Squeezing the Lemon: Using Accident Analysis for Recommendations to Improve the Resilience of Telecommunications Organizations

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Abstract: Telecommunications networks form critical infrastructure, since accidents in these networks can severely impact the functioning of society. Structured accident analysis methods can help draw lessons from accidents, giving valuable information to improve the resilience of telecommunications networks. In this paper, we introduce a method (TRAM) for accident analysis in the Telecommunication domain by improving AcciMap, which is a popular method for analyzing accidents. The improvements have made AcciMap more efficient and instructive by explicitly identifying ICT aspects of the accidents, extending the method to support the evaluation of crisis organizations and introducing additional notation for feedback loops. This resulted in TRAM, a method with a 25% improved efficiency over AcciMap, while also addressing ICT aspects, leading to concrete actionable results that can help telecommunication organizations grow more resilient.

1 INTRODUCTION

Telecommunications networks are a vital part of our society and form a critical infrastructure. Any accidents[1] that impact the availability of this infrastructure can have crippling effects on society, from malfunctioning traffic control systems to unreachable emergency services. The consequences of these accidents may be broad, ranging from financial losses to physical damage and damage to health. If emergency services cannot be reached in time or cannot reach their destination in time due to gridlock caused by malfunctioning traffic control systems, this may even result in casualties. Having resilient telecommunications infrastructure is therefore a concern of governments and they have established enforcement agencies called regulators to ensure this resilience. In the European Union, public operators of telecommunications networks and/or services are required by law to report any large accident that results in service unavailability to their regulator.

Just reporting accidents does not prevent new accidents. To make sure an accident is well-understood and appropriate measures are taken to prevent the accident from recurring, a thorough analysis must be conducted. The results of this analysis need to be taken into account when defining improvement actions for the appropriate organizations or organizational units concerned.

Accident analysis methods have been researched and applied since at least 1941 (Heinrich, 1941). In 1997, Rasmussen introduced AcciMap (Rasmussen, 1997), which is an accident causation model and analysis method that not only considers the technical aspects of an accident, but also the social context. By also considering this aspect, the method explicitly recognizes that activities like training, human resource management and organizational culture also play a role in the development of an accident. The combination of the technical and the social context is called the *socio-technical context*. In 2009, Branford introduced the *Generic AcciMap Method* (Branford et al., 2009), which included a workflow for drawing up AcciMap diagrams with the key players of the organization.

AcciMap has been applied in many different sectors (Wienen et al., 2018), but to our knowledge not in telecommunications. More generally, we found few literature sources that even describe analyses of

[1]In Telecommunications, accidents are often called ‘incidents’, even when they are damaging. As the common understanding in accident analysis is that anything that causes harm (*e.g.* to service, hardware or people) is called an accident (Leveson, 2011; Harms-Ringdahl, 2013; U.S. Department of Energy, 2000) and (Doytchev and Szwillus, 2009), we use the term telecommunication *accident* in this paper.

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telecommunications incidents (Bukhsh et al., 2020). We observed in a previous case study (Wienen et al., 2019) that considering the socio-technical context to telecommunication accidents is a useful addition to the analysis of these accidents: by considering this context, a company can identify latent factors that can exacerbate accidents and malfunctioning countermeasures that fail to inhibit accidents. We also demonstrated that AcciMap, and more specifically the Generic AcciMap Method, can be effectively applied to telecommunications accidents. In (Wienen et al., 2019), we reported on a case study on a DDOS attack on a Telecommunications operator and we showed that applying AcciMap to it yielded positive results. That case study gave rise to improvements to the method, resulting in an updated method that we called TRAM (Telecommunications Related AcciMap). In this paper we validate these improvements to the method by applying TRAM to a second case study on a telecommunications accident.

This paper is structured as follows: Section 2 discusses the background of this research, Section 3 introduces the changes to AcciMap, resulting in TRAM, Section 4 describes the steps in the method illustrated by the application of the method in our case study, Section 5 presents the results of the case study which we discuss in Section 6, and Section 7 contains our conclusions and suggestions for future research.

2 BACKGROUND

2.1 Telecommunications

The telecommunications domain is a highly technical domain, under heavy competition and driven by technological progress as much as market forces (Meena and Geng, 2022). Many telecommunications networks (most notably incumbent PTTs and cable operators) have been around for a long time and have been going through many mergers, creating a large base of legacy equipment and technology, which sometimes is not even compatible with each other. This leads to specific problems that can render the network more fragile than desirable. Telecommunications networks are strongly connected and issues propagate very fast through that network (Pitsillides and Sekercioglu, 2000). The domain is furthermore characterized by strong competitiveness. Market pressure leads to lower prices (Fernández and Usero, 2009) and thus lower margins, and investment decisions are driven by market share, putting stress on the distribution of scarce resources, e.g., where to invest money, namely in maintenance or new services, or whether to have cost reductions to provide cheaper services to the customer. The decisions made in these circumstances may have negative consequences for the robustness of the services and they become visible during large accidents, so that these accidents may shed a light on decisions made months or even years earlier.

2.2 Accident Analysis

Companies can have several reasons to analyze accidents. A typical use case is improvement of stability. This use case is concerned with preventing the next accident, or at least preventing the previous accident from happening again (Underwood and Waterson, 2013; Stringfellow, 2011).

There are three families of accident analysis models (Hollnagel, 2002; Hollnagel and Goteman, 2004): *Sequential*, *Epidemiological* and *Systemic*. Sequential models describe accidents as a series of events; epidemiological models add latent factors to the accident, which are factors that failed to prevent the accident or that aggravated the consequences of other factors; and systemic models finally add tight coupling to the model, in which parts of the system are so tightly linked that the propagation of errors or mistake can go so swiftly that a run-away process may ensue or a positive feedback loop can occur. Systemic models start by modeling the context in which the accident occurred and then describe the accident in terms of organizational functions (Hollnagel et al., 2014) or a systems theoretic model (Leveson, 2011).

We have selected an epidemiological model (AcciMap) as a basis for the development of an accident analysis method that takes the specific needs of the telecommunications domain into account.

3 TRAM

This section presents TRAM (the Telecom Related AcciMap Method), which is the method for modeling and analyzing accidents in the telecom domain that we developed by extending the *Generic AcciMap Method* (Branford et al., 2009). This extension was a result of our previous research (Wienen et al., 2019). In this section, we also introduce the case study that we performed to validate the method.

3.1 The Method

TRAM prescribes the steps defined in the Generic AcciMap Method in (Branford et al., 2009), which are shown in Figure 1, extending them with one step that is indicated in green. We added more features to the

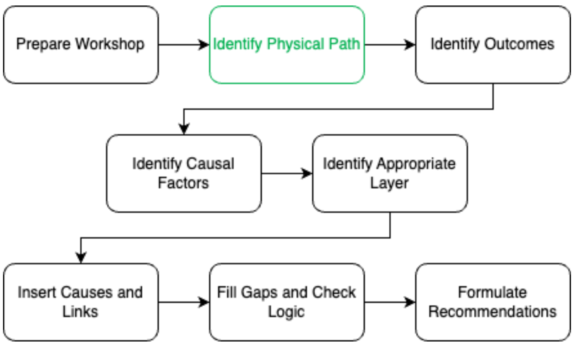

Figure 1: TRAM steps (our addition to the Generic AcciMap Method is in green).

method, which we describe in this section. In these steps a diagram represents causal factors that contributed to the accident, linked by arrows that denote a causal connection, *i.e.* if *A* caused *B*, then an arrow is drawn from *A* to *B*. The diagram is layered, denoting different areas of influence for the company. The bottom part of the diagram contains the outcomes, which are the consequences of the accident. Figure 3 and Figure 4 show an example.

Applying TRAM starts by studying the available information and finding the relevant staff for the analysis workshops. Relevant staff have domain knowledge of the different aspects of the accident, taking the different functions in an organization into account. Once these experts have been identified in the organization, they are invited to the accident analysis workshop. In this workshop, the physical path (*i.e.*, the technical failures that caused the accident), the outcomes and the appropriate layer for analysis are identified, after which the workshop participants identify causes and link them to effects, which are either causes for further effects or outcomes. They fill the gaps in and check the logic of the model that represents the accident. The ultimate goal of the analysis is for the final model to generate enough insight so that recommendations can be formulated.

Avoiding the Blame Game. In a previous case study (Wienen et al., 2018), we spent a lot of time reassuring participants in the workshops that we would not be assigning blame to them due to perceived or actual errors they made. To prevent this from happening, we took time to address this issue at the beginning of the workshop. Moreover, we also started out by describing the physical events that led to the accident. In this way, we started out with a discussion about technical facts, which were perceived to be neutral. This positively influenced the mood in the session, after which discussing actions from participants became less of a threat.

Splitting up the Analysis. We observed that there may be more than one phase in the development of an accident. An accident can cause another accident or a crisis that needs to be resolved. These different phases can sometimes be described independent of each other. If this becomes apparent during a workshop, it provides an opportunity to work in parallel: divide the group into two subgroups that each treat one of the phases. The results are then discussed in the combined group, amended where necessary and finalized. This parallellization makes the process more efficient.

Describing Crisis Management. In our previous research we also observed that a large part of the accident's resolution time was spent managing the crisis that ensued after the accident itself. This led us to apply AcciMap to crisis management, trying to answer the question 'why did it take so long to resolve the accident'. AcciMap turned out to help there as well. After our previous work, we added a new *Category of Cause* to the Organization layer, namely *Crisis Management*, which covers the following aspects: (i) crisis management organization absent; (ii) unclear mandate during crisis; (iii) unclear roles and chain of command; and (iv) inadequate facilities.

Add the ICT Layer. Telecommunications networks strongly depend on ICT. Both software, hardware, configuration and data are relevant and separate aspects of an IT system and they do not have a dedicated place in the layers of the Generic AcciMap. Due to this strong dependence, they deserve focus. Branford's categories of cause only feature hardware, which may be the most robust part of an ICT network: software, configurations and data are much more volatile than hardware. Hardware is only mentioned as an aspect of Equipment and Design, while the other aspects of that category (poor quality, defective, aging, untidy, missing or poorly maintained equipment or tools) strongly suggest that this is aimed at machines and tools, not computer hardware. So, these are good arguments for extending Branford's Categories of Cause. However, as errors in the ICT layer lead to problems in the operational (physical/actor) level and also influence decisions at the organizational level, we have not added a new category of cause to either layer, but rather introduced a new layer with these categories of cause.

Improve Efficiency and Lead Time. Telecommunications operators experience fierce competition, so that efficiency of processes is a main business driver. Therefore, in TRAM we aimed to make the accident analysis as efficient as possible. Most effort is put into the workshops, due to their attendance. Minimizing the number of workshops has a large impact on the total number of person-hours invested in the investigation. Splitting up the analysis and working in parallel as mentioned before decreases the duration of the workshop. Furthermore, by creating and reviewing the diagrams offline (and between the sessions), we were also able to improve the review process: the analysts who run the analysis create the graphical representation of the accident (the diagram) on their own and send it out for review prior to the next workshop, asking for review remarks before reconvening. The researchers then process these remarks and have a reviewed version of the diagram available at the start of the next workshop.

3.2 The Accident

In the accident we analysed to validate our method, during routine maintenance on a power switch in a telecom company in 2018, a system failure caused a short interruption in the power supply. Power was restored within a minute, but the interruption had a significant follow-on effect.

During the accident, the power outage caused some parts of the network to go down. Under normal circumstances, the network can deal with such outages since it is designed with redundant parts to compensate for them. However, due to planned maintenance elsewhere in the network, the fallback links were not active. This caused a drop in capacity and congestion in other parts of the network.

Many companies rely strongly on machine-to-machine communication, *i.e.*, communication between devices that runs over the GSM network. Examples are sensors for measuring water levels in canals and rivers that send measurements from time to time to a central control system. When a device cannot send information, *e.g.*, due to a network error, it keeps retransmitting until it finally receives a confirmation that the information has been received by the control system. These types of devices constitute part of the Internet of Things (IoT) network that partially runs over the GSM network.

The congestion caused information from the IoT devices to be dropped, after which the devices tried sending the information again, causing a positive feedback loop that added even more traffic to the already congested network.

The only way to stop this cascade was to block all devices and to release them one by one once the congestion was resolved. Unfortunately, the company did not have a clear administration, so they could not easily find which SIM cards belonged to which type of device. Therefore, they had to disable all devices, including regular mobile phones. This in turn caused the roaming service to break down, so that customers of the mobile network were not able to use the network of other providers, resulting in complaints from customers and roaming partners.

It took the company sixteen hours to completely restore the service, with substantial financial and reputation losses.

4 STEPS AND APPLICATION

This section describes the individual steps in TRAM alongside their application to the accident.

The method uses a predefined structure for ordering causal factors that contributed to the accident. This structure is drawn on a screen, whiteboard or brown paper wall and serves as a foundation on which the next steps are executed. The structure defines five layers, which describe distinct types of causal factors:

1. The *External Layer* covers all factors external to the organization that the organization cannot change itself. It contains the following blocks:
   (a) *Government Block*, covering factors like (inadequate) legislation or budgeting issues.
   (b) *Regulator Block*, covering factors like (inadequate) enforcement of regulations.
   (c) *Society Block*, covering factors like vandalism and market pressure.
2. The *Organizational Layer* covers factors like inadequate risk management or training. These factors are under control of the organization.
3. The *ICT Layer* provides better visibility for the critical role ICT plays in telecommunication, both as an enabler and as a product or service. The layer is one of our additions to the Generic AcciMap Method.
4. The *Physical / Actor Layer* describes immediate actions and events leading to the outcomes, including hardware malfunctioning and human error.
5. The *Outcome Layer* covers the (usually adverse) outcomes of the accident, such as outage and financial loss through missed revenue.

4.1 Workshop Preparation

To prepare for the workshop, we studied the accident reports created by the company so that we could understand which departments were affected by or played a role in the accident. We invited 8 participants to the workshop, who were chosen to make sure all relevant departments were represented in the workshop, as prescribed by the Generic AcciMap Method.

4.2 Workshop 1

In the beginning of the workshop, we introduced the TRAM method to the participants.

Identify the Physical Path. As a first step, the physical path of the accident was identified. The group used notation taken from the Fault Tree Analysis method (FTA) (Lee et al., 1985) for this step (*see*Figure 2. The approach in this step is to only consider the causal factors that are directly linked to the accident and that are physical events, which means that no actions performed by actors should be considered. The purpose of this exercise is to lay down a common image of the accident without evoking discussions about blame. Everybody agreed on the physical events and this resulted in the diagram depicted in Figure 2. This diagram showed that the accident actually could be considered as a combination of two accidents: a power failure and a roaming service outage. This prompted us to divide the participants into two groups, which has been another improvement we made to the Generic AcciMap Method based on our experience from our earlier research. After each subgroup completed their respective diagrams on flip over sheets, the diagrams were combined and the result was discussed with the entire group.

Identify Outcomes. In this step, the outcomes of the accident are identified. Outcomes are the consequences of the accident and they are mostly detrimental. The outcomes of this accident were customer complaints and partner complaints, leading to extra calls to the call center and reputation damage.

Identify Causal Factors. In this step, the Causal Factors are identified. These are factors that directly or indirectly contributed to the accident. The method for identifying causal factors is to ask the participants to write down these factors on sticky notes. In our workshop, we first asked the participants to write down factors without any guidance. After around 10 minutes, we gave them a list of categories they could use to jog their memory. TRAM uses the categories of cause from the Generic AcciMap Method. We added *Crisis Management* as an extra category since crisis management played a crucial role in the validation of our previous research. Actually, it turned out that crisis management played no role in this particular accident.

Table 1: Categories of cause for identification of causal factors.

Government
Financial Issues
Communication & Information
Risk Management
Training
Actor Activities and Conditions
Human Resources
Physical events, Processes and Conditions
Regulatory Bodies
Equipment & Design
Auditing & Rules Enforcement
Manuals and Procedures
Crisis Management
Society
Defences
Organizational Culture

Identify Appropriate Layer. In this step, the appropriate layer for the causal factor is identified by sticking the notes to the appropriate places on the brown paper wall. This is a physical activity that invites the audience to already discuss the meaning of a factor, increasing the quality of the factor.

Insert Causes and Links. In this step, a first draft version of the AcciMap diagram is built by modeling the causal links between the different factors, e.g., factor *A* caused factor *B*, or factor *C* was one of the contributors to factor *D*. After this step, the workshop was finalized. The researchers then created the final diagrams (Figures 3 and 4) based on the results of the workshop.

Positive Feedback Loop. During the meeting, we identified a positive feedback loop, as mentioned in Section 3.2. We introduced new notation to represent this loop and for breaking it, which we discuss in Section 5.1.

4.3 Workshops 2 and 3

Fill Gaps and Check Logic. In this step, the researchers presented the diagram they produced offline based on the draft version created in the first workshop and discussed it with the participants. The aim of this discussion was to verify the relations between

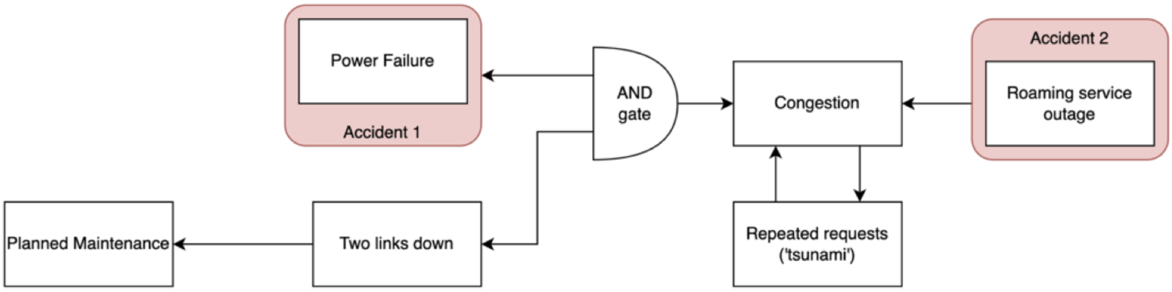

Figure 2: The physical path of the accident.

the causal factors and the completeness of the diagram. As a result, we changed some terminology and rewrote part of the diagram to more adequately reflect what happened. At the end of this step, we had identified 56 causal factors, resulting in the diagrams in Figures 3 and 4.

Formulate Recommendations. After completing the diagram, recommendations for each causal factor are formulated. This is done by considering how to (i) *prevent* the causal factor from happening, completely preventing the consequence, and/or (ii) *control* the causal factor during its development, diminishing the consequence, and/or (iii) *compensate* for the consequence of the causal factor.

We posed these questions for each causal factor, resulting in a total of 60 recommendations.

5 RESULTS AND FINDINGS

As a result of the workshops, we drew one diagram. Due to the size of the diagram, we split it up into two parts, one (Figure 3) describing the power outage and another (Figure 4) describing the roaming failure. Due to company confidentiality, we are not allowed to share the exact causal factors and use numbers instead. The triangles are connectors which show where the two parts need to be connected to form the complete diagram of the accident.

Figure 3 shows the TRAM diagram of the power failure. The newly added ICT layer only contains 1 causal factor, hardly justifying a layer of its own. One causal factor (#13) can be included in two Categories of Cause. One causal factor has a modest number (5) of incoming links (#16). This may suggest that it played a central role in the development of the accident, however, it is only one of four factors that link the organization layer to the physical layer. This implies that there is no clear central point of failure.

Figure 4 shows the TRAM diagram of the roaming failure. One part of the diagram stood out: we found a positive feedback loop which we discuss in the sequel. The roaming failure itself (#23) is the result of a relatively simple cascade combined with the feedback mechanism. However, many factors contributed to the long lead time of the accident (#25), which indicates that solving this consequence may take a lot of effort in different parts of the organization. The ICT layer is much more populated that in the power outage, namely 17 causal factors versus 1. This indicates that the ICT environment played a large role in the development (and the prolonged duration) of the incident and the underlying data confirms this.

5.1 Feedback Loops

As part of the analysis of the roaming failure, we discovered a positive feedback loop that exacerbated the accident in the Company's network. To indicate this loop, we introduced additional notation: the loop itself can be represented by joining the constituting causal factors with arrows. However, in order to resolve the accident, an operator had to break the loop. The link that was broken to stop the loop is indicated with a valve symbol ($\bowtie$). The action breaking that link is indicated with a causal factor box (β) with a pointer to the valve. This reparative action had its own consequences, leading to the outcomes under γ. Since breaking the loop was part of the resolution of the accident (and not of the accident itself), we indicate these factors with Greek letters.

5.2 ICT Layer

For the Power Outage, the addition of the ICT Layer did not provide extra insight. For the Roaming Failure, however, the addition was very instructive, since a large part of the diagram is related to that layer. This also gave us the opportunity to formulate new categories of cause for this layer.

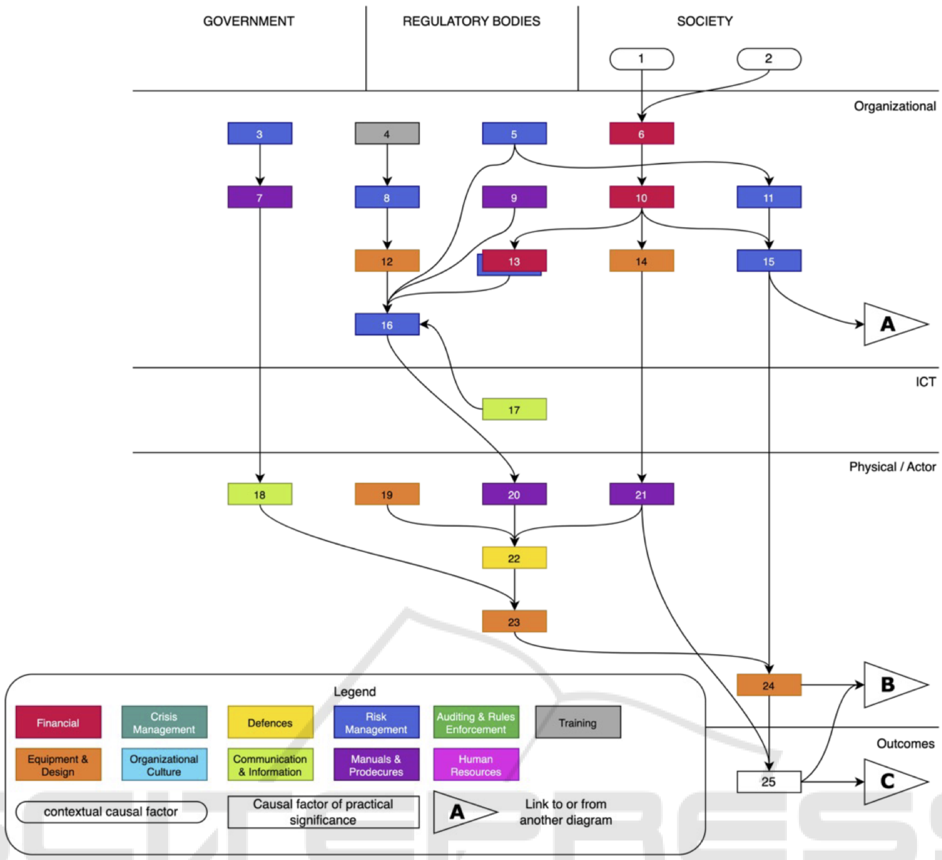

Figure 3: TRAM diagram of the power outage. Note that causal factor 13 has two colors: it fits in both categories. The triangles labeled *A*, *B* and *C* are the connections to the TRAM diagram in Figure 4. The factors in both diagrams have been numbered independent of one another. Number 13 in this diagram has no relation with number 13 in Figure 4.

Table 2: Categories of Cause for the ICT Layer.

Software	Network
Hardware	Configuration Management
System Management	

5.3 Recommendations

For the power outage, we identified 38 recommendations. For the roaming service outage, we identified 22 recommendations. Tables 3, 4 and 5 provide more detail about the causal factors and recommendations we identified in our analysis. Branford's Categories of Cause (Branford et al., 2009) proved to be appropriate for our causal factors. Our proposed category Crisis Management is absent, as this accident did not call for an analysis of the crisis organization. The resolution was smooth, albeit time consuming, and did not call for crisis management.

Table 3: Number of identified causal factors and recommendations per stage and AcciMap level (Ext: External; Org: Organizational; P/A: Physical/Actor).

	Org	Ext	ICT	P/A
Causal Factors				
Power Outage	2	14	1	7
Roaming Failure	0	6	17	1
Recommendations				
Power Outage	3	23	3	9
Roaming Failure	0	5	19	1

5.4 Effort and Lead Time

The total effort invested in the analysis was 114 person hours (*see* Table 7), which is 53% of the effort used for our previous research. This is at least in part due to the efficiency gains we have introduced. This brought the number of workshops and meetings down from 5 to 3. If we measure the complexity of the accident analysis by the ratio of causal factors and causal links between the two accidents, the improvement still

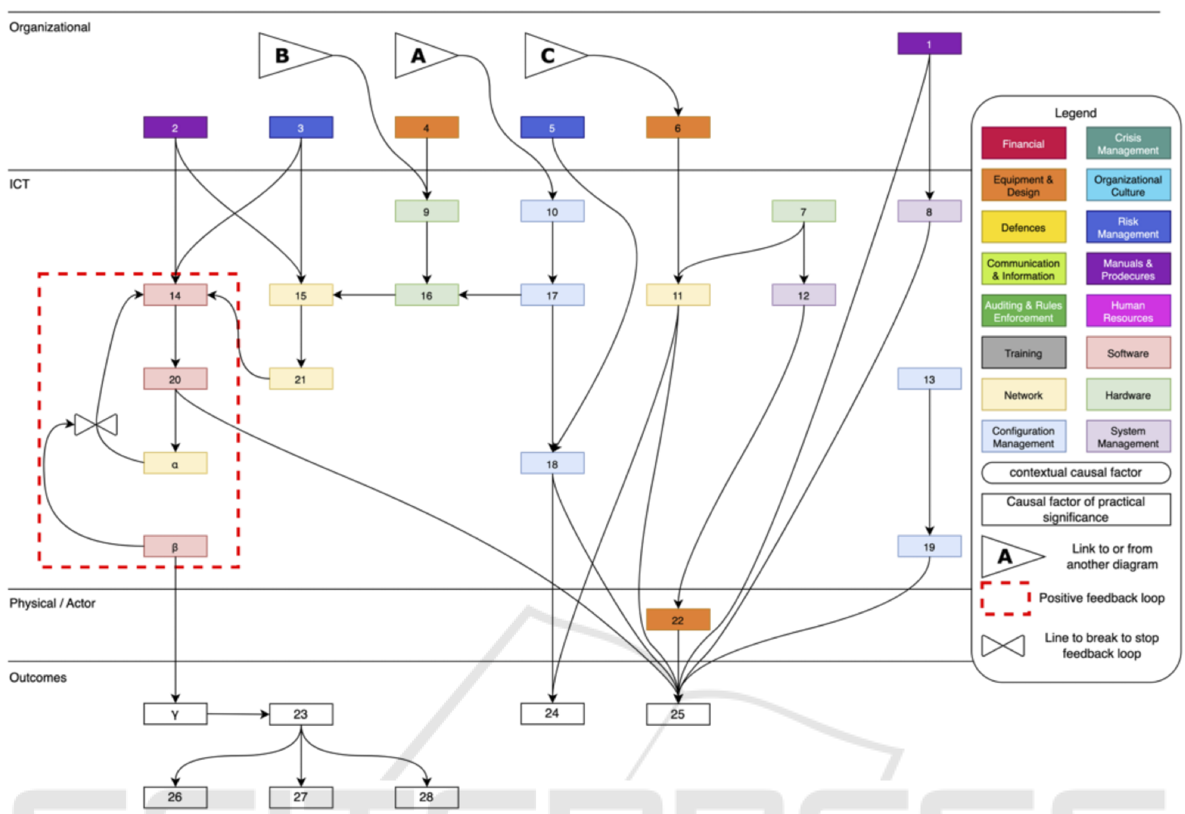

Figure 4: TRAM diagram of the roaming failure.

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Table 4: Recommendations per category of cause for the power outage (Org: Organizational; P/A: Physical/Actor).

Category of Cause	Org	ICT	P/A
Financial	4	0	0
Equipment & Design	3	0	3
Defences	0	0	1
Communication & Information	0	0	1
Auditing & Rules Enforcement	0	0	0
Risk Management	9	0	0
Manuals & Procedures	6	0	4
Training	1	0	0
Software	0	0	0
Hardware	0	0	0
Configuration & Management	0	3	0
Systems Management	0	0	0
Network	0	0	0
Data	0	0	0

holds. If $n_{cf,x}$ denotes the number of causal factors in case study x and $n_{cl,x}$ the causal links, and with Q_y the ratio between the numbers of causal factors or causal links (y), we have:

$$Q_{cf} = \frac{n_{cf,2}}{n_{cf,1}} = 0.69; \qquad Q_{cl} = \frac{n_{cl,2}}{n_{cl,1}} = 0.72$$

This would imply that case study 2 was about 30%

Table 5: Recommendations per category of cause for the roaming failure (Org: Organizational; P/A: Physical/Actor).

Category of Cause	Org	ICT	P/A
Financial	0	0	0
Equipment & Design	1	0	1
Defences	0	0	0
Communication & Information	0	0	0
Auditing & Rules Enforcement	0	0	0
Risk Management	1	0	0
Manuals & Procedures	3	0	0
Training	0	0	0
Software	0	0	0
Hardware	0	3	0
Configuration & Management	0	4	0
Systems Management	0	9	0
Network	0	3	0
Data	0	0	0

less complex than case study 1, but took 47% less time. Correcting for the lower complexity by multiplying the time spent on case study 1 (t_1) by 0.7 (the factor by which accident 2 is less complex), this still yields an improvement of 25%:

$$t_{1,corr} = 0.7 \cdot t_1 = 151 \text{ hrs}; \quad \frac{114}{151} = 0.75$$

Table 6: Relevant measurements from the first case study as reported in (Wienen et al., 2019) and this case study; t denotes the time invested in the case study; n_{cf} is the number of causal factors and n_{cl} the number of causal links. For the time invested in case study 2, *See also* Table 7.

case study	t	n_{cf}	n_{cl}
1	216	81	95
2	114	56	68

6 DISCUSSION

We introduced three new elements when designing TRAM: the ICT layer (with its Categories of Cause), the Physical Path and the Crisis Management Category of Cause. We also introduced efficiency improvements. During the execution of the current case study, we observed that the addition of the ICT layer provided more insight into the accident. The high number of causal factors show that ICT aspects play a very important role in the roaming failure.

The addition of the ICT layer gave us the opportunity to formulate new Categories of Cause for this layer. These categories are now determined by the accident we analyzed. They were sufficient and not too detailed for this accident. Based on our findings, we anticipate they may prove equally useful for other accidents. If this list is adequate or if it needs to be adapted is a subject for future research.

Starting with the physical path helped in two aspects: it showed that the accident was actually a combination of two accidents, enabling us to split up the group and it set the scene for a constructive discussion, since the group agreed on the physical steps for the accident and thus had an early success. The discussions during the rest of the workshops were focused on substance and we only had to direct the discussion away from blame a small number of times.

This accident did not feature the Crisis Management Category, so we were not able to assess its usefulness.

During the analysis, we identified a behaviour pattern that TRAM had not yet taken into account: the positive feedback loop. A result of the current case study is additional notation to represent this pattern.

The efficiency measures (splitting the groups, doing offline work) had a positive result on the effort put into the analysis, since it took 25% less effort than our previous research after correcting for complexity. However, this conclusion is only based on the difference in these two case studies. More analyses need to be done to get statistically significant results.

Experts' Opinion

The company concluded that "This method is a good method for accident analysis in the Telecommunications domain and that it contributes to finding improvements. The case study has led to a number of changes in the company, under which the planning of an annual Business Continuity Management (BCM) test. The discussions in making the diagram itself were essential in formulating the right improvements. The explicit principle of no blame has led to the complete set of insights and improvements."

7 CONCLUSION

We performed this case study to validate the changes we made to AcciMap when developing TRAM. Based on this case study, we conclude that our improvements to AcciMap are useful. By adopting the principle of no blame and by starting out from a pure physical perspective, the participants were able to steer away from discussions about blame, leading to a comprehensive set of insights and improvements. The addition of the ICT layer led to more specific recommendations in the ICT domain, which is pertinent to telecommunications.

Splitting the group helped conducting the workshops more efficiently, as did the offline generation of the diagram and review. This yielded an improvement of 25% after correcting for complexity.

The recommendations from the method were actionable: several have already been implemented and the company believes they have already led to resilience improvements.

We were able to improve TRAM itself as well, since the addition of notation to represent the feedback loop gives more insight in runaway processes. It provides insight into ways of breaking the loops. Introducing these controls into the operation of an organization will enable that organization to break the loop in a more controlled way, leading to a more robust and resilient operation.

Future research will determine whether and to what extent we can enhance the method's efficiency even further. Gathering more data to fill out the categories of cause for the ICT layer is another area to investigate.

Additionally, creating a systematic way to prioritize recommendations will help companies plan improvement programs more effectively. Recommendation prioritization is another open research direction.

The results of this research are limited by the validation being based on one case study, which makes it

Table 7: Time invested in this case study was only 53% of the time invested in our previous case study: 114 person hours versus 216 (Wienen et al., 2019).

activity	duration (hrs)	participants		person hours
		Company	Researchers	
workshop I	4	8	2	40
workshop II	4	7	2	36
workshop III	3	5	1	18
preparations	4	-	2	8
reporting	12	-	1	12
total				**114**

harder to generalize the conclusions. Another limitation is that it is hard to compare accidents of different complexities. We have chosen to measure the complexity by comparing the numbers of causal factors and causal links. Future research may show whether this is an appropriate way of quantifying the complexity of accidents.

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