooked. Thus, an in-depth analysis of the reports was carried out to ensure that all the necessary information related to the events was captured.

3.1. Data in the Electricity Sector

In total six major recent blackouts were analysed, as listed in Table 1. All events include a contributing element related to human performance, in particular that of power dispatchers; they differ in the magnitude of the service loss and the duration of recovery.

Table 1: List of major blackouts

Event	Year	Service loss	Time to recover	Causes related to human involvement
USA – Canada blackout [15]	2003	~ 70 GW	Up to 2 weeks	• System understanding - planning • Dispatchers' situational awareness • Maintenance practices
Italy [17]	2003	~ 27 GW	Up to 19 hours	• System understanding • Dispatchers' situational awareness • Maintenance practices
Continental Europe [18]	2006	~ 16 GW	Up to 2 hours	• Coordination between Transmission System Operators • Training
USA [19]	2011	~ 8 GW	Up to 12 hours	• System understanding - planning • Dispatcher' situational awareness
India [20]	2012	Up to 84 GW in total	Up to 2 days	• Coordination between the State Load and Regional Load Dispatch Centres
Turkey [21]	2015	~ 11 GW	Up to 10 hours	• Awareness of system's operational condition • Maintenance practices

The information provided in the reports showed that human involvement was neither the main cause in any of the blackouts nor could it result on its own to the event and its cascading failures. Nonetheless, it was also found that if the dispatchers performed better while executing their tasks, the magnitude of the blackouts and their subsequent consequences would had been alleviated.

3.2. Data in the Railway Sector

In total eight serious railway accidents involving traffic controllers were analysed, as shown in Table 2. The corresponding reports were derived from the French Land Transport Accident Investigation Bureau, the U.K. Rail Accident Investigation Branch, the US National Transport Safety Board, the

European Railway Agency Database of Interoperability and Safety, the Swiss Federal Railways and the Accident Investigation Board Norway.

Table 2: List of serious railway accidents

Event	Year	Service loss	Time to recover	Causes related to human involvement
Austria [22]	2006	Suspension of traffic on this line section	Not clearly indicated	• Communication • Procedures • Safety culture • System design
France [23]	2006	Suspension of traffic on this line section	Not clearly indicated	• Supervision - Teamwork • System design - HMI • Training • Procedures • Safety culture
Switzerland [24]	2006	Suspension of traffic on this line section	Not clearly indicated	• Time pressure • Teamwork • Communication
USA [25]	2007	Suspension of traffic on this line section	Not clearly indicated	• Distraction • Safety culture • Procedures
Czech Republic [26]	2008	Suspension of traffic on this line section	Not clearly indicated	• Teamwork • Communication • System design • Workload • Fatigue • Situational awareness
USA [27]	2009	Suspension of traffic on this line section	Not clearly indicated	• Quality of procedures • Safety culture • Situational awareness
United Kingdom [28]	2010	Suspension of traffic on line section and level crossing	Not clearly indicated	• Distraction • Time pressure • Familiarity
Norway [29]	2010	Suspension of traffic on this part of the station	Not clearly indicated	• Training • Communication • Teamwork • Safety culture • System design • Procedures

In contrast to the electricity sector, the information included in the railway reports revealed that the human involvement was indeed the main cause of the presented accidents and that all the events could have been prevented if human operators had executed their tasks better.

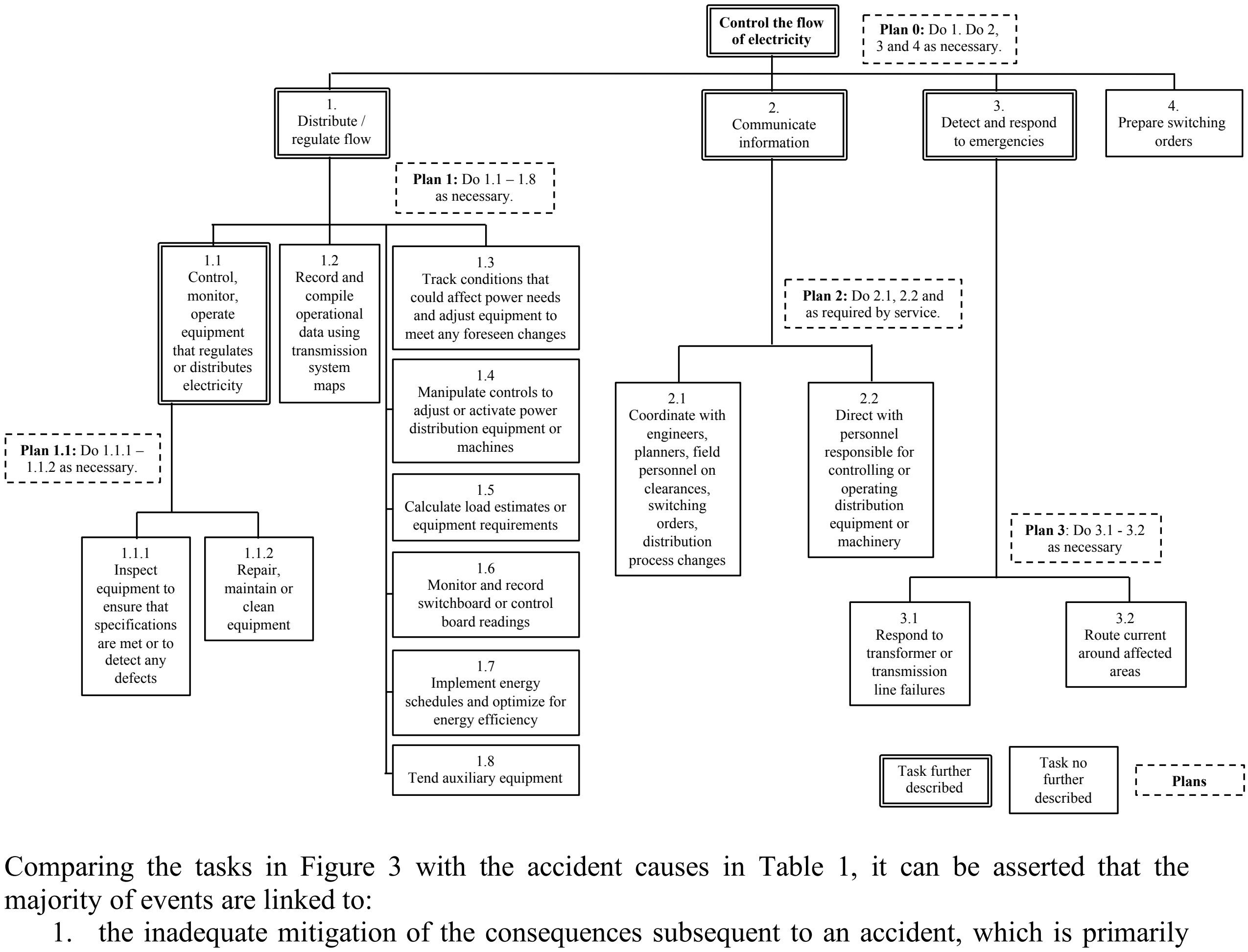
4. RESULTS FROM THE REPORTS ANALYSIS

First, the Hierarchical Task Analyses (HTA) were constructed of the tasks the dispatchers in the electrical network and railway control rooms need to perform to achieve certain goals, based on

information extracted from the reports. The former are also known as power plant distributors and dispatchers, while the latter as signallers and controllers (depending on the area of responsibility). The findings were corroborated with insights from the relevant literature [30-35]. The corresponding HTAs are illustrated in Figures 3, 4 and 5.
In general, electricity power plant distributors and dispatchers control the flow of electricity as it travels through a network of transmission lines from the power plant to industrial plants and substations, and then flows through distribution lines to residential users. Similarly, the railway signallers (dispatchers) are responsible for directing and coordinating the safe movement of railway traffic on a specified territory from a central and/or regional location, while the railway controllers are in charge of guarding the safe train traffic along a large part of the network.

The main task for an electricity power plant dispatcher, as it can be seen in Figure 3, is to "*control the flow of electricity as it travels from generating stations to substations and users*". Four main functions shall be executed by a controller, (i) control, monitor and operate the current converters, voltage transformers, and circuit breakers over a network of transmission and distribution lines, (ii) prepare and issue switching orders to route electric currents around areas that need maintenance or repair, (iii) detect and respond to any type of emergencies, and finally (iv) work with plant operators to trace and solve any electricity generation issues, as well as coordinate any plant support activities. Each of the four main functions is further divided leading eventually to nine total sub-functions.

Figure 3: The Hierarchical Task Analysis for an Electricity Power Plant Dispatcher



Comparing the tasks in Figure 3 with the accident causes in Table 1, it can be asserted that the majority of events are linked to:

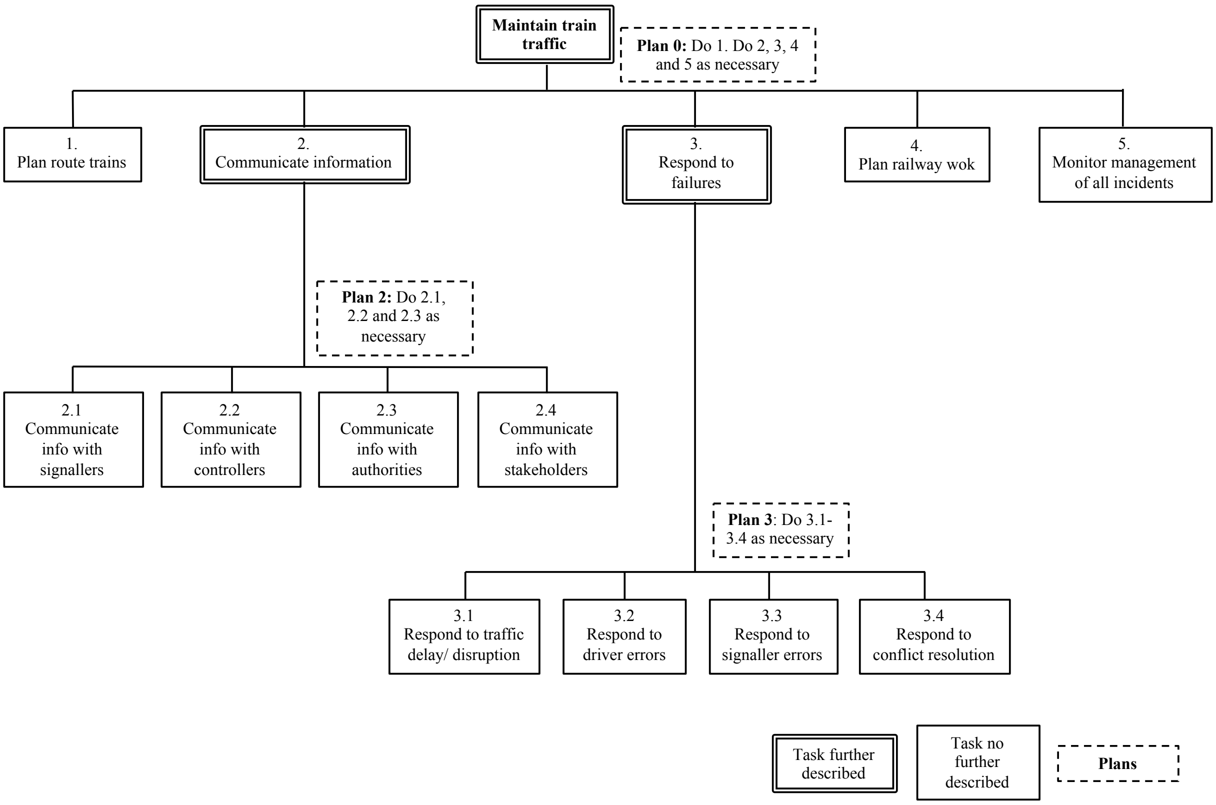
1. the inadequate mitigation of the consequences subsequent to an accident, which is primarily associated with the lack of system's understanding, the electric power plant dispatchers' situational awareness and potentially lack of training and inadequate procedures
2. the lack of equipment testing and maintenance implementation, demonstrated mainly by the inadequate maintenance practices and training

3. the inadequate coordination of plant support activities, indicated by the lack of coordination between the involved actors and entities

Figure 4, in turn, illustrates the activities of railway traffic controllers and indicates their primary goal as "*maintain train traffic*". Traffic controllers ensure train traffic along a large part of the network by overviewing train services, particularly during times of national disruptions. Based on extracted information the main task is divided into five subtasks: (i) make an overall plan of train routing; (ii) communicate the necessary information to signalers, controllers, authorities and railway stakeholders; (iii) respond to failures; (iv) plan long term railway works along the network; and finally (v) monitor the management of all types of incidents.

The traffic controllers responsible for the maintenance of the train traffic along a specific part of the network are called signalers, and their main activities involve the: (i) setting of train routes; (ii) communication of the necessary information to the train drivers, other signalers, railway personnel; (iii) response to failures; and (iv) authorization of railway works in the section of their responsibility. The signalers HTA is shown in Figure 5.

Figure 4: The Hierarchical Task Analysis for a Railway Controller



Similar to the rationale followed for the electrical power plant dispatchers, comparing the tasks in Figure 4 and 5 with the causes related to human involvement in Table 2, it can be claimed that the events were, to a vast degree, caused by:

1. the inadequate communication of the necessary information among the railway personnel, expressed in cases by poor communication and teamwork, time pressure and occasionally familiarity
2. the poor train routing, indicated mainly by the lack of concentration (distraction), and inadequate procedures, while in some cases by the inefficient system design, lack of situational awareness, dispatchers/controllers increased workload and time pressure
3. the inadequate coordination of railway works, demonstrated by the lack of coordination and poor teamwork, and often lack of clear procedures

Figure 5: The Hierarchical Task Analysis for a Railway Signaller (Dispatcher)

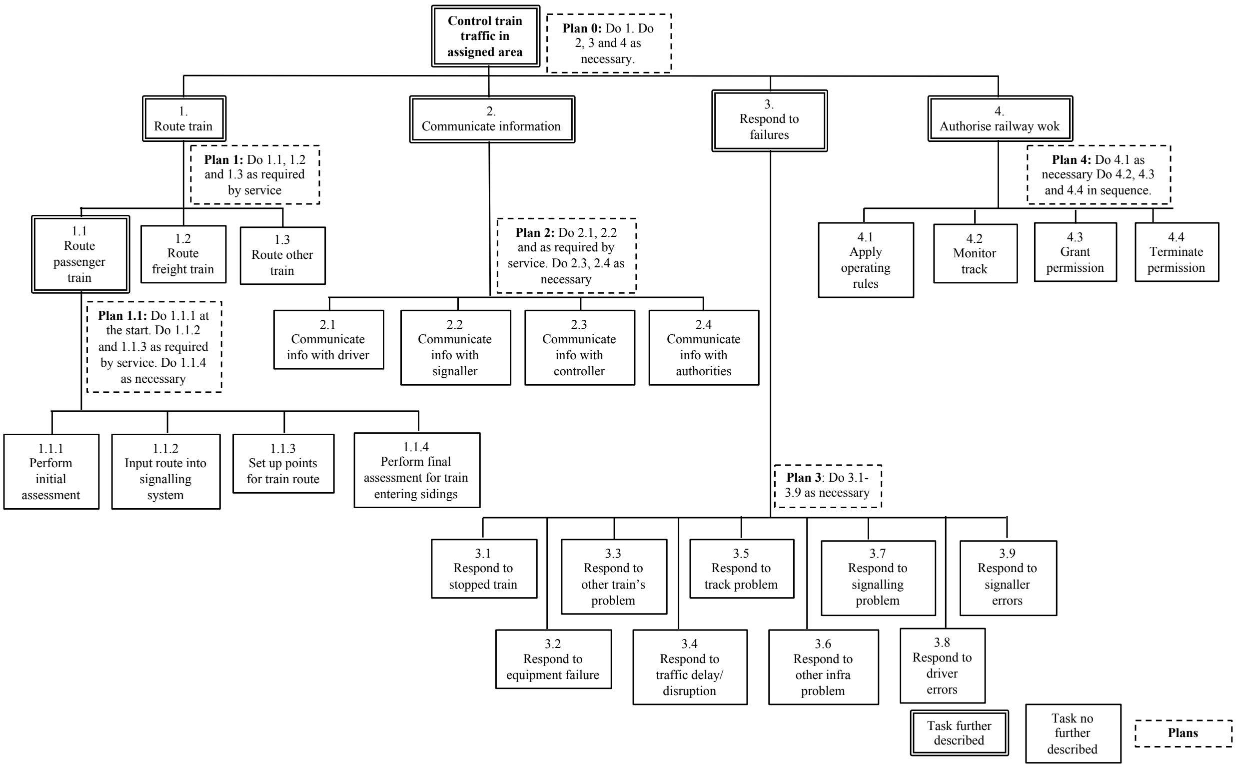


Table 3 summarises the PSFs findings for both sectors and it reveals that more than 80% of the identified factors are matching. In contrast to the electricity sector, however, for all the railway events *safety culture* was either explicitly or implicitly identified as a major contributing factor to the occurrence. This observation could be explained either by differences in the accident reporting between sectors or by cross-sectoral differences regarding the developed and provided lists of PSFs. For instance, numerous PSFs taxonomies can be identified in the literature tailored to the railway sector [e.g., 36], yet none is found for the electricity (dispatching) sector. Distraction and task complexity have also found to be associated only with the railway and electricity sectors respectively. Again, such findings could likely be explained by the different reporting schemes between sectors.

Table 3: The Identified Dominant PSFs per Type of Operator

Railway Traffic Controllers / Dispatchers	**Electricity Power Plants Dispatchers**
Quality of procedures	Quality of procedures
Situational awareness	Situational awareness
*Distraction **	*Task complexity **
Teamwork / Crew dynamics	Teamwork / Crew dynamics
System design	*Ergonomics / HMI*
Workload, time pressure, stress	Workload, time pressure, stress
Experience / training	Experience / training
Adequacy of organization (safety culture)	*Adequacy of organization (staffing and resources)*
Communication	Communication

** indicates factors that differ across sectors*

Another major difference between the two sectors is related to the magnitude of the service loss and the corresponding time to recovery for this service. In the electricity sector, significant events affect a great amount of people for a period of time that varies largely depending on the area where the event occurs and the surrounding infrastructure and resources. On the other hand, in the railway sector, the affected population subsequent to a disruption is significantly lower; those on board at the time of the event and those who intend to travel on the affected line. The duration of the loss of service may vary substantially depending on the type of the railway infrastructure and the location of the event. In addition, a difference is observed on how detailed is the reporting of the service recovery time in either of the sectors. While the recovery period in the electricity sector is explicitly mentioned, for events in the railway sector there is no clear information for the duration of the recovery period. The focus of the investigation process in the railway sector is primarily on the loss itself (the cause of the disruption), whereas the duration of the disruption is examined just as critically in the electricity sector.

With respect to the information presented in Figures 4 and 5, it can be argued that the tasks of the railway signallers and controllers are similar, whereas their main difference stems from the scale of the operation. Indeed, while a signaller is responsible for a small, specific part of the network, a controller's responsibility covers a larger area, which encompasses several signallers. Considering the tasks presented in Figure 3 and comparing them with those shown in Figures 4 and 5, it can again be claimed that they are alike to a great extent. However, it seems that the dispatchers in the control rooms of electricity power plants are required to perform more activities related to the testing, as well as improvement of the equipment and infrastructure compared to their counterparts in the railway control rooms.

5. STATISTICAL FINDINGS

Kendall tau's correlations were used to indicate any relationships between the identified PSFs, tasks, severity of consequences (service loss) and recovery time within each sector and between the two sectors. Kendall's tau is a non-parametric correlation, which is generally preferred in relative small samples compared to its counterpart, the Spearman correlation [37]. For the statistical tests in this study, the statistical package IBM SPSS Statistics 24.0.0 was used.

5.1. Relationships between variables within electricity sector

The qualitative analysis of the blackout reports suggested that certain PSFs were associated with specific events. The Kendall's tau non-parametric correlations, using the variables PSFs, magnitude of loss and recovery time, however, did not corroborate any significant correlations ($p>.05$) between the type of the PSFs with either the magnitude of the service loss and/or the recovery time. No clear conclusions can, therefore, be drawn as to what to extent each of the PSFs may have decisively contributed to an event. For instance, had the design of the system been more efficient, failures happened independently would have not produced any substantial disruption on the system, despite the lack of human operators' situational awareness.

On the other hand, it cannot be overlooked the fact that specific PSFs appear to be more dependent to some of their counterparts, e.g., situational awareness with system understanding, and teamwork with training.

To build more resilient systems a more detailed investigation of the PSFs involvement in an event is required aiming at determining the exact degree of contribution of each one of the PSFs associated with a specific event.

5.2. Relationships among variables within railway sector

Compared to the electricity sector, findings in the railway domain were more concrete. In particular, Kendall's tau statistics, using the variables PSFs and magnitude of loss, showed that the PSF *safety culture* is significantly ($p<.05$) associated with all the events, regardless of the duration of service disruption. Additionally, potential associations between the PSFs and the events that occurred under disrupted operations were analyzed. Statistics confirmed that the PSFs quality of procedures,

communication, teamwork, training, and workload are significantly ($p<.05$) associated with such events.
Similar to the electricity sector it can also be claimed that certain groups of PSFs are more interrelated than others, e.g. situational awareness with system understanding, as well as teamwork and training. However, again, no statistical significance could support this observation.

The available railway data, in contrast to the electricity sector, do not support any statistical analysis on the recovery time. Subsequently, no solid findings can be drawn regarding the impact of the PSFs on the recovery time of railway service operations.

5.3. Relationships between variables in the two sectors

The variables PSFs, type of infrastructure, magnitude of loss were used for the analysis of any relationships between the two sectors. Results did not reveal any significant correlation ($p>.05$) between the identified PSFs and the infrastructure type. However, any generalization requires attention because the resultswere derived to a large extent from the analysis of service loss events of the same magnitude.

Thus, it will be useful to analyze events of different magnitudes in both the electricity and railway sectors and explore whether the severity of an event may be affected by the existence/contribution of specific PSFs. Finally, in the case of the PSFs that were identified only in one of the two sectors, although at first sight those PSFs seemed to contribute only to the occurrence of events in that specific sector, data were not sufficient to statistically justify such argument.

6. CONCLUSION

Modern critical infrastructures (CIs) are coupled, mutually dependent and interconnected, while their actors can substantially contribute with their planning, decisions and actions towards building (or not) resilience. Therefore, when designing for resilient CIs the dependencies among the systems, as well as the corresponding human contribution should be taken into account. Within this context, in this study we investigated potential dependencies among the energy (electricity) and transportation (railways) sectors focusing on the critical tasks that the operators of those systems are expected to perform under normal and disrupted operational conditions.

Firstly, retrospective analysis of accident data identified the critical tasks, while hierarchical task analysis provided detailed insights on the tasks complexity, differences and similarities. Secondly, the factors that affect the performance of the operators while conducting their tasks were also determined. Findings show that tasks with similar attributes across sectors may result in different resilient performances in recovery time and service loss terms. Kendall’s tau statistics, on the other hand, showed that the identified PSFs have no significant influence on disruption, in terms of magnitude of loss and recovery time, in the different sectors. Thus, the relevant actors may have to concentrate on the differences between the systems’ surroundings, the available and alternative resources, as well as support that could substantially contribute to the prevention and mitigation of the potential disruptions and their subsequent consequences.

Although our findings provide some useful insights regarding the similarities and differences between sectors, generalization of the results at large requires caution, statistical weighting and the exercise of judgment. Furthemore, any interpretation of the results shall take into consideration the substantial differences amongst the operational systems, not only across sectors, but also within sectors. For instance, in the railway sector, while the Piccadilly Line services of London Underground Limited in London are manually operated, the Jubilee Line services are automated.

Thus, future work not only will investigate in more detail the tasks and contextual information in the two sectors, but also in other sectors, including emergency (evacuation), communication and healthcare aiming at providing a more comprehensive list of cross-sectoral critical tasks and best practices. We expect our findings to valuably support operators, policy makers and other relevant actors involved with the design, construction, operation and maintenance of critical infrastructure systems.

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