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ARTICLE

Logistic transport in extreme environments: the evolution of risk and safety management over 27 years of the polar traverse

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ABSTRACT

In this article we seek to explain how safety mechanisms and risks evolve over time. The article focuses on a sociotechnical system, that of a polar traverse (a transport operation in a polar environment). In the study spanning a period of 27 years data were collected with ethnographic participative observations on three of the 56 traverses already achieved. Activities were traced from the whole 1398 daily reports and scale models of the convoy vehicles were used to reconstruct events during the traverses. Self-confrontation interviews were also conducted. A traverse feedback process was carried out which revealed that (1) whereas proactive safety is aimed at maintaining the continuous improvement of a system, reactive safety makes it possible to maintain the system's level of safety; (2) the development of redundancy and mixed technology contribute positively to the safety system. Improvements made to the safety system, its dynamics, and embodied resilience are discussed as well as the study limitations and implications.

Practitioner summary: This article seeks to understand how safety has been ensured in logistical transport in extreme conditions in a case study extending over a period of more than 27 years. The study investigates how risks and safety mechanisms have evolved and the benefits of developing a traverse feedback process to improve safety.

Abbreviations: IPEV: French Polar Institute (Institut Polaire Francais); DDU: Dumont d'Urville (French coastal antarctic station)

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Proactive-reactive safety; extreme situations; dynamics; risks; system improvement

1. Background

This research was conducted in collaboration with the French Polar Institute Paul Emile Victor (in French, *Institut polaire Paul Emile Victor- IPEV*). The construction project for the scientific station Concordia (first wintering in 2005) was at the origin of the first polar traverse in 1992. Concordia is located on the Antarctic continent 1,150 kilometres inland from the French coastal scientific station, Dumont d'Urville (DDU) (Figure 1). At its inception in 1992, the goal was to create a reliable and economic means of transportation for the construction equipment and supplies needed on the remote site of the permanent Franco-Italian station, Concordia. The traverse, which is a group of vehicles and their loads moving in convoy across the Antarctic continent in complete autonomy, connects both stations three times during austral summers. The duration of the round trip DDU-Concordia is approximately 23 days during which different situations occur; some of these situations are anticipated (Villemain and Godon 2017), others are unforeseen.

The standard convoy is composed of approximately 10 people driving three snow trains towing sleds loaded with containers and fuel tanks. Two or three levelling machines can be added to this convoy (Figure 2). The main objective is to convey the goods to the site as quickly as possible with the best fuel efficiency.

Even if there have been no major accidents so far, operational and/or technical incidents have regularly occurred during the traverse journey (for more information, see Villemain and Godon 2015; 2017). This is the context of the present research.

There is a long tradition of using ergonomics to examine safety and reliability (Amalberti and Hourlier 2007; Weick 1987), however, few studies have investigated safety and reliability in hostile environments. The

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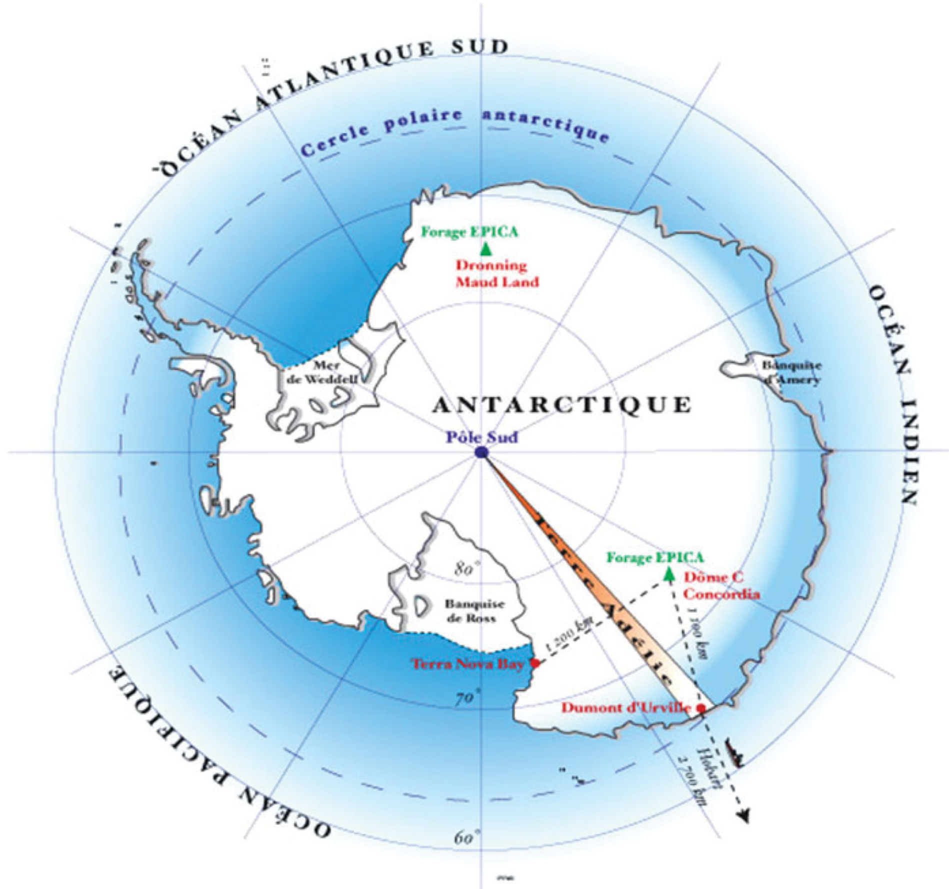

Figure 1. Map of Antarctica with the French station (Dumont D'Urville) and the continental station (Concordia). The Traverse connects these two points.

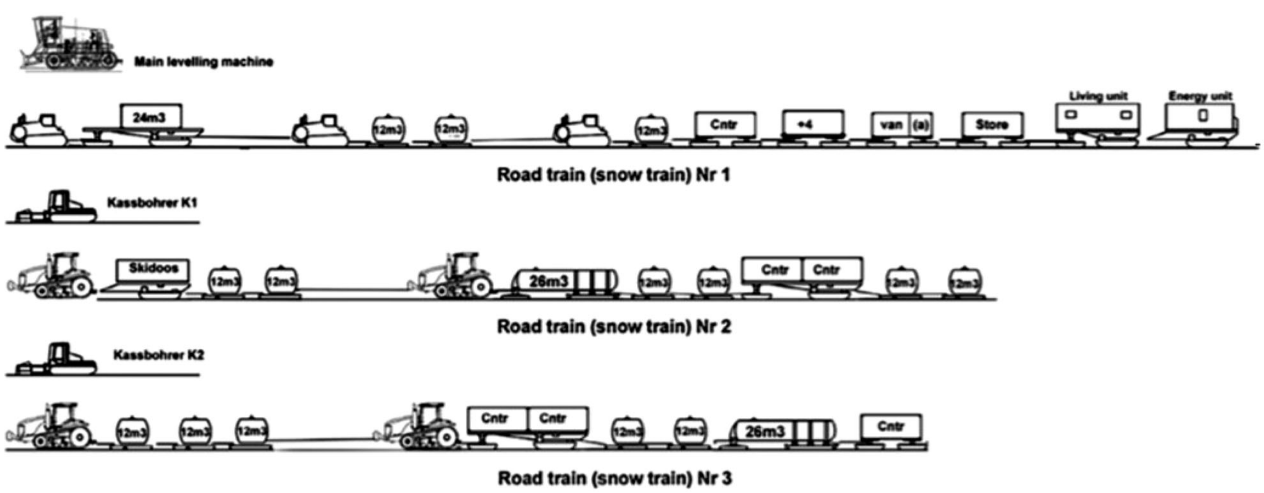

Figure 2. Composition of the convoy at the start of the traverse.

aim of this study is to gain an understanding of safety and reliability in such hostile environments by studying human activity, its organisation, and how a safety system is maintained over time in extreme, changing, dynamic and uncertain contexts. In short, the study seeks to understand how risks and safety evolve in a socio-technical system in extreme conditions.

1.1. The traverse, a sociotechnical system

In the sixties, the term "system" was explored through ergonomic research. Within Ergonomics, the notion of the "system" is defined as the joint consideration of the components of a system in their interactions. This characterisation has had a lasting impact on ergonomic studies (Montmollin 1967; cited in Leplat 2013). The notion of the system has been associated with "system thinking" (Simon, 1996/2004), "systems dynamics" or the "systemic approach" (de Rosnay 1975; Le Moigne 1990), and with "complexity" (Morin 1990), or "self-organisation" (Atlan 2011). In accordance with the focus of our study, we have attached importance to research examining *the transformation of sociotechnical systems* as proposed by cognitive systems engineering (Hollnagel and Woods 2005; Woods and Hollnagel 2006), that is to say, synergistic combinations of humans, machines, environments, work activities, organisational structures, and processes (Carayon et al. 2015; Noy et al. 2015). In the case of the polar traverse, we use the term sociotechnical system to refer to a complex synergistic combination of human, technological and organisational resources which undergo? transformations to maintain a resilient safety system.

1.2. A resilient system with proactive and reactive approaches

Developing resilience involves creating a resilient system and maintaining and managing this system's resilience. A system can be resilient if workers can adapt through an understanding of the context in which this adaptation takes place. Adjustments are made both by the individuals and the organisation, and sometimes in an improvised manner (Hollnagel 2012). A system must enable operators to anticipate events and learn from experience (Hollnagel 2009) thanks to feedback and flexibility because when critical situations occur improvisation enables resilience (Weick 1993).

In resilience studies a proactive approach is essential to ensure prevention and enable the system to adapt to changing conditions prior to the occurrence of undesirable events. A proactive approach involves the allocation of resources for improved safety and enables resilient organisation (Dekker et al. 2008). Short-term responses with a reactive approach are too restrictive and cannot guarantee the safety of a system and its maintenance (Daniellou, Simard, and Boissières 2009; Hale and Heijer 2006). A proactive approach is therefore essential to address evolving risks in a challenging environment and to enable a system to evolve towards a permanent state of readiness.

Previous polar studies highlighted improvisation as a way of ensuring a system continues to function at the lowest possible level of risk (Villemain and Godon 2015) through the deployment of collective and individual expertise in real time in an enabling environment (Villemain and Lémonie 2014). Reactive and proactive approaches used during a traverse to cope with unforeseen events have been described in a previous article (Villemain and Godon 2017). This article examines the proactive and reactive approaches in a historical case study on the evolution of safety. Proactive management is a strategy which enables the convoy organisation to be a dynamic system. A proactive approach can be developed in an autonomous organisation and allows the system to evolve constantly. This has been recently observed in a study on safety management in the risk-prone activity of spearfishing (Villemain and Buchmann 2019). More can be gained by understanding how resilience can be maintained over a long period of time and how a safety system can evolve. That is why we propose a case study on the maintenance of a safety system over a long period of time.

1.3. Background on risk and safety management on the traverse

On the traverse, risks were considered in the usual experiential manner by the traverse designer who incorporated safety mechanisms into its design and general organisation. Risk management thus relied on a formalisation of existing risk-related situations as well as the implementation of safety mechanisms for the traverse from its creation. The absence of any human casualties over the 27 years of traverse operation bears witness to the benefits of a built-in design and an experiential approach with an absence of traverse procedures, in spite of the fact that these are normally regarded as key pillars of risk management and accident prevention (Amalberti and Hourlier 2007; De Keyser 2003).

In a previous study (Villemain and Godon 2017) the occurrence of unexpected events such as mechanical breakdowns, equipment breakages, navigation errors, and bad weather were observed during the traverse. It was noted that it is impossible to determine which problems or failures will arise, when these is going to occur, where precisely in the convoy, and which equipment will be affected; it was also noted that it is impossible to determine the consequences that such situations may entail. In this regard, such events can be considered as unforeseen. At each halt of the convoy a daily report was sent to the French and Italian stations detailing technical problems. We established a record of the occurrences of unforeseen events from these reports.

Table 1. Summary of the methodology used.

	Materials	Traverse reconstructions
Data collected	1398 Traverse diary reports: Chronological presentation of the evolution of incidents on the traverse. Scale models: description of the composition of the traverse convoy and its evolution. Supplementary documentation: Inventories and equipment purchased.	Traverse designer presented with: • The reports and traces: risks and incidents observed (7 self- confrontation interviews). • The scale models: reconstruction of the composition and organisation of the convoy (4 self-confrontation interviews).
Objectives	Construction of tools to analyse the evolution of the traverse.	Analysis of the evolution of the risks and safety mechanisms, dynamic reconstruction.

Analysing risk prevention over the past 27 years of traverses can help to understand how safety is managed in the long term in extreme environments with the occurrence of unforeseen events. How has safety evolved in 27 years? What role does experience play in maintaining safety? The question of risk has already been studied regarding an Antarctic base providing residential facilities (Villemain and Lémonie 2014), however, studying risk seems even more relevant in the case of an isolated convoy in transit. At such temperatures (from −20 °C to −60 °C), the slightest action may constitute a risk, not only for individuals, but for the entire group, due to limited medical support and to isolation[1]. The traverse is a complex and dynamic system of social and technological components interacting with a hostile environment which restricts work activity. It is also a complex adaptive system integrating multiple interacting components to ensure productivity and safety. The priority should not be to focus on why incidents and mishaps occur and whether people make mistakes, but whether the system is organised to manage risks and prevent incidents and accidents from occurring.

2. Methods and materials

2.1. The traverse designer

The traverse designer was the head of the Concordia project. The implementation of a transport system was a part of the project for the construction of the station; therefore, as the head of the Concordia project the traverse designer was also the client of the transport system. At the beginning of the project, he was 41 years old with 14 years of experience in Antarctica and was the manager of the Dumont d'Urville station. He is now 68 with 40 years of work experience on the Antarctic continent and is arguably one of the world's most experienced traverse designers, having completed a total of 66 convoys. His first traverse was a scientific convoy with personnel from the original crew of the French Antarctic programme. After this traverse, he observed similar operations conducted by foreign operators and looked at the equipment proposed on the market. In the French and international Antarctic community, he was the person who possessed the best combination of experience and technical knowledge. Responsible for the design, the implementation and the success of the programme, he was also the guarantor of safety.

2.2. Data collection methods and procedures

The research was carried out in two main phases (Table 1). The first phase consisted in a traverse feedback process in which activities were examined (Cahour and Licoppe 2010) by means of daily reports during a period of 27 years. The second phase consisted of working with the traverse designer to analyse these safety mechanisms and identify the original reasoning which inspired him to implement these mechanisms, sometimes going as far back as the beginning of the project in 1992.

2.2.1. The traverse feedback process and the tracking of activities

According to course-of-action theory, an activity is situated in and inseparable from the environment in which it takes shape, and the actor participates in the construction of the situation (Varela 1989; Varela, Thompson, and Rosch 1991). An activity can be shown, described and commented on at any moment (Theureau 2006) under certain methodological conditions thanks to tracking. In this study daily traverse reports and the elaboration of scale models were used in this tracking process.

In total, this work of traverse reconstruction required approximately 500 hours. We studied all the reports written during the traverse from 1992 until the present (a total of 1398 reports since 1992 covering 57 traverses). These were listed in a table, indicating the traverse number and date, the incidents encountered, the interventions, the duration of the interventions, the traverse duration, the number of machines and the amount of equipment present in the traverse. The aim was to get as much information as possible about the traverse and its progress. Incidents were listed as well as changes in the equipment. Analysis of the daily traverse reports enabled us to build a chronological map (De la Garza and Weill-Fassina 1995) of the evolution of incidents since 1992. Facts, actions, circumstances, and risk categories were classified and ordered sequentially from the beginning of traverse activities, based on the daily reports. Thus, we were able to establish combinations of events and their chronology. The scenario corresponding to each traverse configuration at that time was reconstructed with a scale model. The daily traverse reports were drafted based on the same template during the entire 27-year period. Thus, data were comparable since information such as dates, incidents, equipment, and human interventions was available in the same format.

To help the traverse designer conduct this historical reconstruction we used scale models, with orange models representing tanks, blue models representing containers, and a yellow model representing the medical unit, plus tractors and levelling machines. Using these models, we identified the different elements governing the activity at the time, such as the traverse designer's thinking and experience and how this related to the intended goals, particularly in terms of risk management and safety mechanisms or the development of risk-management strategies.

Whilst such models tend to be used more for future designs and represent prescriptive items using scenarios, we chose this method to assist the traverse designer to recall aspects of his work and to think back over the 27-year period. The reconstruction therefore is an historical safety record. The aim was to stimulate recollections by presenting the designer with reconstructed situations using models of traverse components during in-depth interviews. We considered the chronology of events on the different traverses and provided complementary information with daily traverse reports written at the time. Thus, the safety mechanisms were attributed to each period.

2.2.2. Traverse reconstruction illustrating the evolution of safety mechanisms

According to the method developed by Cahour and Licoppe (2010), in which existing or constructed traces such as audio and video recordings, written reports, and scale models are used to gain access to an interviewee's representation of past or present activities, the traverse designer was presented with two types of traces of the traverse activity: the daily traverse reports and scale models. Seven self-confrontation interviews (Theureau 2010) were conducted based on daily traverse reports dating back three years to reconstruct the original design of the traverse and to track its evolution as well as that of its safety mechanisms.

The traverse designer reviewed the reports which provided details on changes in the organisation and technical safety adjustments. Only periods with a significant number of incidents resulting in organisational, human or technical modifications to the traverse design were recalled and commented on by the traverse designer. The goal of these interviews was to help him reconstruct past situations and actions. He was asked to describe the traverse conditions at the time and explain how specific choices were made in its design.

To recall information dating back 27 years required the use of specific, innovative and adaptable interviewing methods to highlight the dynamic changes which occurred (Carayon et al. 2015). The objective was to reconstruct with the traverse designer his actions and the events as he experienced them. We took inspiration from the techniques of psycho-phenomenological elicitation (Vermersch 2009) and self-confrontation (Theureau 2003), inviting the participant to describe and comment his actions by reviewing the daily reports with him or by using scale models to help materialise these past events and actions. By using these interview techniques (elicitation and self-confrontation interviews) we were able to understand how the traverse functioned and how its design evolved over the period of 27 years. Among the questions asked were the following: 'What were you trying to do?', 'What objectives were you pursuing at the time?', 'What had you observed in the field which made you take this course of action?', 'After this observation, what did you say to yourself?', 'What were the risks?', 'What did you decide to do next?' By using such an approach, the interviewee's recollections of past actions were linked to what was meaningful for him at that time. Moreover, each situation was described action by action to clearly identify any elements that may have been left unspoken and to ensure the recollection clearly reflected the actor's experience.

In this case the method consisted of showing scale models to the traverse designer and getting him to talk about a specific moment during a traverse that we had defined in advance. After he reconstructed the various traverse convoys with these scale models, he was asked to describe and comment on the respective configurations of the convoys and the choices that were made which led to these changes. In the same way as with videos in the self-confrontation method

(Theureau 2010), the scale models were meant to stimulate the traverse designer's memory and provide a detailed insight into his thinking at the time. Using the self-confrontation method made it possible to analyse the traverse designer's experience when developing safety mechanisms during the traverse whilst taking into consideration traverse organisation in the long-term. The analyses of these experiences through the succession of reconstructed events made it possible to elicit what the traverse designer perceived, felt, knew and did (Theureau 2015, 2006). Understanding the changes was helped by identifying the succession of links between the situations considered, the decisions made, and actions taken, and by focussing on what was meaningful for the designer at the time (i.e. traverse modifications introduced by the designer from 1992 to 2017 to ensure safety).

Four self-confrontation interviews using the scale models (lasting 1 hour 30 minutes on average) were conducted with the traverse designer to gain a better understanding of how the traverse was designed to ensure safety. To help him recall events, we decided to begin from the present and to go back in time. Since the events occurred over such a long period, three separate periods were identified. One period from 2006 to the present, corresponding to the last part of the developmental phase of the traverse, a second period from 1996 to 2006 (covered in two self-confrontation interviews) which involved adjustments and consolidation, and a third period from 1992 to 1996 which was the period of the birth and infancy of the traverse.

2.3. Data analysis

2.3.1. Chronological categorisation of hazardous situations and safety mechanisms

After collecting the daily traverse reports and the interview transcriptions, we established a list of typical risks and safety mechanisms. Data were analysed in three steps. First, we identified the categories of hazardous situations in the traverse from field observations. We categorised all information (thematic units, Corbin and Strauss 2008) in relation to incidents, accidents and safety mechanisms. Second, we identified temporal markers of traverse experience from the daily traverse reports and split the chronological data from 1992 to the present day into three periods. Each period was identified by using the activity reports and the corresponding event/time record identified by the traverse designer. We retained from the daily reports only the incidents that caused a change or a new traverse configuration: these could be organisational, human, or technological changes deemed significant by the traverse designer. Finally, based on self-confrontation interviews, initial categories of hazardous situations were described, and detailed information was added relating to each chronological sequence for each of the three periods described previously, going back in time from the present to the beginning of the traverse experience.

2.3.2. Traverse reconstruction

We presented the traverse designer with scale models and asked him to arrange the models to represent the traverse configuration today. He was then asked to reconstruct the traverse configuration for each period using the scale models and his reports. Based on these reconstructions, self-confrontation interviews were conducted, recorded with a digital recording device and transcribed verbatim. These data were first analysed using a qualitative thematic approach: the researcher read each transcription several times and used a notepad to take general notes on the meaning of the designer's statements to get a better sense of the whole experience (Thomas and Pollio 2002; Wiersma 2014). The goal was to identify descriptive patterns reflecting important changes in the configuration of the traverse. Meaningful units were established by underlining words that stood out as significant in the transcriptions and which answered the question, *'How is this relevant to the evolution of safety in the traverse?'*. These meaningful units were arranged into categories or themes by grouping them according to similar meanings and in relation with the evolution of the traverse in human, technical and organisational terms. Inventories and lists of purchased equipment were used to check for any inconsistencies in the descriptions of the traverse configurations, the scale model reconstructions, the traverse reports, and the self-confrontation interviews. When the traverse designer evoked a period and a traverse configuration with the scale models, the list of purchased equipment was used to confirm whether the stated number of machines, sledges or tanks was correct.

2.4. Reliability and validity

Reliability was established in several ways. First, the results of the study were drafted in the language used by the traverse designer which provided a wealth of detail and was extracted from the interview transcriptions (Kerry and Armour 2000). Second, validity cheques were carried out for each interview by providing the designer with a copy of the interview transcription to verify accuracy or to clarify points discussed.

From the raw data collected during the interviews, the work consisted of data selection and sorting. In view of the mass of data collected from the daily traverse reports (1398 reports), we selected information that was relevant for reconstructing the evolution in the safety of the traverse.

This study has both internal and external reliability (Vermersch 2009). Internal reliability was assessed by checking the authenticity of the transcriptions and ensuring that the respondent commented on the evolution of the safety of the traverse; only comments concerning single and unique moments in the 27-year period were collected. External reliability was ensured using a triangulation process. In this instance, the objective was to correlate data obtained during interviews with activity traces, such as daily traverse reports and the reconstructions with the scale models.

After formatting, the results were presented to the traverse designer, and were validated by him, then finalised following discussions and further interviews when necessary, until all points were clarified.

3. Results

The results relate to the following themes identified in relation to evolution of risk and safety management: proactive approaches for improving safety, reactive approaches for maintaining safety, and technological redundancy and technological mix.

3.1. Traverse feedback: Balancing continuous improvement with safety

3.1.1. Actions to maintain continuous improvement of the system in a proactive approach

Lessons have been learnt from the data collected which have highlighted the evolution of the traverse and of its safety mechanisms since 1992. The data collection process identified 9 sensitive situations which could have caused accidents and 64 mechanisms which contributed to traverse safety (Table 2). This feedback process helped to gain an understanding of the safety mechanisms.

Results obtained from the traverse feedback process show that the main safety mechanism involves a proactive approach, with an anticipation of risks ensuring continued improvement in the system (Table 3).

Our results indicate that when nothing happens and no risks are identified, the system, while continuing to anticipate risks, focuses mainly on improving the efficiency of production. Solutions for improving the system are organisational and technological. All these actions contribute to improvements in the traverse design, including living and working conditions. For example, electronic navigation in the 90 s was not efficient because GPS accuracy was limited by the US government. Although GPS was a major improvement compared to other navigation systems such as the theodolite, from the beginning the traverse crew sought additional methods of locating previous traverse routes. Initially, radar beacons were positioned along the route, but their installation was a demanding task and the result lacked precision. An attempt was then made to retrace the faint track marks left by the previous traverse. The fact that natural tracks sometimes remained visible gradually led to the idea of marking out the route so that it would remain visible from one year to the next. To do this a levelling machine was used to create an embankment downwind from the route that could easily be located from one year to the next.

3.1.2. Actions to maintain the safety level of the system in a reactive approach

The second safety mechanism, which resembled more a reactive approach, emerged following the occurrence of unforeseen events. Following these events, operational changes were made, new equipment was introduced, and the traverse and safety mechanisms were modified. Only three important unforeseen events occurred during the 27-year period which lead to the adoption of organisational and technological solutions and modifications in the safety system of the traverse.

For example, in 2014, the fuel froze due to an unusual and significant drop in temperature. After many attempts to recover the situation[2], the traverse team devised two solutions perfectly adapted to the circumstances. An initial response was to heat the fuel by means of a controlled fire lit beneath one of the fuel transport tank. The second solution involved fuel drums being placed inside an empty heated transport container used during the first leg of the traverse. One of the transport tanks is now permanently fitted with a large heating blanket. This transport tank is used every year, it is connected to an electric generator mounted as an accessory on a tractor which produces the necessary power. This example shows how operators develop know-how enabling them to address critical situations, thus leading to the use of new technology (a prototype silicon heating blanket) and

Table 2. Key hazards, observations and safety mechanisms identified across the 27-year period.

Hazardous situations	Events / Observations	Date	Safety mechanisms developed
1. Loss of energy generating systems	Assessed in the traverse design	1992	Portable gasoline-operated electric generator
	Insufficient to keep the convoy operational	1999	First vehicle with an electric generator
		2000	Second vehicle with an electric generator
		2008	2 electric generators on the grading prototype
		2010	1 recent vehicle with an electric generator
		2014	2 recent second vehicles with electric generators
2. Navigation system failures	Assessed in the traverse design.	1992	Solar compass for direction and "theodolite" for positioning
	Very demanding, requires reassessing position every 2–3 hours, many calculations	Nov 1993	GPS system trials (constellation Navstar)
• Following the route • Following the route in bad weather conditions • Recovering loads	Need to grade the track and place physical landmarks as complements to GPS navigation	1995	Wider implementation of the GPS receivers
		1996	Inclusion of the grading machines: snow mounds placed at regular intervals to make it easier to follow the track
		1997	First radar tracking snow mounds, then installation of a supplementary radar
	The solution of snow mounds being insufficient for precise navigation	1997	Creation of a snow mounds along the entire length of the track
	Visibility problems due to bad weather conditions	1998	Opportunity – Attempt at using new spotlights on one vehicle to be able to see differences in levels in the terrain surface – 4 spotlights
	insufficient luminosity to identify the track	2001	Attempt at using 2 spotlights (with electric generator) on 1 vehicle
	Spotlights corresponding to the needs	2002	Installation of 4 spotlights per vehicle on 2 vehicles (with electric generators) Testing new sunglasses improving spotlight spectrum compared to solar spectrum
	Losing loads or tanks left behind on the way	2007	Radars to spot isolated or lost loads
	Lack of precision for staying on the existing track due to extreme weather conditions + technologic evolutions	2008	Attempt at using Attitude GPS / Furuno Attempt at using bi-constellation GPS
		2009	Wider use of bi-constellation GPS (Russian Glonass and Navstar US)
	Satisfactory solution	2011/ 2014	3 vehicles with bi-constellation GPS, one on the leading vehicle – Galileo compatibility
	Satisfactory solution	2010	Installation of 2 light beams on two vehicles
		2014	Installation of electric generators
3. Communication system failures	Assessed in the traverse design	1992	HF radio transceiver Daily position report
	Too heavy: Inmarsat Test	Nov 1993	Rental of a portable Inmarsat A equipment
	Imarsat A too expensive	1994	Use of Inmarsat M (phone, fax) and C (Telex) communication terminals, use of an Iridium terminal (phone, email).
	Technological evolutions	2007	Use of an Iridium terminal (phone, emails) Standard C and HF systems maintained
4. Fire in inhabited units, energy, food supplies	Assessed in the traverse design	1992	Construction in no flammable class materials Dispatching living quarters on different sleds
5. Food wasted • Cold chain compromised • Problems preserving food	Assessed in the traverse design	1992	Canned food Supplementary food depots on the convoy
	Fear of potential health problems	1992	+4 °C in the convoy (+4 °C = with heat)
		1995	Basic supplies of frozen food
	Too much time wasted during the halts, poor dietary balance	1998	Complete pre-cooked meal kits prepared ahead of time
6. Fuel problems	Estimation of vehicle consumption	1992	Calculations based on manufacturers' data
• Errors in fuel consumption estimates	Assessed in the traverse design / Frozen fuel	1992	Diesel fuel prepared for temperatures of −35 °C (dewaxing) Bringing along kerosene Bringing along heating resistors to warm up liquids

(*continued*)

Table 2. Continued.

Hazardous situations	Events / Observations	Date	Safety mechanisms developed
• Frozen diesel fuel	Errors in fuel consumption estimates for the return trip	Nov 1993	Conversion charts to calculate the amount of fuel to be left behind
	Highlighting the need for backup reserves	1995	Purchase of tanks with a capacity of 20 cubic metres to organise a depot 300km away from the DDU station
	Fuel depot too close to the point of departure	2001	Moving the tank 510km away from the DDU station
	Thickening of the diesel fuel due to a delayed departure and very low temperatures	Feb 2014	Equipping a sled tank with an external heating blanket and an insulating cover plugged into an electric generator on a tractor
7. Areas with crevasses	Assessed in the traverse design	1992	Track left by the first Traverses in the 60s Probing the ground with metal rods
	A vehicle opened a crevasse due to a sudden change in the route	2007	Route established based on crevasse location Positioning performed by helicopter
	Load opening a crevasse	Nov 2011	Georadar trial
	Crevasses evolved and moved	Nov 2013	Systematic use of a geological/glaciological georadar for surface probing/glaciology at the beginning of each season
8. Vehicle breakdowns, broken equipment	Grading: Assessed in the traverse design	1992	Ground graded to limit wear and breakage of vehicle parts Repair workshops and stock of spare components included on the convoy
	Heavy tractors with breakdowns impossible to move	2009 Feb 2016	Skis for transportation Carpets for transportation
9. Work and living Conditions	Assessed in the traverse design	1992	Presence of a doctor within the traverse staff
• Glare linked to the altitude and the cold temperatures	Long days	Nov 1993	Succession of tasks to be performed during the entire day on the traverse
• Fatigue • Injuries • Infections	Need for efficiency to save time during halts	Nov 1993	Synchronising preventive maintenance tasks in the evening Distribution and distribution of the tasks to be performed
		Jan 1996	People working in pairs Specific organisation of convoy halts

bringing about changes in the organisation and configuration of the convoy (the tank with the blanket has to be placed behind a tractor equipped with an electric generator).

We can see that, with regards to reactive safety, unforeseen events can be a consequence of proactive safety, associated with the intention of improving the system: the fact of seeking to maintain a high level of performance in the system and of going faster can lead to decisions being taken resulting in dire consequences. For example, changing the initial route of the traverse resulted in a machine half-fallen into a crevasse. This came as a direct consequence of seeking improved performance. However, following this situation, other safety mechanisms were developed.

3.2. Redundancy and a mixed safety system

The traverse feedback process enabled us to list the technologies used on the traverse in Table 3. The results show a duplication of the traverse safety systems. For each type of risk-related situation, redundant safety mechanisms have been developed to ensure overall safety. For example, 16 techniques have been developed to address navigation system failures, nine have been developed to address physical and medical problems, seven to address fuel problems, six to remedy a fault in energy production, five to address the problem of crevasses and food loss, four concern breakdowns, equipment breakage and communication problems, and there are two systems for dealing with fire hazards. The systems implemented for a given hazardous situation have been reviewed and the number of times they were used during the 27-year period varies from zero, in the case of fire hazards, to ten times, in the case of navigation system failures. It seems that situations experienced in situ contribute much more to the development of safety systems.

4. Discussion

This aim of this study was to carry out an historical analysis of the Polar traverse to understand how safety management evolved over a period of 27 years. The results

Table 3. Pro-active and reactive safety over 27 years of logistic transport in extreme situation.

Pro-active safety: continuous system improvement			
Improvement of living and working conditions		Reactive safety : system safety modification	
1992-	Emergency electrical energy production: original emergency supply system insufficient for standard operations In-house design (from portable electric generator) *Improvement of operational system => Installation of an electric generator on some tractors*	1995-	Errors in the estimation of diesel fuel consumption Organisational solution (safety depot set up midway) *Modification of the working conditions*
	Navigation system very demanding, not efficient for driving in bad weather Technological evolution (from theodolite) *Driving activity facilitation => GPS, multi constellation receivers, navigation software* In-house design (from tracking markers using tubes, snow amounts, radars) *Tracking / plotting activity facilitation using existing technologies and new equipment: lightning devices using power from the electric generators fitted on tractors*	2003-	Attempt to optimise the route → Opening of a crevasse Internal solution (Back to the previous route) Operational solution (plotting crevasses with helicopter and accurate satellite Technological evolution (use of georadar at the beginning of the each season) *Modification of the solution to detect crevasses*
	Inefficient communication system of poor quality Technological evolution (from HF radio) *Inmarsat then Iridium telecom constellation* Internal organisation (Daily position report) *Improvement of safety on the traverse*		
	Too much time lost during daily stops, improving the efficiency of the organisation Organisational evolution *Improved meal preparation => pre-cooked meal kits and better dietary management* Work Organisation (Task distribution, synchronising preventive maintenance, maintenance tasks) *Improvement of operational organisation* Internal organisation (use of pre-cooked meals) *Meals Prepared by medical doctor*		
	Fuel management Technical status and technological evolution (Dewaxed fuel, mixing with kerosene, heating plugs) *Improvement of the diesel fuel quality* *Tank with fuel for the return journey left on the sides of the traverse track*	2014-	Frozen diesel fuel occurrence Technological solution (Specialised heating through a heating blanket (Not direct heating) *Modification of the working conditions*
2019-	Breakdowns or broken equipment Technological evolution (specialised skis shoes) *Carpets replacing skis, improving grading and levelling works* Organisational opportunities (Stock of spares on board the convoy) *Improvement of engineers' working conditions Improvement of living conditions on the traverse*		

show that safety mechanisms have been significantly reviewed since the beginning and hazardous situations have also continually evolved. The results of this research show that safety is a dynamic and complex process. In the following section, the discussion deals with (1) improvement in the system's ability to manage safety and the need to consider safety questions from a reactive perspective and in real time; (2) the dynamics of the system and the positive impact of the absence of written procedures; and (3) the existence of embodied resilience as a process. In the last section, limits and implications are put forward.

4.1. System improvement for the management of safety

Results show an alternation between a pro-active approach to safety in which the improvement of the system is the objective and a reactive approach in which the system is transformed to improve safety. Proactive safety, or passive safety, can be a consequence of a general transformation of the system and reactive safety, or active safety, can be a consequence of local adaptations (studies on activity analysis by Terssac & Lompré, 1995/2002). Both cases involve *safety in action* (Terssac and Gaillard 2009), but with differing priorities.

According to our results, in terms of the allocation of resources proactive safety is not directly focussed on improving safety (Dekker et al., 2008) but may depend on a general improvement of in the system rather than just on improvements in safety. Research on paradoxes and the theory of change (Watzlawick, Weakland, and Fisch 1974) may provide some insight into the fact that it is not by focussing on safety that safety is improved. As the approach indicates, the causality of the system is not linear but circular because the cause of an action cannot be dissociated from the effects of other actions (Morin 1990). According to Cartesian logic, if something is wrong, its opposite is right. However, experience is made up of opposites (Jung 1952 cited by Watzlawick, Weakland, and Fisch 1974). For all these reasons, safety must be considered when hazardous events occur, otherwise the cause of the problem may be wrongly interpreted resulting in an inappropriate solution (Bateson 1972, cited by Watzlawick, Weakland, and Fisch 1974). Safety must be reflected on in real time and not in anticipation. In this case, proactive safety is an opportunity for modifying situations, enhancing experience and improving system efficiency.

4.2. A dynamic safety system

As previous studies on the management of unforeseen events on the polar traverse have demonstrated, the organisation is constantly reviewed during the traverse, even if nothing special occurs, and this contributes to maintaining a dynamic system (Villemain and Godon 2017). The same mechanism applies on a larger scale regarding the traverse design. This explains why our results showed that the proactive approach to safety was prevalent, not so much for the sake of improving safety but for the sake of improving the system.

Contrary to a logic in which safety it set as a priority, initial modifications are essentially made to address technological challenges. As a result, the system is dynamic and its organisation is perceived as a dynamic process in a state of permanent reconstruction (Tsoukas and Chia 2002; Weick 1995). The technology mix used during the traverse – archaic and modern technologies in conjunction with the duplication of safety mechanisms – can also constitute a source of danger by creating a dependence on technology and thus, paradoxically, can decrease operator empowerment and flexibility (Hollnagel 2014). Technologies transform the nature of work and the nature of organisations (Flach et al. 2015).

Changes in the traverse system are made possible by its intrinsic flexibility which allows for the regular testing of new technologies on the traverse. An advantage derived from this is that written procedures are kept to a minimum, enabling the system to adjust easily. The absence of procedures and specific training increases flexibility and adaptability in the system. Interaction with the environment is the determining factor in traverse safety and may explain the absence of written procedures which are supplemented by the expertise of operators. However, in the case of the polar traverse, this system was weakened by the fact that the expertise was principally possessed by a single person close to retirement which presented an additional challenge to the continued construction of safety.

4.3. Embodied safety and embodied resilience

As previously established (Villemain and Godon 2015, 2017), risk is considered inherent to human action and is accepted as such. For example, traverse members know the existence of crevasses, yet the traverse route crosses crevasses. Decisions taken during the traverse or in its design automatically integrate risk but do not focus on it. This corresponds to an appropriation of the safety system according to the enactive theory developed by Varela (1989) and is characterised by the activity through which individuals construct their world of actions, thoughts or affects that are significant to them in relation to the specificity of their environment: safety activity during traverses is not determined before the beginning of the traverse but is continuously adjusted during each traverse and safety is built through each situation. The traverse feedback process demonstrates the system's ability to deal with unforeseen events and to manage the risks that continue to evolve. Skills have been developed by operators in relation to the introduction of new technologies on the traverse, but also by the unforeseen situations experienced that have been needed to build an individual and/or collective traverse experience.

In accordance with the theoretical approach of system resilience developed by Hollnagel (2009), Weick (1993), operators have anticipated events and learned from experience thanks to feedback and a flexible approach: when critical situations have occurred, improvisation has enabled resilience. The maintenance of a technological watch is an integral part of the proactive safety approach, it enables the introduction of new technologies while maintaining the existing level of safety. The introduction of new technologies also indirectly contributes to the training of the operators and the development of their skills. The variety of situations and experiences has resulted in the traverse designer developing expertise in response to the specificities of the polar environment and according to his knowledge of this environment. This knowledge has led to fluidity in the action process, flexibility within the system, and a 'sensory know-how' developed from being exposed to situations and the ensuing experience gained.

This situated framework, focussed on the investigation of safety actions and organisation over time, is defined in opposition to analytical processes (Robbins and Aydede 2009). While isolating safety processes, which typically take the form of an excessive amount of written procedures, the situated safety system considers and examines safety actions as autonomous, situation-sensitive holistic organisations. In an environment where body and mind work symbiotically, there is a need to develop methods that deal with the properties of situated safety rather than with those of analytical or theoretical safety rendered inflexible by an excess of written procedures. This situated safety can lead to enacted and embodied safety, as proposed by Powley in the resilience activation approach (Powley 2009): resilience is socially enacted and embedded (p. 1320). In his presentation of this model, the author refers to the process of resilience activation as the expression of socially constructed safety. Resilience is therefore considered as a process which is activated and deactivated.

4.4. Limitations and implications

Some of the study's limitations are worth mentioning. It might have been preferable to study a larger number of traverses to confirm the typical nature of the preventive measures described in this environment. As with such types of immersive studies data collection was costly. No other studies using the same methodology have been done in this area thus making it impossible to learn from past experiences. In addition, the atypical and original methodology used in this study presented some limitations. For instance, the data collection relied to a great extent on the traverse designer's memory of events over a long period of time therefore some details may have escaped his recollection.

We need to investigate better methods of studying the dimension of safety in its entirety. It would also have been preferable to complete our analysis by gathering data on group activity and to not just take an organisational point of view. These approaches could lead to a focus on collective resilience, a dimension we have not investigated in this article. Considerable research and methodological work are required to gain an understanding of the resilience system at work in the activities of traverse personnel in a polar environment. The study design involved the in-depth analysis of a single case. Due to its particularities, conducting such research in the polar environment is like conducting a single case study, which means there is a likelihood that the findings are only applicable to such highly specific working environments.

Practical implications could also be highlighted. Results from this study could provide invariant factors which may contribute to analyses of organisational strategies for the management of high-risk situations or crises. Paradoxically, the invariant factor is the variability of the environment related to uncertainty and unpredictability. This therefore requires considering safety as a dynamic and flexible process built through each situation encountered and not as a predetermined system. The study of long-term risk management in extreme, isolated and confined environments covers a whole range of different environments such as military (Waterson et al. 2015), maritime, space, underwater and prison environments.

A dynamic system in perpetual motion, through the search for continuous improvement engaging proactive safety, introduces a dynamic and unstable dimension able to respond in a reactive way to unforeseen and unstable situations. In some cases, risk seems to infiltrate fixed and predetermined organisations much more easily. In a system rigidified by excessive recommendations and procedures it becomes difficult to introduce change (Villemain and Godon 2017) and build a dynamic safety process.

5. Conclusion

Experience gained within a sociotechnical system over time is not often taken into consideration. However, the results of our study show the importance of studying safety in a sociotechnical system over time and the need to collect data from feedback in the long term to gain a better understanding of the evolution of safety management. This article demonstrates the importance of gathering historical and organisational records of safety systems. The traverse feedback process also demonstrated that risks continuously evolve.

The methodology used was original and diversified, involving both a review of historical records and reconstruction of the original traverse design and development. Some risks have been reduced thanks to better practices, experience gained (knowledge), and technological developments (greater efficiency of existing systems and new equipment). Other risks that could not be eliminated, such as crevasses, have had to be circumvented. Whereas in the 90 s challenges were more technical and technological than safety-related, today the establishment of safety systems has become a major issue in the organisation of traverses. Whilst preventive actions will never be enough to eliminate all risks, these results bring us a step closer to an understanding of risk-generating mechanisms.

The question remains whether the development of specific competencies, skills, and risk awareness in such atypical environments might not bring about a trivialisation and therefore a minimising of risks, causing operators to make dangerous decisions which could jeopardise their lives. Therefore, training is a central issue and the question which needs to be addressed is how to train a group while preserving heterogeneous experiences and different professional backgrounds? This question is currently being studied and will be presented in a future article (Villemain & Lémonie, accepted). The specific know-how for the management of critical situations is developed through the experience of managing unforeseen events.

To enhance the understanding of safety systems within a broader perspective, longitudinal studies are necessary. Questions regarding the efficiency of written procedures and adaptive safety (and training) need to be addressed in further research.

Notes

1. We specify that the authors are familiar with the way the traverse is designed and how it functions thanks to ethnographic studies conducted previously (Villemain and Godon, 2015, 2017).
2. For details, Villemain & Lémonie (accepted).

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