

Abstract

High-risk industries are operating in an increasingly complex and dynamic environment; this leads to new perspectives on the role of the human operator in the safety management system, encouraging organizations to exploit the uniquely human capabilities of operator teams in order to maintain safe operations. Crew resource management is a popular framework for training operator teams, but has not yet been adapted to accommodate this theoretical development in any major way. Through an action research project within N-USOC, a control room supporting science missions at the International Space Station, a prototypical CRM course is developed for a distributed team working in a complex-dynamic environment, guided by theoretical analysis of safety literature and by the specific needs of the N-USOC context. Adaptive decision making strategies and skills are identified as important success factors for the human operator, along with developing team processes to increase the team capacity for managing safety margins. For N-USOC operators, building this desired adaptive expertise while learning how to manage workload and utilize domain expertise in time-critical situations is especially important. While the development of CRM training for N-USOC is not complete, the study represents a foundation to build upon for the organization, and a theoretical contribution to safety research.

Keywords: crew resource management, space, safety, reliability, dependability, training, decision making, resilience, action research.

Acknowledgements

As a very eventful year draws to a close with the much anticipated delivery of my master's thesis, I am almost lost for words – maybe not surprisingly, as I have put a lot of the words I did have into this thesis. I will still try to manage to give some credit where it is due.

First of all, I would like to thank every single member of the CIRiS and N-USOC staff, for accepting me into your midst, and making me feel so welcome throughout this project. Thank you for sharing information, sharing offices, sharing lunch breaks, sponsoring my numerous Post-it notes, and even allowing me to miss my first dozen of curling stones bearing your team name. You guys are great; go CIRiS Rockets!

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“If I had eight hours to cut down a tree, I’d spend six sharpening my ax”

Popularly attributed to Abraham Lincoln (1809-1865)

Safety in Action

Designing a Crew Resource Management prototype for N-USOC

The exploration of human spaceflight was undoubtedly in its heyday during the 1960s, as the space race between the USA and the Soviet Republic culminated in the first moon landing. Ever since, both the public interest and the government funding of space activities has been somewhat in decline, at least compared to the practically limitless budgets of the golden years. Attention turned mainly to in-orbit activities like communication and surveillance satellites, and low gravity research, and the semi-permanent Soviet/Russian space station Mir had for a long time a unique capability to sustain astronauts staying for longer durations than a few weeks (NASA, 1998), before being replaced by the more modern International Space Station (ISS) in 2000 (Fong, 2001). Over the last couple of years, the interest in deeper space exploration has started rising again, and while China are sending robots to probe the moon, the US National Aeronautics and Space Administration (NASA) are once again turning their sights to the red planet of Mars, even unveiling prototypical space suits for future human explorers.

These enticing prospects come at a cost, and not only a financial one. Space activities are inherently risky, mainly due to the enormous amount of inertia in any kind of inaccuracy during the planning stage, meaning that the consequence of an error is likely to take place much later, when there is no return option, whether this is about launching another telecom satellite, a routine equipment shipment to the orbiting ISS, or the first ever manned spaceflight to Mars. While the focus of safety management – ensuring safety throughout the process – for a long time was almost purely technical, at this stage more and more evidence has accumulated for the effects of organizational and human factors of safety on major disasters; the occurrence of which the space domain, unfortunately, is not unfamiliar with. Starbuck & Farjoun (2005) summarized one major accident that has struck the space domain in recent years.

The Columbia Disaster

The space shuttle *Columbia* was launched to execute the STS 107 mission, a 16 day routine science mission, on January 16, 2003. On descent to Earth February 1, the shuttle disintegrated upon entering the atmosphere, killing all seven astronauts onboard. An extensive investigation was set in motion to uncover the causes of the accident, and the proximal cause of the accident was quickly determined. Immediately after launch, a small piece of insulating

foam from the external fuel tank had come loose, and struck a hole in the heat shield protecting the spacecraft during reentry, allowing superheated air to melt the structure of the left wing and thereby causing the shuttle to come apart.

Though this explained the accident in its entirety, it was not the main conclusion of the investigation board. Looking beyond the physical process, the accident was determined to be caused by a string of errors of judgment among decision makers in the ground crew, ignoring what, in retrospect at least, seemed to be clear, tell-tale signs that could have prevented the accident. Human error, then, had a clear impact on the subsequent accident, but this was not to be the main focus for the accident investigators, either. The root causes of the accident were found to be a declining safety culture all the way from the top of the NASA organization, causing safety goals to be yielded to financial and time pressures, thus influencing decisions made by managers all the way to the executive end of the organization. This was an unnerving *déjà vu* for NASA administrators, as similar causes had somewhat cautiously been suggested for the 1986 *Challenger* shuttle disaster (Starbuck & Farjoun, 2005).

Human Dependability

With the technical side of safety somewhat downplayed in recent years, the focus on the non-technical skills and the dependability of the human contribution has been on the rise. The European Space Agency (ESA) describes human dependability thus:

“Human dependability is about the contribution of the human in a space system to safety and reliability. Machines can fail, so can ‘people-in-the-loop’ of space systems, sometimes with catastrophic consequences. ESA’s Dependability and Safety Section therefore has a longstanding interest in the subject of human dependability: how can the incidence of human error be reduced, and its effects minimized?”(ESA, 2010).

The view of the ESA organization is that lessons should be taken from the aviation domain, sharing best practices and utilizing human dependability expertise from other domains.

One of the major tools for training non-technical skills in the aviation domain is the mandatory Crew Resource Management (CRM) training; a continuously refreshed course addressing and complementing the technical training with the teamwork-related, cognitive and workload-related issues that shape performance (Kanki, Helmreich, & Anca, 2010). This is a widely used framework, also in the space domain, and is being practiced by both ESA and

NASA. However, the latest, more systemic views of safety management have not really been translated into non-technical skill training, and in the CRM community, the view is that the next generation of CRM training needs to address this theoretical development. In order to contribute to this development, the first research question of this thesis is as follows:

Research question 1: How can the recent systemic approaches to safety management be translated into CRM training?

The Importance of Context

In the knowledge management literature, the primary distinction of knowledge is that of explicit versus implicit, or tacit, knowledge, as famously defined by Michel Polanyi (1967, in Nonaka, 1994). Explicit knowledge refers to the concrete knowledge that can be expressed and shared as words or numbers, formulae, procedures and similar (Alavi & Leidner, 2001; Nonaka & Konno, 1998; Nonaka, 1994). The tacit knowledge is comprised of two dimensions: the cognitive element consisting of the mental models of the individual, and the technical element consisting on the skill and know-how that applies to the context (Alavi & Leidner, 2001; Nonaka & Konno, 1998). These two forms of knowledge are mutually supportive, and knowledge creation is a spiraling process of interaction between them through four processes (Nonaka & Konno, 1998). The four processes of knowledge creation are socialization; the process of capturing tacit knowledge from direct interaction with the people involved, externalization; converting tacit knowledge to explicit knowledge in order to make the knowledge transferrable, combination; capturing and systematizing bits of explicit knowledge into more complex sets combination and internalization, and internalization; converting the newly created knowledge to tacit knowledge in the organization through training and exercises (Nonaka & Konno, 1998).

The upshot of this is in agreement with more specific and experiential observations in team training research that a close contextual adaptation to the domain in question is absolutely necessary for CRM training to be effective (Kanki et al., 2010). Taking the consequence of the above view of knowledge creation there can, in reality, be no designing training without a user; the two are intertwined. With this in mind, I identified the need for a second research question, and decided to make contact with NTNU Social Research's Centre for Inter-Disciplinary Research in Space (CIRiS), who staff a control room dedicated to scientific experiments onboard the International Space Station through a long term project

named N-USOC, gaining entry to their organization as hypothetical end users of a prototypical CRM course for the space domain. This led to my last research question:

Research question 2: How does the specific context of control room support for ISS operations guide the recommended syllabus for CRM training?

Established Domain Practice

In an effort to systematize the CRM course design methodologies, Salas, Wilson, Burke, Wightman et al. (2006) proposed a progression and checklist for the design, implementation and evaluation of CRM training in an organization (Figure 1). For the purposes of this thesis, the elements of the two first stages, *needs analysis* and *design* are highlighted.

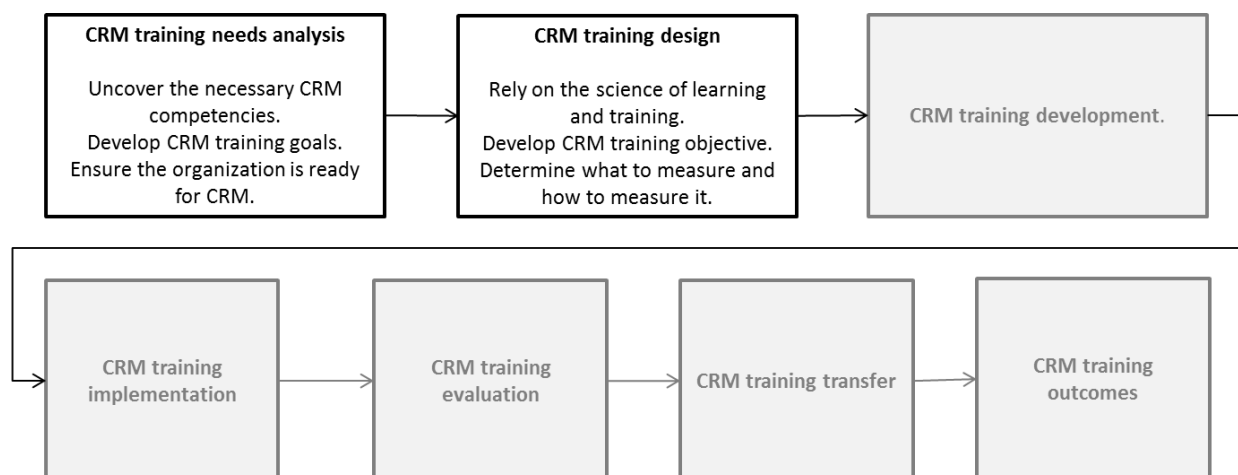


Figure 1. Progression of CRM course building. This shows the scope of development of a CRM course in this thesis (Adapted from Salas, Wilson, Burke, Wightman, et al., 2006, p. 7).

Typically for training interventions, a task analysis is conducted to uncover the knowledge, skills and attitudes necessary to accomplish a task. In CRM training, however, a team task analysis uncovers both task work and teamwork skills necessary for task performance. Relying on subject matter experts is vital because of their superior knowledge of the task domain. Training goals are developed based on the information from the needs analysis, the necessary competencies to be trained guiding the selection of existing CRM modules, and the adaptation to the context.

The design phase is arguably the most critical and time-consuming phase of building a CRM training course. Here, objectives and measures for CRM training are systematically designed and prioritized based on the identified skill requirements. Suitable delivery modes

are chosen based on the uncovered objectives, ending with a blueprint of what the training program should look like; a prototype for CRM training. Salas et al. (2006) emphasized the need to keep in mind that learning is mainly behavioral and cognitive, and that this, not technology, is the main focus of training – a point which, in their mind, is not object of sufficient attention from many practitioners.

The evaluating and participative way in which CRM training is designed gives away its methodological connection to the practitioner research tradition of action research, with roots in Kurt Lewin and the Tavistock Institute's work in the first half of the 20th century (Coughlan & Coughlan, 2002; Trist, 1981). This tradition states that research is to be done in action, rather than about action, with a participative process where the outside researcher interactively involves the members of the system under study as fellow researchers, solving the organizational problem through recurring cycles of planning, action and feedback. Embedded in a systems approach to the socio-technical environment, action research aims at developing holistic understanding of the complex work environment through different kinds of sources of knowledge, the important thing being that the sources of information are suitable to the conclusions that are drawn on their basis (Coughlan & Coughlan, 2002).

Not surprisingly, this is in line with Nonaka's (1998; 1994) models of knowledge creation and Argyris & Schön's (1978) theory of action approach to organizational learning. By adhering to an action research approach, my aim is to contribute to double-loop learning in the N-USOC organization with a CRM approach, setting the stage for team members' reflection on the actions of themselves and others, and the governing values and constraints that shape them.

The Dual Goals of the Thesis

In an action research approach, the goals are always dual; solving a real-world problem and contributing to science (Coughlan & Coughlan, 2002). So it is with this thesis. The theoretical contribution I hope to make with this work involves on one hand the analysis of literature that informs the adaptation of CRM principles to a systems view of accidents, on the other hand, it is an account of the process of domain adaptation through the different kinds of information that became available to me during my nine-month stay with the organization. Together, these two approaches aim to investigate and provide information of the first research question.

The problem that was “solved” – hyphens added because the limited scope of this thesis does not really mean anything is solved, rather a process is set in motion – is the

reported desire for complementing technical operator training with non-technical skill training. In line with Salas et al.'s (2006) framework, I aim to develop a first draft, a prototype of CRM training for N-USOC, based on the theoretical evidence of the literature study and the specific needs of the organization uncovered through participation. However, these goals are inseparable, and must be reported as such.

On Style

This duality of research goals has implications for the style of writing used throughout the thesis, and the presuppositions of advance knowledge on the part of the readers. Although, as an academic thesis, it is written within the context of psychological research, it must be designed to be illuminating for professionals within a broad array of domains; at the very least reflecting the breadth of competences in the N-USOC organization. Therefore, this thesis is written for a general, rather than a specialist, audience, and will treat emerging subjects consequently.

Lastly, as this opening section has already established, abbreviations have turned out to be something of a necessary evil, despite this researcher's reservations toward in-text abbreviations.

Method

Knowledge Acquisition

From an action research framework follows a relatively pragmatic attitude to the types of knowledge that can illuminate a research question. I have used two main methods for acquiring knowledge; a theoretical approach to uncover explicit knowledge, and an ethnographical approach to get the tacit dimension.

Theoretical discussion. The selection process of literature has been a recursive one; shaped initially by theoretical recommendations from other sources, but subject to continuous change due to the exploration of the contextual factors and relevant tasks.

The primary outset, as stated in research question 1: *“How can the recent systemic approaches to safety management be translated into CRM training?”* was to examine the main tenets of a system-based perspective, and see how these can be represented in, and translated into, a CRM training approach. Thus, the natural starting point was to study some of the most comprehensive and/or seminal works in safety management and CRM training, and using these to inform further selection of literature (Table 1). A broad approach was taken, trying to draw historical lines and parallels between the general developments in the safety field and the more specific developments of CRM training.

Table 1

Primary literature consulted.

<u>Topic</u>	<u>Title</u>	<u>Author</u>
Safety management	Normal Accidents	(Perrow, 1999)
	Human Error	(Reason, 1990)
	Resilience Engineering: concepts and precepts	(Hollnagel, Woods, & Leveson, 2006)
Crew Resource Management	Crew Resource Management	(Kanki et al., 2010)
	Safety at the Sharp End	(Flin, O'Connor, & Crichton, 2008)
Decision making	Judgment under uncertainty:	(Kahneman, Slovic, &
	Heuristics and biases.	Tversky, 1982)
	Making Decisions Under Stress: Implications for	(Cannon-Bowers & Salas, 1998b)

Individual and Team Training		
Method	Organizational Learning: a theory of action approach	(Argyris & Schön, 1978)
	The Oxford Handbook of Cognitive Engineering	(Lee & Kirlik, 2013)

For a budding organizational psychologist, focusing on the two cognitive skills of situational awareness and decision making was a natural choice, as well as a logical one considering the proposed paradigm shift under study, and so the chosen literature for decision making, specifically, snowballed from the safety literature.

Several search engines have been employed to find relevant literature to illuminate the research questions, and although the primary sources in physical form have laid the foundation for the literature review, in the end a lot of the referenced material consists of published articles available online. The main method of searching for literature has been through Google Scholar; a tool that, because of its inherent multidisciplinaryity, was a good fit with the very multidisciplinary field that has been studied, finding referenced material in domains as diverse as knowledge management, organization theory, learning, sociology, anthropology, economics and cybernetics, in addition to psychology.

Ethnography: Participant Observation. In order to collect contextual data for this thesis, I described my research ideas to the head of research at CIRiS, and was shortly granted an office (the first of several) in their office landscape, where I started spending most of my days in August 2013. The staff was made aware of my function and the topic of my thesis, and treated me as a fellow co-worker right from the start. During my 9 month stay, I had several opportunities to gather informal, tacit knowledge by attending group meetings, joining console operators on routine job tasks, the ubiquitous lunch breaks, sharing office space, joining the Christmas dinner and participating on the curling team. Some of the ways in which I participated were supremely helpful to my studies, and will be described below.

Operator training course participation. A major source of knowledge during the stay at CIRiS was the chance to join a new control room operator through the theoretical part of the training program, delivered as 11 sessions over 5 blocks, spanning over six weeks (Table 2). The operator training was conducted either in a conference room or on-console, depending on the learning goals, with one operator in charge of the specific training session, instructing

two trainees, including this researcher. Additionally, the N-USOC training manager was present in order to evaluate trainee performance.

Table 2

N-USOC operator training sessions

<u>Block</u>	<u>Session</u>	<u>Content</u>	<u>Reference</u>
1	1	N-USOC Introduction	(Berg, 2014)
2	1	N-USOC Ground Segment	(Hauan, 2014a)
	2	N-USOC Security	(Hauan, 2014b)
3	1 + 2	EMCS Payload definition	(Hauan, 2014c)
	3	EMCS Overview and Crew Operations	(Hancock, 2014a)
	4	EMCS Payload Hazard Control and Anomaly Handling	(Coelho, 2014)
	5	EMCS Payload Ground Operations and Monitoring	(Hancock, 2014b)
4	1	N-USOC Ops Concept	(Danielsen, 2014)
5	1	Experiment Integration: Overview	(Mohammad, 2014a)
	2	Experiment Integration: Ops Planning	(Mohammad, 2014b)
	3	Experiment Integration: Crew Procedures	(Mohammad, 2014c)

The benefits of these training sessions were many. In terms of explicit knowledge, they gave a quite detailed overview of the work domain, the organizational constraints of the interfacing organizations and the concrete work content of the operator tasks. The one-to-one distribution of experts and trainees, combined with an informal atmosphere, also made for valuable discussions of the operators' experiences with control room work, giving insight in the tacit knowledge surrounding the explicit work content, as well as some enlightening stories and incidents from previous experiments.

Half the N-USOC crew was involved in preparing and delivering operator training within their specialty field, providing the opportunity to gain insights from many experienced operators, and a natural way of making quite detailed notes of relevant information, tacit knowledge and stories not supplied in the printed course material. The final part of the operator training was not yet started when this thesis was due; undoubtedly participation in the simulation and certification part would have been a valuable experience for data collecting purposes, but it would also have been an unnecessary cost to the organization to invest in training an extra control room operator.

Conference participation. In order to get a sense of the current practice and future directions of human dependability in the European Space Agency (ESA), CIRiS and the Norwegian Space Agency offered me the chance to take a vacant seat as part of the N-USOC delegation to the Human Dependability Workshop in Oberpfaffenhofen, Germany in October 2013. This biennial conference is ESA's main stage for discussing the state of the art in human dependability and staking out directions for the coming years, featuring presentations from several domain specialists in ESA's main partners, the German (DLR) and French (CNES) aerospace agencies, as well as subcontractors within the technical and organizational safety fields.

The conference was a great opportunity for fly-on-the-wall observation of the way safety priorities and trade-offs are viewed and discussed by the ESA organization, and the way training for ESA astronauts and control room personnel is conducted.

Contributing to research on N-USOC. The Centre for Inter-Disciplinary Research in Space is part of a research foundation, and as such, they produce a significant amount of knowledge, often in the shape of conference articles describing the N-USOC project in a number of scientific disciplines. Having already contributed to a planned questionnaire in conjunction with a multi-actor simulation session, I was asked to contribute with my psychological domain knowledge in two conference articles (now under review) during the spring of 2014 (Table 3). Working with two CIRiS researchers, one of which is also part of the N-USOC project team, the article collaboration provided the opportunity to discuss task related topics with key personnel, as well as taking part in regular work activities and building rapport with team members.

Table 3

Contributions to conference articles

<u>Title</u>	<u>Conference</u>	<u>Reference</u>
Exploring the impact of mental models on teamwork and project performance.	European Conference of Knowledge Management	(Danielsen, Valle, & Stene, 2014)
Successful and Safe Operation - A Combination of Individual, Team and Organization Training.	European Conference of Knowledge Management	(Stene, Danielsen, & Valle, 2014)

As well as providing opportunities for knowledge elicitation, the collaborations and resulting articles also provided documentation and informal member checks for some of the background information that, until then, had been based on casual conversations alone.

Member checks. Member checks are regarded as an important part of validating ethnographical findings in an action research paradigm (Coughlan & Coughlan, 2002), and although the iterative way a CRM course is built would supply ample opportunity for member checks and participant evaluation in the development stage, for the purposes of validity in this thesis an initial check of my impressions and suppositions about the context was checked and corrected by key informants among the N-USOC team.

Data Analysis and Representation

The goal of both the problem solving action and the theoretical contribution aimed for by this thesis is the outline of a CRM course content, divided by key modules, topics within these modules, and learning objectives for each module. While using the most common approach from current CRM training as a starting point for the modules, the prioritized topics and objectives have developed in the course of the data collection, simultaneously affected by the theoretical, literature-based approach of addressing the first research question, and the participatory, multi-source knowledge acquisition process of addressing the second research question.

Being a visual processor of information, I used a very visual – and as it turned out, very public – way of organizing this information: writing emerging objectives and topics on Post-it notes and organizing them on my office wall, continuously moving, adding, discarding or revising these findings throughout the learning process (Figure 2). This turned out to be not only a suitable tool for analysis, but also a helpful aid in uncovering tacit knowledge within the organization, as my ‘wall of colors’ frequently acted as a conversation-starter about teamwork



Figure 2: The 'wall of colors'. This picture shows themes emerging over my workspace. Photo: Private.

and safety in the workplace. By this function, it provided valuable member input not only to the tasks and environment under study, but also in preliminary stages of coding and prioritizing topics.

A basic framework for analysis. CRM training is the most widely used framework for non-technical skill training, and is now spreading from its aviation roots to a wide variety of similar domains. One of the reasons behind this popularity is the perceived validity of the approach, and although domain adaptations of the key modules do occur, I tentatively started out with the six main modules as described in Appendix A as a starting point for analysis (Table 4):

Table 4

Preliminary categories for CRM modules

<u>Module</u>	<u>Coding</u>
M1: Teamwork	Topics that deal with behaviors that affect others in a group and the outcome of the collaborative efforts
M2: Leadership	Topics that deal with the management of constraints that set a framework for the work.
M3: Situational Awareness	Topics that deal with the gathering, construction and sensemaking of factors in and around the work content
M4: Decision making	Topics that deal with the process of moving from interpreted reality to action
M5: Communication	Topics that deal with the practices of sharing relevant information with involved stakeholders
M6: Personal limitations	Topics that deal with factors in the work environment that shape performances, especially workload issues.

Using a deductive approach, the CRM objectives identified by the theoretical work and the domain knowledge were loosely grouped into these tentative modules, based on their fit with the coding criteria. Simultaneously, the CRM topics of each module were recursively induced from the evidence in the data and from the suggested objectives as they emerged. The theoretical contributions from resilience engineering, in particular, had a big impact on the organization of the topics.

The main idea for the structure was to balance two goals: a theoretically sound organization of the selected training objectives, and a pedagogical and practical approach to carrying out actual training, organizing the objectives and topics in the context where they would make most sense to a trainee.

Theory

Crew Resource Management

Crew resource management, or CRM, training is the most widely used strategy to train *non-technical skills* in high-risk industries. These are “*the cognitive and social skills that complement technical skills, and contribute to safe and effective performance*” (Flin et al., 2008, p. 1). CRM training, although a quite general team training framework, is designed to support performance on the ‘sharp end’ of high-risk organizations; the operators on the frontline actually performing the safety-critical tasks and making key short-term decisions under time pressure. (Flin et al., 2008)

The aviation origins. In the early 1900s, the pioneers of aviation were overcoming a seemingly insurmountable technical challenge to be able to do that which had eluded man for centuries, the challenge of flight. These early 20th century pilots, as a result, were brave men, decisive and hardy. This image was subject to change as the aviation industry grew in the course of the century, and flight became commonplace. The aircrafts were no longer the single- or even two-man crew prototypes or fighter planes, but increasingly larger people carriers, and so the complexity surrounding aviation grew, with larger crews supporting the larger planes, and the rates of take-offs and landings increasing exponentially. As the introduction of reliable jet-driven transport caused a sharp decrease in technical failures and accidents, the focus of attention turned to the human contribution to accidents – specifically, the working relationship in commercial jetliners between the pilot and his first officer (later referred to as his co-pilot).

This eventually led to an emergence of formal human factors training in several major carriers by the early 1970s (Kanki et al., 2010). Nevertheless, a string of serious accidents shown to involve non-technically related errors occurred in the course of the 1970s, specifically, failures of interpersonal communication, crew coordination, decision making and leadership. The conclusion that the primary cause of aviation accidents was this kind of *human error* led to the development of Cockpit Resource Management, or CRM for short, a human factors training program originating from NASA in 1979, designed to address these shortcomings (Flin, O’Connor, & Mearns, 2002).

Early CRM: generations 1-4. The relationship between the captain and his second in command was the starting point for CRM training in the first generation, focusing on

changing individual patterns of behavior; assertiveness on the part of the first officer, enabling him to report his observations and weighing in his opinion where, previously, he would have felt compelled to remain silent; openness on the part of the captain, requiring him to both listen to and seek out the opinions of his first officer. In the second generation, this individual approach was supported with group dynamics, while at the same time integrating some of the contextual specificity of the air transport domain by focusing on cockpit-specific procedures (Salas, Burke, Bowers, & Wilson, 2001).

While these changes made a difference in the cockpit itself, there was a realization that many of the same challenges needed to be addressed in the way the cockpit crew interacted with its immediate surroundings; namely, the technical ground crew, air controllers and cabin crew. In short, this realization meant that the concept of the ‘crew’ would have to be redesigned, and so, in the third generation of CRM, the ‘C’ no longer stood for ‘Cockpit’, but ‘Crew’, and CRM training started including members of all relevant professions (Kanki et al., 2010). This was an important step, considering the consequences of this new, more complex definition of what could comprise a crew in any given situation. At this point in time (early 1990s), crew resource management training was accepted as an integral part of mandatory crew training, though not really with the same content in every instance. The fourth generation of CRM, therefore, consisted mainly of proceduralization, validation and standardization, tying the human factors training more closely to the technical crew training, and designing evaluation tools, like safety audits, to be used in real-life line operations (Salas et al., 2001).

Current CRM topics. In the last decades, the global shift in the view of errors has gradually affected some changes in how safe operations are achieved. The complex view of the socio-technical system added by the contributions of epidemiological and systems views on accidents neatly explain the potential for accidents that was not adequately covered by generation 1-4 CRM training – the careful building and following of safety procedures and engineering of safety features allowed for a significant decrease in the risk posed by component failure accidents, but was less effective when faced with increasingly common system failures.

The theoretical developments of Perrow (1984/1999) and Reason (1990), among others, have impacted the way training is conducted, primarily introducing a systems perspective to the concepts of failure and error. Improving organizational barriers to identify latent conditions that could contribute to adverse events meant the concept of proactivity

needed to be added to the practice of reactivity (Reason, Hollnagel, & Pariès, 2006; Zimmermann, Pariès, Amalberti, & Hummerdal, 2011). Safety management was starting to be seen as something that would have to include every layer of the organization, and the concept of safety culture grew in popularity (Guldenmund, 2000).

In CRM training, this theoretical development led to a focus on managing errors and sources of error than eliminating either; elimination seen as theoretically impossible due to ‘normal’ accidents, and ‘managing’ illuminating the focus on organizational correctives (Reason et al., 2006). Consequently, this has been labeled ‘threat and error management’ (Kanki et al., 2010). This fifth generation of CRM takes a three-pronged approach to error management; firstly, detecting threats that could generate human error; secondly, catching errors that are made through early detection; and thirdly, managing the consequences of the errors that do occur. This is referred to as ‘the error management troika’ (Salas et al., 2001).

The core modules that a current CRM training program should consist of are more or less universally agreed upon at this point, although the specific wording is somewhat variable and domain-specific (Flin et al., 2003, 2008, 2002; Flin, Wilkinson, & Agnew, 2014; Heemstra, 2013; O’Connor & Flin, 2003), covering a range of topics from the individual to team levels that CRM training is primarily designed to address (Appendix B).

Team work. The widespread and increasing use of teams in all kinds of organizations has attracted an enormous interest in investigating every aspect of team behavior throughout the last century of psychological research (Flin et al., 2008). A team is “*two or more individuals with specified roles interacting adaptively, interdependently and dynamically towards a common and valued goal*” (Salas, Sims, & Burke, 2005, pp. 561–562). This very wide definition of the team concept highlights the great variety of teams that can be identified, and they differ on many parameters; e.g. the number of team members, the duration of membership, the homo- or heterogeneity of composition, the distribution in time and space, and the duration of the collaborative effort. As a result, the number of team taxonomies is almost comparable to the number of teams themselves (Salas et al., 2005).

Teams are, in other words, a complex and multidimensional construct, and so it stands to reason that several views and models of teamwork exist that try to capture this complexity in generalizable and manageable terms. Letsky, Warner, Fiore, Rosen and Salas (2007) describe teamwork as “*the dynamic, simultaneous and recursive enactment of process mechanisms which inhibit or contribute to team performance and performance outcomes*”. Given the overlap between CRM training and the knowledge base of general team training

from which CRM principles are derived, it should come as no surprise that established best practice from team literature is reflected in the teamwork topic.

In current CRM research, a central framework for team collaborations has been Eduardo Salas and associates' proposed 'big five' of teamwork. This model proposes five discrete teamwork components; team leadership, mutual performance monitoring, backup behaviors, adaptability and team orientation, supported by three coordinating mechanisms; shared mental models, mutual trust and closed-loop communications. Taken together, these mechanisms should predict success in any form of teamwork (Salas et al., 2005). The teamwork components postulated by this model are found throughout a recommended CRM syllabus, and forms a theoretical backbone of the training approach.

Mutual performance monitoring. The individual team member in a well-functioning team has a responsibility for keeping an eye on team members' work as well as his or her own. This safety net of checking behaviors ensures that procedures are understood and followed, that the situation is still nominal, and that no team member experiences a sudden rise in workload. Closely tied to mutual performance monitoring, backup behaviors means reallocating internal resources to assist a team member both, ideally, when mutual performance monitoring reveals an uneven workload distribution, or when assistance is asked for. There are several ways to effect backup behaviors, e.g. by offering advice or feedback, assisting with or taking over a task or a part-task (Salas et al., 2005). The ability of a team to offer information both timely and un-asked for is a main characteristic of effective teams (Flin et al., 2008).

Considering and supporting. The beneficial effect of social support on job outcomes is well-established through organizational research. For CRM training, this is especially related to Salas' concepts of team orientation and mutual trust. Team orientation is mainly an attitudinal dimension describing both a preference for working with other people and a tendency to employ healthy group processes to enhance team performance (Salas et al., 2005).

Defined as the belief held in the group that each individual team member will perform actions that are important to the team, hold the team members' interests at heart, and help the team towards their common goal, mutual trust is a necessary foundation of effective teamwork. Helpful team behaviors like mutual performance monitoring and backup behaviors are dependent on the trust element in order to be interpreted correctly, and also to be utilized in an efficient way without unnecessary expense of resources (Salas et al., 2005).

Distributed Teams. Over the last few decades, the increasing globalization and advancing technological opportunities to collaborate across geographical boundaries has led

to a sharp increase in the number of distributed teams and virtual organizations; work groups that share some of the initial characteristics of teams, but are either partly or wholly distributed in space and time. As a result, there is an increasing demand for team members that can contribute to distributed and short-term teams with expertise (Flin et al., 2008; Kozlowski, 1998). While the virtual team members may occasionally meet, their linkages are temporary in nature, and the success of these teams and organizations depend on shared and interdependent processes designed to meet common goals (Grabowski, Ayyalasomayajula, Merrick, Harrauld, & Roberts, 2007; Jarvenpaa, Knoll, & Leidner, 1998).

The main complication arising from this distributed state is that of increased conflict on all dimensions; task, affective and process. While collocated team research has shown task and process conflict to be conducive, rather than threatening, to team performance (Flin et al., 2008), distributed team research has shown all three dimensions to be detrimental to performance in distributed teams (Hinds & Bailey, 2003). From a safety perspective, virtual organizations are especially challenging in the sense that risk identification is complicated by their temporary nature, complex interactions, and abundance of different safety cultures (Grabowski et al., 2007). The issues of geographical dispersion and technological mediation are challenging to important predictors of team success, but these threats can be alleviated by establishing a temporal rhythm for the teamwork by arranging face-to-face meetings at important points in the project cycles (Hinds & Bailey, 2003; Kirkman, Rosen, Tesluk, & Gibson, 2004; Maznevski & Chudoba, 2000).

Communication. Like teamwork skills, good communication is an overarching foundation and fundamental supporting process for good teamwork (Salas et al., 2005), and is likely to be implicitly or explicitly trained in all CRM topics. Still, there are some basic traits of communication that are deserving of stand-alone attention in a CRM course.

Communication, then, is defined as “*skills for the exchange (transmission and reception) of information, ideas and feelings, by verbal (spoken, written) or non-verbal methods*” (Flin et al., 2014, p. 14), and is widely regarded as an improvable skill through organizational policies or training interventions (Flin et al., 2008).

One-way and two-way communication. Typically, communication can be described as either one-way or two-way, each form carrying different implications for the way the message is designed, transmitted, encoded, decoded and received. A simplified view of this process can be derived from Shannon & Weaver’s (1949) mathematical model of communication (Figure 3).

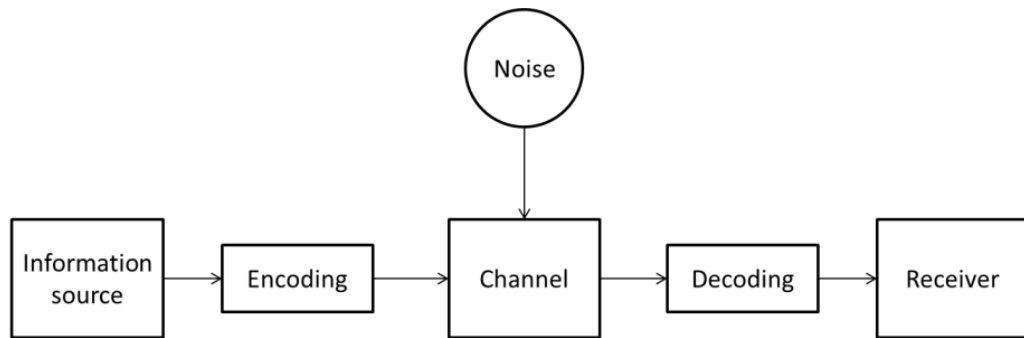


Figure 3: Shannon & Weaver's model of communication. The communication goes through several phases before reaching the receiver (Adapted from Weaver, 1949).

One-way communication has the advantage of being clear, precise, and with minimal variety due to the single encoding/decoding procedure and the single exposure to noise, however it requires initial precision and planning, the responsibility stays with the sender, there is no opportunity for feedback, and the sender cannot tell if the receiver is paying attention (Flin et al., 2008; Weaver, 1949).

Two-way communication involves the opportunity for the receiver to respond to the sender by giving feedback, either informational, corrective or reinforcing, in a closed feedback loop (Flin et al., 2008). A specific form of two-way communication is by now a ubiquitous CRM module in the communication category: closed-loop communication, also represented by practicing asking/listening techniques. Closed-loop communication is a specific form of communication designed to make sure information between any two team members is sequentially given, received, understood and confirmed. Reducing misunderstanding and delay in information transfer is at the heart of effective team collaboration, and so effective communication is part of any helpful team process (Salas et al., 2005).

Types of communication. Channels, or media, of communication in organizations are varied, for the most part according to the needs of the information that needs to be shared. One dimension that affects effective transmission and reception of messages is the richness of media that is used, according to media richness theory (Daft & Lengel, 1986). The richness of media involves the opportunity to communicate through non-verbal cues; e.g. voice cues, body language, facial expressions and touching behavior, as well as verbal communication, and can be thought of as a continuum ranging from written information, through voice communication and teleconferencing, to face-to-face interaction (Daft & Lengel, 1986; Flin et al., 2008).

Another dimension is the synchronicity of communication, ranging from instantaneous, as in face-to-face interaction to completely asynchronous, like written reports, or taped video messages. Choosing a proper communication medium is important to the team effort, especially considering the added difficulties of distributed team collaborations. Though evidence is mixed, groupware applications have been proposed to have an ameliorating effect on communications issues caused by distribution in time and space (Flin et al., 2002; Hinds & Bailey, 2003).

Communication skills. Drawing on research from high-reliability organizations, four aspects of communication have been identified as especially suitable for training-based improvements of communication: explicitness, timing, assertiveness and active listening (Weick, Sutcliffe, & Obstfeld, 2008).

Explicitness means clearly and briefly communicating the necessary information, without taxing the attentional capacity of the recipient more than needed. Clarity involves striving for unambiguity through ensuring necessary information is being passed through, and this is balanced with brevity; not exceeding the required information (Flin et al., 2008). This is often achieved through formalized and pre-defined communication patterns, like NASA's voice-link protocol.

Sensitivity to the timing of communication is especially important during high-tempo phases of high-risk operations, as distractions like cross-talk can add considerable risk when workload is already high (Flin et al., 2008). The teamwork quality mutual performance monitoring can alleviate this risk, as it increases sensitivity to others' workloads, and facilitates the unasked for sharing of information when needed (Flin et al., 2008; Salas et al., 2005).

The roots in cockpit resource management means assertiveness and listening skills in different team roles are part of the foundation of CRM training, but they are no longer the main foci of training in communication (Kanki et al., 2010). Still, the ability to remain objective and task-focused, to inquire for additional information when necessary and advocating the value of a perceived threat are not getting any less valuable as teams are becoming increasingly diverse, and collaboration across different domain expertise is becoming daily trade (Flin et al., 2008).

Situational awareness. Situational awareness is closely linked to the psychological terms perception and attention, a continuous monitoring of the situation in order to assess the state of the system and detect changes (Flin et al., 2008). It is defined as “*developing and maintaining a dynamic awareness of the situation and the risks present (...), based on*

gathering information from multiple sources in the task environment, what the information means, and using it to think ahead about what might happen next” (Flin et al., 2014, p. 13). Situational awareness is a product of selectively attending to cues from external and internal sources, filtered through the human memory system; the sensory, working and long-term memory. Special interest is taken in the working memory, with its widely known limit of “seven, plus or minus two” chunks of information at a time; the limitation of the working memory is the main reason for much of the CRM recommendations in any topic (Flin et al., 2008).

Levels of situational awareness. The most widely used model of situational awareness is that of Endsley (1995, in Flin et al., 2008), who suggested that three levels of awareness corresponds to three awareness skills: gathering information, interpreting information, and anticipating future states (Figure 4).

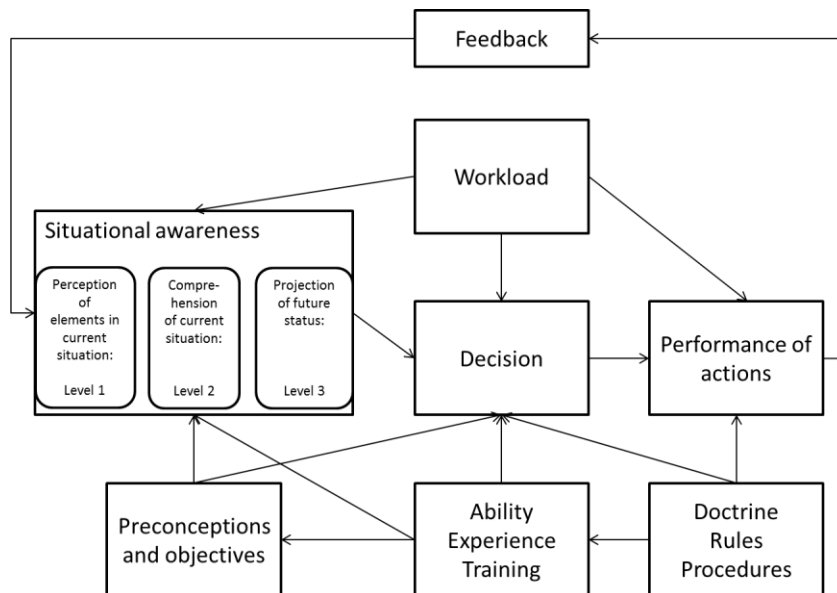


Figure 4: Endsley's model of situation awareness. The model describes a feedback flow with situational awareness in a key role (Adapted from Flin et al., 2008, p. 23).

Humans are not especially good at monitoring tasks, and are prone to several well-known fallacies in level 1 situational awareness, like tunnel vision, change blindness and attention lapses. Nevertheless, on level 2, we try to make sense of the information in a comprehension process, relying heavily on pattern matching and constructing good mental models of the situation (Flin et al., 2008).

Mental models. A major focus of CRM training in the situational awareness topic is the development of mental models: internal representations of the task environment by cognitive schema that allow people to interact with the world, similar to Wittgenstein's prototypes (Johnson-Laird, 2010; Mohammed & Dumville, 2001). As the team aspect of

CRM training has become more central, this focus has shifted to the development of shared mental models in the team, inspired among other sources by the team literature provided by central CRM researchers like Eduardo Salas (e.g. Salas et al., 2001, 2005; Salas & Cannon-Bowers, 2001).

Shared mental models entail a degree of commonness in these individual mental models, a common understanding of the environment, performance expectations and information requirements. By sharing mental models, team members are able to anticipate each other's needs, thus coordinating team efforts towards their common goals. This is an important prerequisite for mutual performance monitoring to take place in a meaningful way (Salas et al., 2005).

Anticipation. The third and final level of situational awareness is utilizing the comprehended and sorted impression of the circumstances to make predictions about future states. This is the key to safe human monitoring of complex control tasks, and results from a form of mental simulation of the perceived information's impact on future system behavior (Flin et al., 2008; Kahneman & Tversky, 1982; Phillips, Klein, & Sieck, 2004).

Decision making. Decision making skills are the “*skills for diagnosing the situation and reaching a judgment in order to choose an appropriate course of action*” (Flin et al., 2014, p. 14). Though this definition of decision making is very general, the actual content of a decision making module is bound to vary greatly, not only according to the domain context to which the course is adapted, but also the safety management view of the organization in question. Different circumstances require different decision making strategies (Flin et al., 2008); a topic for discussion in a later section.

Training decision making. While classical decision making training has been most concerned with teaching complex techniques for choice evaluations between options, the framework of naturalistic decision making has altered the way the high-risk community sees situational awareness and decision making, and this is starting to have implications for training (Flin et al., 2008; Klein, 2008). This will also be elaborated in a later section, for now a look at some decision-making training frameworks will have to suffice as examples of the typical CRM course.

In aviation, two rather similar processes are being taught: British Airways' DODAR (Diagnosis, Options, Decision, Assign tasks, Review) and Lufthansa's FOR-DEC (Facts, Options, Risks and benefits, Decision, Execution, Check) illuminate the clear parallel with Endsley's model of situational awareness, but also an understanding of the decision process that is still built on the concept of analysis and reasoned choice (Flin et al., 2008). In the same

vein, NASA employs a decision making process aptly named STAR (Stop, Think, Act, Review) for their ISS crews on and off ground (Noe, Dachner, Saxton, & Keeton, 2011). While these programs certainly have merit, some situations and circumstances may require alternative decision making strategies that do not require as much time and mental workload; more on that later.

Leadership. The mythical qualities of leadership, innate or trainable, have been extensively studied, and continue to be a topic of enormous interest in many scientific fields. While a team leader can be defined as someone who is formally or informally chosen to coordinate or direct the work of fellow team members, leadership is operationalized as “*skills for directing, managing and supporting a team in order to accomplish tasks for set targets*” (Flin et al., 2014, p. 15). Leadership, as addressed by typical CRM courses, is mostly related to desired behaviors from the formal team leader in a hierarchically structured team, and thus assumes a certain set of coordinating and facilitating responsibilities, as well as interfacing with the organization as a whole. Team leadership is a facilitative role, coordinating team efforts, organizing resources, defining goals and guiding the team towards these goals on both the individual and the collective level. It is within the responsibility of the team leader to monitor and synchronize individual efforts while at the same time monitoring the environment to ensure resilience towards sudden change (Salas et al., 2005).

Planning and prioritizing. The planning, prioritizing and coordination tasks are the bread and butter of traditional team leadership, and involve the chief responsibility for making sure performance goals are being met (Flin et al., 2008). This also includes the management of trade-offs and ensuring proper standard operating procedures are in place, two topics that are very salient in safety management systems.

Resource management. The team leader is responsible not only for managing her own workload, but for that of the team as a whole. This means understanding and monitoring the main contributors to workload, and organizing countermeasures such as workload sharing, adding time or resources, or activating or relieving the influenced team members (Flin et al., 2008). Both high and low workload (peaks and dips) need to be addressed. In safety-critical situations, research has shown a need for adaptive teams that can assume different constellations depending on the situation; in such circumstances, the team leader has an especially important responsibility (Flin et al., 2008; Rosen et al., 2011). Adaptability means an ability to recognize unexpected deviations from the expected plan, both internal changes and changes in the work environment, and adjust actions appropriately in response to the change of situation (Salas et al., 2005).

Transformational leadership. A great deal of interest in leadership theory in the last decades has been dedicated to the leadership style of transformational, or charismatic, leadership. Basically, the transformational leader shows leadership through inspiring team members, encouraging creativity, intellectual stimulation, and considering team members individually (Flin et al., 2008). Although the recommendation is that these traits are combined with methods of the more classical transactional style – exchanging rewards for effort – the motivating features of transactional style is especially suitable for an informal organization of high-functioning, highly educated team members, and also fit well with the positive-psychological and human-centered spin on safety management described later.

Followership. Just like leadership, followership is a skill that has to be learned, akin to the relationship between assertiveness and listening skills in the communication topic, and involves taking a supportive role and not undermining the team leader. The relation between leadership and followership is complex, intertwined and mutually dependent, so the leadership style is very likely to affect the followership experienced. From a training point of view, the ‘romance of leadership’ where team success or failure is commonly (and wrongly) attributed to the leader’s skill may be a source of insight (Flin et al., 2008; Tversky & Kahneman, 1974).

Personal Limitations. Most of the CRM course content on this module has been on the effects of stress and fatigue, as a lot of operators in the high-risk industries that employ CRM training may encounter not only extremely long shifts or extreme spikes in workload, but both at the same time; consider for instance the emergency room physician at the end of a fourteen-hour shift. Although stress and fatigue are generally considered negative for human performance, compensatory control theory states that self-regulatory processes can compensate to a certain degree for a limited amount of time, but at a physiological cost for the individual (Johnsen et al., 2013). Considering the far-reaching implications of prolonged stress on employee health and well-being (Demerouti, Bakker, Nachreiner, & Schaufeli, 2001; Karasek & Theorell, 1990) and the dangers to safety posed by overloaded operators in a high-risk environment, it is natural that this module is very important to most CRM courses.

Stress. Stress is commonly defined as “*a particular relationship between the person and the environment that is appraised by the person as taxing or exceeding his or her resources and endangering his or her well-being*” (Lazarus & Folkman, 1984, in Flin et al., 2008, p. 157).

Acute stress occurs when an individual is exposed to what is appraised as life-endangering and extreme, and the fight-or-flight response is triggered. Although the stressful

event itself is of relatively short duration, extremely high-stress events are known to cause psychological states such as post-traumatic stress disorder (Flin et al., 2008). Acute stress can be brought on by such things as high workload, emergencies, unusual problems, or high stakes; all of which are likely to occur in many high-risk environments, especially the most highly rated stressor; uncertainty. No individual factors have been shown to reliably protect against acute stress, but team support and cohesion have shown a mitigating effect (Flin et al., 2008).

Chronic stress, on the other hand, refers to a repeated negative experience caused by exposure to threat or excessive demands, *stressors*, in the workplace, and is linked to psychological outcomes like burnout and job outcomes like rate of turnover (Demerouti et al., 2001; Karasek & Theorell, 1990; Maslach, Schaufeli, & Leiter, 2001). There are a few competing models that seek to describe the relationship between stressors, alleviating factors and negative or positive work and health outcomes, such as Karasek and Theorell's (1990) demand-control model or Schaufeli and colleagues' (Demerouti et al., 2001) job demands-resources model. Although not identical, they both postulate that there are stressors in and around the workplace; like workload, poor working conditions, relationships, change, role ambiguity, and lack of support, that are ameliorated or counterbalanced by resources; such as psychological resilience, optimism, fitness, social support, and coping strategies.

A common means of training for psychological resilience to stress effects is the concept of overtraining, meaning repetition of a task or part of a task until it has been automatized, or performed with a minimum need of cognitive resources. This frees up higher-order cognitive resources for dealing with more critical issues (Cannon-Bowers & Salas, 1998a). This is a natural (and unavoidable) part of any repetitive task training, and indeed in everyday behavior: take, for example, the act of changing gears while learning how to drive a car. While cognitively demanding at first, therefore leading to oversights on other aspects of safe operation, by the time the driver's license is earned the new driver has automatized the gear change, and can spend cognitive resources on attention elsewhere. Still, there is a trade-off involved when overtraining tasks and part-tasks, which an operator should be aware of, and employ the constant process of metacognition to ensure does not interfere with safe operations.

Redesigning work in order to avoid chronic stress is a very important issue for the organization; the astronauts aboard the International Space Station once executed one day of full-on strike because of stress due to extreme amounts of conflicting and redundant information when speaking directly to different scientists (principal investigators) while

performing experiments. The strike was a success: voice communication with the astronauts is now restricted to one specific role in the main control room of their national space agency, at a large added cost in the training, preparation and planning phases. This says something about the value of stress reduction. Staying aboard the ISS for a bit, the aforementioned STAR process of decision making was originally implemented for overloaded crew members to be able to self-monitor in the face of stressful events, both chronic and acute (Noe et al., 2011).

Many different sorts of training interventions have been executed in order to deal with stress: cognitive control techniques like STAR, physiological techniques like controlled breathing, overlearning a task to the point of automation et cetera. In keeping with the stress models, interventions like removing stressors and training supportive behaviors are also good tools in order to manage stress-related issues (Flin et al., 2008).

Fatigue. With 24-hour manning necessitated by many high-risk industries, human fatigue has a long history as a major safety concern in these domains. It is defined as “*the state of tiredness that is associated with long hours of work, prolonged periods without sleep, or requirements to work at times that are “out of sync” with the body’s biological and circadian rhythm*” (Caldwell & Caldwell, 2003, in Flin et al., 2008, p. 191), although there have been considerable problems both defining and measuring this concept in a meaningful way.

Fatigue can be caused by a number of things, like stress, noise and heavy physical work, but it is also linked to low workloads, something that is common knowledge in transportation. The effects of fatigue include detrimental cognitive, motor, communication and social skills; therefore fatigue threatens good CRM behaviors on multiple levels (Flin et al., 2008).

The only cure for fatigue is sleeping, and so, a number of sleep-related programs can be implemented in order to ameliorate the effects of fatigue on team members; sleep hygiene, power naps, daylight lamps, medication, dietary plans etc. Such may be of little avail if the work requires shifts that conflict with circadian rhythms and normal family life. It is recommended that regular shift workers are given the chance to participate in scheduling shift work, in order to promote beneficial work outcomes and lessen the negative effects of fatigue (Flin et al., 2008).

Modes of delivery. Flin et al. (2008) refer to three main ways of delivering training.

Information-based. The information-based approach is the most widely used mode of delivery, something which is mostly due to its flexibility, low workload and cost, and one-to-many properties. This approach will mostly take the form of a classroom seminar, sometimes

complemented with a curriculum of reading material. The first introduction to CRM skills for trainees is usually conducted by this mode (Flin et al., 2008). For newcomers to this way of thinking about skills, the information-based approach is quick and effective, and applicable in some way to all CRM topics, however the knowledge transfer to skill execution is subject of rather conflicting evidence (Flin et al., 2008; Salas, Wilson, Burke, & Wightman, 2006).

Demonstration-based. Demonstration-based approaches share most of the strengths and weaknesses with information-based approaches; however the cost is often a little higher. Also a one-to-many approach, demonstration based approaches show an audience examples of good or bad CRM behavior; either by role-playing with participants, by acting out situations either live or on video with professional actors, re-enacting incidents or accidents with known sequences of events (Flin et al., 2008).

Practice-based. Practice-based methods are, contrary to the former two modes, an active mode of delivery that engages the participants in performing CRM-related activities. This form of delivery includes activities such as problem-solving exercises, group debriefs, role-play and simulator training. Associated with both knowledge, skill and attitude learning outcomes, it is regarded as the most effective way of training CRM skills; however, it is also more demanding in terms of technology, time and training personnel per participant (Flin et al., 2008).

Simulator training is widely used in a number of complex domains, but most frequently in aviation, where it has come to be regarded as something of a catch-all tool for training pilots. In high-risk industries, the benefit of training skill execution in a realistic, but risk-free environment is rather obvious. The technological development of high-fidelity simulators has been very fast in the last three decades, and in this light, it is perhaps disappointing to note that low-fidelity simulations produced significantly better learning outcomes than high-fidelity simulations (Salas, Bowers, & Rhodenizer, 1998). This is possibly due to an exaggerated focus on the fidelity of simulation, at the expense of designing simulations with learning in mind. To be effective, practice-based training requires guiding, coaching and feedback, and must consistently support and reinforce the execution of good CRM behaviors, instead of overloading the participants with complexity (Flin et al., 2008; Salas et al., 1998).

While simulation is widely regarded as the best way of learning CRM skills, its superiority over conventional approaches like classroom training from a cost-effectiveness point of view needs to be proven (Merien, van de Ven, Mol, Housterman, & Oei, 2010).

Future directions for CRM. The current view of CRM has been described as ‘generation 6 ½’, in the sense that it does not really incorporate what is fast becoming the dominant view of modern safety and risk theory: the systems understanding of accidents and the framework of resilience engineering, preventing so-called ‘black swan’ incidents (Taleb, 2010). Rather, it seems somewhat entrenched in its heritage of minimizing error, while current movements aim to strengthen the positive aspects of human performance. Addressing this gap between theory and practice is arguably the biggest challenge for CRM practitioners in the near future.

However, there is nothing to suggest that the general outline of CRM training is necessarily outmoded in any way. Much of the validity of CRM training – and therefore the ‘why’ of selecting this as a suitable framework for future crew training – lies with the perceived and evaluated usefulness of the approach by the end users, and its solid theoretical foundation across scientific domains. What remains is an adaptation to the current understanding of high-risk industries.

The Nature of Accidents

In order to understand the development of risk theory, the concept of the *socio-technical system* needs to be defined. The term originates from work performed at the Tavistock Institute in the 1950’s, and stems from the realization that social systems and technical systems in the workplace could not be considered separate. This carried a few implications for the organization and analyses of work (Trist, 1981):

- The organization viewed by its functions, rather than job contents
- Focus on work groups, rather than individuals
- Internal regulation by the group, as opposed to external regulation by supervisors
- Increasing variety and response repertoire in the group
- Treating the human being as complementary to, instead of an extension of, the machine.

The perspectives from the Tavistock institute have been very influential in an array of organization-related domains, and the evolution of accident models arguably represents a gradual shift towards their view of the socio-technical system, although the implications above are only just recently being implemented in safety management systems in a structured way. Still, a seed was sown, and with it followed an interest in how the role of the human interfacing with technology should be defined, and what impact this had on safety.

Domino theory. The dominant view of modeling accidents in the first three-quarters of the 20th century, though, can be described as sequential; that is, accidents happen as an outcome of a series of individual steps that occur in a predetermined and somewhat predictable order (Hollnagel & Goteman, 2004; Hollnagel, 2002). This has been expressed, famously by Heinrich (1931) as the ‘domino theory’ or the ‘First Axiom of Industrial Safety’, picturing accidents as the end result of a neat row of dominoes falling (Heinrich, 1931; Hollnagel, 2002). The very enticing supposition is that accidents can be prevented by eliminating error in one or more of the steps leading up to the accidents, and that these necessary precursors for accidents can be identified by building models like fault trees (Reason et al., 2006; Zimmermann et al., 2011).

This line of reasoning did have a tremendous effect on the industrial systems up to the second half of the 20th century, but with the ever-quicken pace of technological progress and increasing complexity, other models were needed to explain accidents in complex systems (Hollnagel & Goteman, 2004). Some very tragic and very public occurrences, like the Chernobyl meltdown and the Challenger space shuttle disasters of 1986, and the investigations spurred by these events, led to conclusions that the sequential models could not fully explain (Reason et al., 2006).

The ‘Swiss cheese’ model. Thus, the view of accidents shifted from a sequential one to an epidemiological view (Zimmermann et al., 2011). Epidemiological models compare accidents with the proliferation of disease (hence the name), as the outcome of coinciding manifest and latent factors, an unexpected and unavoidable result of interaction between different agents and environmental factors in situations that require risk perception. As a result of this, the analysis conducted needed to uncover more complex interactions between factors, and countermeasures had to be designed to address such interactions where they could be found (Hollnagel & Goteman, 2004).

In his seminal work, *Human Error* (1990), James Reason originally set out only to give a cognitive-psychological account of the sources of human error. As a result of the string of catastrophic and very public accidents of the 1970s and -80s, though, he ended up introducing a model of safety management that quickly became *comme il faut* for theorists and, especially, practitioners for more than a decade (Reason et al., 2006). Taking the epidemiological view of accidents, Reason distinguished between active errors; mistakes or violations made incidentally by the sharp end, and latent errors (later, latent conditions); systemic influences comparable to pathogens in the management or workplace dimensions of

the organization, the combination of which would cause an accident (Reason et al., 2006; Reason, 1990).

At the same time, there are healthy workings in any organization that keep these errors from causing accidents – organizational defenses – and the accident “path” needs to pass through one or several barriers in order to cause accidents. Along with the development of this model, in his 1997 version, these barriers were saliently (and coincidentally, as it were) depicted as a succession of layers of Swiss cheese (Figure 5), the accidents happening when the holes were aligned enough for an accident path to slip through (Reason et al., 2006).

Hazards, defenses and losses, then, are the basic elements of accident causation, the hazards passing through defenses to cause losses. The holes in the defenses are caused either short-term, by operator active error, or long-term, by higher level latent conditions (Reason et al., 2006). Safety is ensured

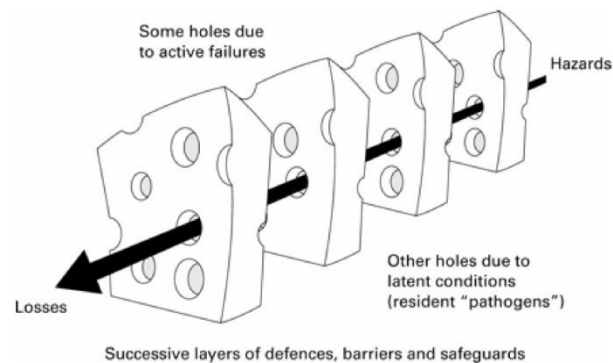


Figure 5: The 'Swiss cheese' model. A popularized image of the accident path passing through organizational barriers (From Perneger, 2005).

through defense-in-depth strategies, strengthening each barrier to minimize the probability of these gaps aligning (Pariès, 2011a; Perrow, 1999; Reason et al., 2006).

Normal Accident Theory. Formulated in the wake of the Three Mile Island nuclear reactor accident in Pennsylvania in 1979, Charles Perrow's Normal Accident Theory (1982/1999) took a quite different view of accidents, holding that the combination of *tight coupling* and *interactive complexity* would inevitably cause a kind of accident that Perrow describes as 'systemic', or 'normal'. Tight coupling describes a situation where processes are time-dependent, sequentially invariant, unifinally designed and with little slack. Interactive complexity describes a situation where one component can interact with one or more components outside the normal sequence, creating unplanned and unexpected sequences of events.

In order to explain the modes of failure in a system, Perrow describes disruption in four levels of increasing seriousness; damage to a single part, damage to an array of parts (a

unit), damage to an array of units (a sub-system), and damage to the system as a whole and its surroundings (Table 5).

Table 5

Perrow's accident levels (Adapted from Perrow, 1999).

<u>Accident level</u>	<u>Consequences</u>
Level 4, accident	Damage or disruption to the system and/or environment
Level 3, accident	Damage or disruption to a sub-system
Level 2, incident	Damage or disruption to a unit
Level 1, incident	Damage or disruption to a part

Perrow separates what he calls component failure accidents; an anticipated upwards string of disruptions, most often starting as a level 1 incident but ending up cascading to an accident level, analogous to the sequential view of accidents, the failure string being reasonably open for anticipation (Perrow, 1999; Reason et al., 2006; Zimmermann et al., 2011). System – or normal – accidents also start with a component failure, but involves the unanticipated interaction of multiple independent system failures, unexpected and incomprehensible to designers and operators of the system (Perrow, 1999). This illustrates the shift from a sequential to an epidemiological view of accidents, and how these paradigms can coexist depending on the complexity of the system. The main difference from the epidemiological models is the forecastability of the interactions between the components; in Perrow's view, these are so complex and unpredictable that they are effectively unavoidable, and therefore 'normal' (Perrow, 1999).

Resilience Engineering.

The theoretical bases of safety management have evolved continuously in the course of the twentieth century, to the point that many theorists now hold that a radical epistemological change is necessary in order to improve the understanding of safety, or even maintain an acceptable level of safety in a world that is growing more complex at break-neck speed. Traditional safety management, as it is called by Resilience Engineering theorists, is firmly rooted in a positivist scientific tradition and a technology optimist view that results in a main strategy of reducing the possible disturbing impact caused by the human element by

zealously designing systems and procedures to the point where every contingency is foreseen and planned for, and correct human behavior where necessary ensures system safety. Major advances in traditional safety management, like Reason's influential 'Swiss cheese' model (Reason et al., 2006; Reason, 1990) have added dynamics and complexity to the framework, but the principles have not changed in any major way (Zimmermann et al., 2011)

Resilience Engineering, on the other hand, represents more of a revolution than an evolution of the field, across frontlines of a familiar battleground for theorists in the human sciences (Table 6). Rooted in the post-modernist, social constructivist frameworks of much theoretical work in the last three decades, this movement has gained a lot of support in the safety field as the theoretical basis has progressed, although not really applied in practice in any major degree (Zimmermann et al., 2011).

Table 6

Safety perspectives. (Adapted from Zimmermann et al., 2011).

	<u>Traditional safety perspective</u>		<u>Resilience Aspirations</u>
<u>Model</u>	Sequential	Epidemiological	Systemic
<u>Accidents</u>	Simple, linear	Complex, linear	Complex, non-linear
<u>System</u>	Cartesian, mechanistic, decompositionist, Newtonian, simple	Cartesian, mechanistic, decompositionist, Newtonian, more complex	Systemic, complex, non-linear
<u>What is examined</u>	Causes, cause-effect links	Active and latent failures	Couplings; resonance, loss of control
<u>Scientific focus</u>	Proximal components	Distal and proximal components	Situated, integrated wholes; emergence
<u>Change action</u>	Reactive response	Proactive attention	Proactive anticipation
<u>Intervention</u>	Error prevention	Error prevention and recovery	Maintaining control, building in slack
<u>Safety paradigm</u>	Normative	Normative with some allowances for mitigating	Local rationality, constructionist

<u>Scientific philosophy</u>	Positivist factors Positivist with some skepticism	Postmodern, social-constructionist
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The way resilience is defined underscores the systemic view of accidents and safety that lies at the center of Resilience Engineering: “*The intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions*”(Hollnagel, 2011a, p. xxxvi).

The definition of safety, from a Resilience Engineering perspective, is ‘the ability to succeed under varying conditions’ (Hollnagel, 2011a, p. xxix), diverging from the common view of safety as ‘freedom from unacceptable risk’ (Hollnagel, 2011a, p. xxix). As a consequence of this, a central premise of Resilience Engineering is that studying and improving the number of things that go right is just as important as avoiding things that go wrong.

Performance variability. Traditionally, safety management systems have had great success focusing on the adverse events, in a mostly manageable system where normal, safe functioning could be achieved mostly by limiting performance variability (reducing the ‘human factor’) mostly through increased proceduralization (Hollnagel, 2011a). The manageability of these socio-technical systems have lessened considerably over the last twenty year, making performance variability both a necessary asset and a liability; it is both the source of negative outcomes and the opportunity for positive ones (Aven & Steen, 2011; Hollnagel, 2011a). The logic behind this is not new, and was succinctly put by Ashby (1958) in his work on requisite variety in cybernetics. Put simply, the law of requisite variety states that the complexity of a controlled system needs to be matched by the range of controlling options available to the controller (Ashby, 1958). Looking at accidents from a statistical point of view, they can be seen as representing the tail of a distribution curve; the result of the variance of the system (Reason et al., 2006).

This arguably makes safety management in complex systems unattainable only through the means of a few simple procedures, and speaks for the necessity of the human controllers and decision makers, in all their human complexity. The concept of autonomous work groups is derived from cybernetic control theory, and states that the more of the key variances can be controlled by the group, the greater work satisfaction will be, and the better

results the group will achieve. The autonomous group can control a much larger variance than the same number of individuals tied together by supervisors (Trist, 1981). This speaks for the importance of teamwork in order to cope with the added complexity of modern safety-critical organizations.

Trade-offs. A key concept in a systems view of safety management is that of a safety envelope; a theoretical window of operation that defines a safe and nominal state, from which factors in the environment may cause a sharp deviation or a slow drift (Hollnagel & Goteman, 2004; Rasmussen, 1997). The management of safety boundaries in the long run is affected by several identifiable trade-offs; conflicting desired states that are to some degree necessary in order to sustain operations.

Efficiency-thoroughness (ETTO). James Reason (1990) stated that all organizations allocate resources according to the goals of production and safety; these goals being compatible in the long term, but safety drawing the shortest straw in the short term as long as there are limited resources. This trade-off has been described as the efficiency-thoroughness, or ETTO, trade-off, in the sense that the scarcity of time, workforce or money will never allow maximization of both efficiency and thoroughness at the same time (Hollnagel, 2002; Reason, 1990; Tjørhom & Aase, 2011). As later examples will show, the ETTO tradeoff has a huge influence on the constraints of the safety envelope, and there is every reason to suspect that this influence is ever growing.

Automaticity/variety (reliability). The core of resilience engineering is that human variability is a necessary asset to ensure safety in a complex, dynamic environment, but looking at earlier theories of safety, this variability is the breeding ground for exactly the kind of human errors safety management is designed to eliminate. This can be stated as a trade-off between automaticity and variety, also referred to as the requisite variety- reliability trade-off (Weick et al., 2008; Weick, 1987). This has not always been recognized, as the concept of reliability, originally defined as a system's extraordinary ability to consistently deliver output above a defined minimum level, has often been employed as a kind of confluence of high risk and high effectiveness (Weick et al., 2008). In this meaning, reliability as a term is not a good fit for the desired capabilities of the human operator in a safe organization.

Short-term/long-term goals. The prudent balancing of key trade-offs is the key activity involved in the managing of safety margins that characterizes resilient controller behavior. The last of the key trade-offs is the ubiquitous balancing of short-term goals and long-term goals. This trade-off is commonly represented by the ETTO trade-off, since

financial goals are often measured on shorter term than safety goals, but this chronic/acute balancing is worth attention in its own right. Including long-term and complex effects of choices made to address short-term issues is a major challenge for situational awareness, but crucial in order to succeed with sacrificial decisions and maintain long-term safety (Tjørhom & Aase, 2011).

The key lesson from the tradeoffs is that there is no operating on the safe side of sorry; pressures from conflicting goals mean that the system must be managed close to performance boundaries (Johnsen, 2010; Rasmussen, 1997). Resilience engineering has been concerned with these trade-offs because it is realized that the fiduciary constraints of sustaining operations and generating profits need to be considered in the theoretical safety management plan. Failure to anticipate the effect of budget cuts and profit maximization on safety culture may well be a source of slow drift toward unsafe states (Rasmussen, 1997), and was identified as a chief contributor to the *Columbia* space shuttle disaster of 2000 (Starbuck & Farjoun, 2005).

Seven resilient traits. In order to manage these trade-offs, the socio-technical system needs a set of capabilities, located either as available courses of action on the sharp end, as system characteristics on the blunt end, or both.

Redundancy. Having several alternate and independent ways to perform a function if the primary solution becomes unavailable – either by using different procedures, different (or spare) technical equipment, or different organizations – is important in order to increase the resilience of an organization (Johnsen, 2010; Johnsen et al., 2013). Still, as Perrow (1984/1999) notes, more redundancy may also increase the likelihood of spurious actuation, as the complexity of the system grows. There are several examples of this; for example, Perrow recounts the failed mission of one of the lunar surveyors called Ranger 6 because a short-circuit in the backup power system designed to ensure photos being taken ended up draining the main power supply, causing the loss of the unit (Johnsen, 2010; Perrow, 1999).

Controlled degradation. In the face of risky system behavior, a resilient system has the built-in ability to perform a partial shutdown, ensuring safety in the intermediate stages of the shutdown process. This has also been termed ‘graceful recovery’ (Johnsen, 2010). The role of the human is key to the ability to ‘rebound and recover’ after a controlled degradation, mobilizing knowledge and competence in concert with impact analysis (Johnsen et al., 2013).

Flexibility. The ability of a system to allow for improvisation in the face of unexpected turns of events by allowing different ways of performing functions within a

specific system is a key to avoid the aptly named brittleness that is a trait of more rigid systems. Flexibility, both in parts or in the system as a whole, is necessary in order to handle unexpected emergencies (Johnsen et al., 2013) .

Managing margins. From a systemic view of accidents, the overarching framework used when monitoring is that of managing margins close to the performance boundaries; monitoring the safety envelope and making sure performance boundaries are not crossed (Johnsen, 2010).

Safe operations can be defined as operations that keep within certain limits that define an acceptable level of risk: a safety envelope (Hollnagel et al., 2006). In a complex sociotechnical system, there are several trade-offs that have to be managed, some of which pit safety against some more immediately salient outcomes, meaning that the margins of operations will almost invariably take place close to performance boundaries (Johnsen, 2010; Rasmussen, 1997). Managing margins is about making sure these boundaries are never crossed, and achieved by making sacrificial decisions and monitoring indicators of drift towards an unsafe state, and keeping a vigilance that has been referred to as ‘ a constant state of uneasiness’ (Johnsen et al., 2013; Ryschkewitsch, Schaible, & Larson, 2009).

Common mental models. The concept of common, or shared, mental models is as important in Resilience Engineering as it is in other models of safety and teamwork, and is a key precondition for effective coordination and collaboration in organizations and teams (Johnsen et al., 2013; Letsky et al., 2007; Salas et al., 2005). Shared mental models enable operators to know what to expect and look for, and to predict the actions of other members of the team in the event of the un-planned for (Johnsen et al., 2013).

Reduce complexity. As held by e.g. Perrow (1984/1999), one of the key factors in system accidents is the complexity of the system, and so, being able to reduce complexity in given circumstances may be a powerful tool for bringing the situation back to a nominal state. The way this is done is by segregating the affected system from other systems, limiting the number of connections and the interactivity, enabling a more complete situational understanding from the otherwise overloaded operator, and more effective communication with affected parties (Johnsen et al., 2013) .

Reduce tight couplings. The tight couplings described by Perrow (1984/1999): rigidly sequenced and interdependent processes with strict time constraints and little slack, are counteracted by adding flexibility, redundancies and slack wherever such tight couplings are detected. Still, as with redundancy, loosening couplings may increase complexity, as tight couplings are most often results of a streamlining process. The option of employing this

method must therefore be carefully weighed and analyzed (Johnsen et al., 2013; Perrow, 1999).

The cornerstones of resilience. Hollnagel (2011) describes what he calls the four cornerstones of resilience, namely: *anticipating*; recognizing and analyzing future opportunities, threats and developments in terms of their potential consequences, *monitoring*; knowing how to look for the critical signs in the environment and system that pose a threat in the near future, *responding*; knowing how to respond to regular and irregular disruptions by planned intervention or ad-hoc adjustments, and *learning*; knowing how to learn from experience, both in terms of success factors and paths to failure (Aven & Steen, 2011; Hollnagel, 2011a).

Anticipation. Five patterns of anticipation can be identified in resilient organizations: 1) the ability to recognize decrease in adaptive capacity in the face of upcoming constraints, 2) the ability to recognize depletion of buffers and reserves, over time or incidental, 3) the ability to shift priorities across goal tradeoffs by knowing where the system is in the trade-off space, and make sacrificial decisions, 4) the ability to shift between and contrast different perspectives, especially in interdependent, multi-actor decisions, 5) the ability to coordinate interdependencies across roles, activities and levels, and 6) The ability to recognize when new ways to adapt are necessary, and learn to do this (Woods, 2011).

Monitoring. Indicators can be thought of as samples drawn from the processes involved in the controlling of the socio-technical system within the safety envelope, providing information on activity in intermediary stages of the control process, before any significant change occurs in the safety outcomes (i.e. departure from the normal situation). They may, alternatively or additionally, be samples drawn from the operation environment that can ‘catch’ any changes that may affect the system output – alone or in concert with other factors. Detecting and adapting to such faint signals has been identified as a key feature of resilient organizations. The hallmarks of a good indicator are objectivity, quantifiability and availability (Wreathall, 2011).

Responding. The readiness to respond relies on two strategies: the proactive one of anticipation, planning, procedures and training, and the reactive one of creating ad-hoc solutions for dealing with the problem at hand (Pariès, 2011b). While the role of anticipation lies in correctly analyzing the potential variability of the situation and, importantly, the coping capacity of the system, resilience is not limited to what is effectively very thorough planning. Indeed, the act of anticipation may make operators blind to what was not anticipated, by

limiting their awareness to checking for anticipated events. The reactive strategy, then, is training to cope with the unexpected, for example through generic team training or learning how to adapt coping strategies according to the potential variability in the situation (Pariès, 2011b).

Learning. While the learning outcomes of traditional safety analyses have mainly focused on learning from adverse events – accidents, incidents – from the past, the basic Resilience Engineering tenet of successes and failures being tied to the same processes leads to the conclusion that successes should be a focus of interest. In terms of effective learning, in should be the main focus, as the occurrence of successes is much higher than that of failures. Learning supports all the other main processes of Resilience Engineering, the efficiency of which would soon be much diminished without the learning input (Hollnagel, 2011b), and in line with the framework of double-loop learning, it must be conducted on several levels, aiming to identify both governing values and constraints of the system that guide action (Argyris & Schön, 1978; Hollnagel, 2011b).

Indicators. The concept of performance indicators is used in a wide array of fields, where the definition and scope of the indicators reflect both what they are intended to uncover, and the view of the sociotechnical system that is under scrutiny. This debate extends to the definition of safety indicators, which is by no means uncontested. In this thesis, John Wreathall's (2009) definition of indicators as "*proxy measures for items identified as important in the underlying model(s) of safety*" (Wreathall, 2009, in Herrera, 2012, p. 17), is used, taking a rather operationalized view of indicators that fits with the concept of CRM training.

According to Herrera (2012), three kinds of indicators can be identified: leading, lagging and current, a balance of which is necessary for safety. This taxonomy is not the only one in use, and some theorists argue that the distinctions are not really important. Though this position has merit, the way different indicators affect the choices made on their advice speaks for differentiation (Herrera, 2012). Indicators are defined as leading if they provide information that means corrective action can be taken prior to a change in safety outcomes; lagging if they reflect an outcome change, and these different ways of addressing a system disturbance implies different trade-offs and mechanisms. Note, however, that the classification is prone to discussion as it depends on the level of analysis, cf. Perrow's levels of accident (Perrow, 1999; Wreathall, 2011): one man's ceiling is another man's floor.

In a complex and dynamic socio-technical system, using indicators is a delicate balance, as illuminating certain details invariably casts shadow on others (Herrera, 2012), however the potential safety upside of appropriate use of indicators makes the identification and study of context-relevant indicators ubiquitous in a safety-conscious organization.

Lagging indicators. Lagging indicators refer to events that have already happened and impacted the system (Herrera, 2012). In most of the widely used safety analyses, lagging indicators have been the main focus of attention, examining factors like accident rates and incident rates in order to quantify the level of safety in the organization as a whole or ‘human reliability’ on individual or group level. Especially in the aviation domain, the focus on lagging indicators and learning from failures has reigned almost supreme (Herrera, 2012).

Even though the rising complexity and low rates of adverse events have necessitated a shift of focus towards more proactive indicators, this does not mean that lagging indicators have outlived their usefulness. Rather, other types of lagging indicators, like event logs and statistics, are needed to supplement the leading and current indicators (Herrera, 2012).

Leading indicators. Leading indicators aim to predict how the system will perform in the future (Herrera, 2012), and can be either direct; individually predicting or even causing adverse events, or indirect; surrogates or proxy measures for performance where direct indicators are lacking or hard to find. Leading indicators are primarily focused on the individual or group level (Grabowski et al., 2007), and as such, they are very relevant for operator training.

Looking at single indicators, though, will seldom be enough to reliably forestall adverse effects, as accidents are mostly caused by complex interaction between several elements that may or may not have a working indicator (Grabowski et al., 2007). Some researchers have suggested developing sets of indicators that could help illuminate such interactions (Grabowski et al., 2007).

Using leading indicators and acting proactively to avoid disasters is already a well-established practice in safety-conscious organizations; however the trade-off between productivity and safety often means that there are competing indicators at any given time. The indicators of economic performance are well-established and relatively easily understood, and thus have a tendency to take precedence over the somewhat vaguer safety indicators (Grabowski et al., 2007; Wreathall, 2011).

Current indicators. The role of the current indicators may be somewhat difficult to grasp, as the definition bridges the clear-cut separation of lagging and leading indicators: whether the system is already impacted. Current indicators describe the instantaneous

functioning of the system, e.g. a graph of power consumption or a peak load in team communication that influence the safety in real-time. As such, they can be construed either as lagging, leading or both (Herrera, 2012). Given the focus on describing nominal as well as off-nominal system functioning in systemic models, current indicators of safety should have something to offer.

A systems approach to CRM training. The first literature to be considered, besides the introductory Crew Resource Management literature, the influence from the systems approach and resilience engineering on the selection of topics and objectives has been profound, even with a feedback loop of analysis guiding the process throughout. Still, with a research goal of investigating possible translation of a systems view of safety into CRM training, it is perhaps only natural that this framework gets a defining role in this prototypical CRM course.

Resilience cornerstones. The four cornerstones of resilience, as described by Hollnagel (2011a), are descriptions of general skills that are comprised of several more concrete skills, and as such, they are well suited to be treated as topics in a CRM course. Anticipation and monitoring, in my definition, are connected to the way knowledge is acquired and interpreted by the operator, and so they fit nicely into the Situation Awareness (M3) module. Responding, on the other hand, addresses the action required from the first two phases, and is located in Decision Making (M4).

Managing margins. The main message from resilience engineering and the systems perspective to CRM training is the need for the operator or operator team to continuously monitor the state of the system for unexpected fluctuations due to sudden or chronic changes; a quick sprint or a slow drift towards the boundaries of the safety envelope. This not only involves monitoring system behavior itself, but also noticing in a structured way how implementation of or changes in practices surrounding key tradeoffs like the ETTO trade-off causes the safety envelope to expand or contract.

The upshot for CRM training is manifold; excellent situational awareness (M3) is a must in order to make sense of the complexity, decision-making skills (M4) in order to make the sacrificial decisions across goal trade-offs. Performance-shaping factors (M6) like stress, boredom or fatigue seriously threaten the ability to maintain the required state of vigilance, while teamwork skills (M1) like mutual performance monitoring and backup behaviors provide task support, and considering behaviors the social support to ameliorate these adverse effects. Finally, communication skills (M6) like assertiveness and advocacy may be crucial to

the typically empowered operator in a high-reliability organization when communicating a need for change in goal priorities to the blunt end of the organization, contributing to upward resilience.

The management of margins is the main framework for situational awareness, and acts as a backdrop for all activities in this module. Specifically, though, the idea of margins is addressed in the leadership (M2) module, as the process of defining margins.

Responding options. The way the resilient organization acts when exposed to stress is arguably what defines it as resilient, and by this logic, the way the sharp end selects countermeasures to an anticipated or perceived adverse event is crucial for maintaining resilience. The principle of graceful recovery through the devices of sacrificial decisions, reducing complexity and loosening couplings may serve as very useful pointers that should inform individual or team generation of response options, and key dimensions on which to evaluate and choose between such. In the CRM context, they fit naturally as specific objectives under Decision Making (M4), under the Responding topic, however the concepts of tight coupling and complexity should also be treated as important precursors of off-nominal events in the Situational Awareness (M3) module.

Indicators. While all types of indicators – leading, lagging and current – are necessary for good safety management, the conclusion drawn from literature is that some of the resources currently spent on gathering and updating lagging indicators could well be spent on identifying reliable leading indicators. Classified as monitoring skills, the knowledge, skills and attitudes regarding indicators are located in the Situational Awareness (M3) module, under the Monitoring topic.

Learning. One of the cornerstones of the Resilience Engineering framework (and also other frameworks, etc.), the ability to learn from experience is a crucial factor for an effective safety management system. In this context, learning does not just mean recording adverse events in order to prepare for the next incidence; it is a dynamic, constant activity that must be ever-present in the organization. A key to effective learning in a current view of safety management is reporting not only adverse, but also successful or serendipitous events.

Learning is a complicated theme to address in a training seminar, as it needs to be a continuous process in the organization, however setting rules for the management of knowledge is within the leadership (M2) domain.

Redundancy. Having alternate way to perform an operation if the primary solution becomes unavailable, either by using different procedures, different (or spare) technical equipment, or different organizations, is an important resilient attribute (Johnsen, 2010). For

example, the limited space for keeping technical spares on the ISS, and the time and cost involved in procuring them, along with tight schedules, is a serious threat to redundancy. Being more of a planning issue than an operations issue, it is treated as part of Leadership (M2).

The human controller and adaptive expertise. The complex, dynamic nature of the real-world setting means that the expertise involved in control of these circumstances must have the same element of dynamic. This calls for a specific expertise in assessing emerging and rapidly changing situations, prioritizing goals, and taking strategic action through team coordination and adaptation of strategies – what Kozlowski (1998) refers to as adaptive expertise. Adaptive expertise demands conceptual knowledge of the problem domain, enabling the expert to recognize the kind of change that necessitates adaptation of strategies and goal prioritization (Kozlowski, 1998).

From a resilience point of view, then, the key to ensuring lasting safety in unforecastable, complex-dynamic environment is within the response variability and decision making capacity of the human operator at the sharp end. One of the main implications is that the role of the human operator can no longer be thought of as solely a restriction for optimal performance, but rather a necessary prerequisite for enduring safety and organizational resilience to adverse, off-nominal events (Hollnagel & Goteman, 2004). The processes of human failure are the same as human successes, only much rarer, and so the virtues of successful human operation should be a focus of study. Using the favored tool of accident investigation, several authors have looked at the successful recovery of the *Apollo 13* crew.

The recovery of Apollo 13. Intending to land on the moon, the *Apollo 13* mission of 1970 was cut short when an oxygen tank audibly exploded en-route, leading to the mission being aborted. The problem was, the explosion and the ensuing damage to the spacecraft had impaired the steering capability of the vessel, so that attaining the correct and safe reentry angle would be nigh impossible, so the prospects of saving the crew were grim. Thankfully, many unrealistic scenarios had been practiced beforehand, and so the ground and space crew were able to collaborate efficiently in real-time, ending up with a novel solution to the problem, as the booster rockets of the lunar lander module were employed to help the spacecraft get the right angle for reentry. The crew, including commanding officer Jim Lovell – now commonly remembered with Tom Hanks' face – was saved (Johnsen et al., 2013).

The unmistakably human contribution to this extraordinary recovery exemplifies the current shift back towards the human, rather than organizational, impact on operational safety,

however this time with a main focus of supporting human performance conducive to safety instead of minimizing or eliminating error. The focus is beginning to shift, from the ‘blunt end’ of management, back to the ‘sharp end’ of operations, by exploiting the specific expertise of human decision makers (Klein, 2008).

Expert Decision Making

Decision making is a very complex process that involves gathering and synthesizing a wide array of information from many different sources, both external and internal to the decision maker, and then weighing this information on many dimensions before a conclusion can be reached. Decision making can be said to work in three distinct, but not independent, stages: the generation of options, the evaluation of alternatives, and the choice of a final course of action (Fellows, 2004). It is a process and a phenomenon that has been thoroughly studied across the centuries, but still not completely understood.

Up until the mid- to late 1980s, most decision researchers held a view of decision making that is now commonly referred to as ‘classical decision making’, drawing on Bayesian probability theory, and multi-attribute utility theory. This set of theories was mainly prescriptive, aiming to identify the ‘right’ way to make decisions for a rational actor (Cannon-Bowers & Salas, 1998a; Cohen, Freeman, & Thompson, 1998; von Neumann & Morgenstern, 1944).

Bounded rationality. A massive and popular critique against the rational-actor view of decision making was made by Herbert Simon (1972), with his theories of bounded rationality, referring to the belief that important constraints in human and organizational decision making arise from limitations in the actor as an information processor. Connected to the concept of cognitive dissonance, Simon’s theory postulated that rationality has certain limits, it is bounded by uncertainty, incomplete information and complexity, preventing the actor from calculating the optimal course of action as prescribed by classical decision theory (Simon, 1972).

By studying the game of chess – a popular metaphor for real-life decision making in any decision research tradition – Von Neumann & Morgenstern had defined rationality by proving mathematically that for each set of possible decisions, there was a subset that would lead to the desired result (Simon, 1972; von Neumann & Morgenstern, 1944). Simon countered this view with the game theorists’ own admission that the fact that a defined set of optimal moves existed did not really help the player choose a move, and pointed to the vast

number of theoretically available moves at each stage. Simon's interest lay in the strategies the chess players used to handle this complexity, and found that human players constrained their available moves to a set of moves that would be good enough; a *satisficing* decision process, before proceeding to choose an alternative between these satisfactory alternatives; *optimizing* his strategy. The bounds of rationality constraining the chess player mean that these processes represent approximations of the complex reality (Simon, 1972).

Heuristics and biases. While expected utility theory, as one of the most influential scientific theories of the 20th century, had enjoyed overwhelming support, several studies, drawing on Simon's bounded rationality, began questioning the existence of this rational actor supposed by the theory. Through a series of examples and a wealth of quantitative research, Kahneman & Tversky (1979) set out to disprove the dominant theory of expected utility, showing that the completely rational actor did not really exist, in the sense that people consistently did not make the decisions predicted by expected utility theory. Kahneman & Tversky's *prospect theory* could, among other things, predict the already well-known risk aversion that people exhibit, the bread and butter of insurance companies for several decades before expected utility theory was theoretically challenged (Kahneman & Tversky, 1979). In the course of decades of research, several ways in which cognitive processes within each human being were illuminated, pointing to a number of cognitive biases due to the human tendency to use heuristics for everyday decision making; specifically, representativeness, availability, and anchoring (Tversky & Kahneman, 1974). Sadly, the constraints of this thesis does not allow for colorful examples of such, however many can be found in Daniel Kahneman's entertaining popularization and summary of the heuristics and biases research, "Thinking, Fast and Slow" (Kahneman, 2011).

Dual processing systems. Heuristics and biases, then, stem from two conflicting ways of reasoning that influence the way humans reach decisions and make sense of their surroundings. This can be visualized as two separate systems: System 1 and System 2. System 1 relies on cognitive schema, prototypes and memories to quickly categorize any event and decide on a course of action through heuristics; rules of thumb that are easily applied to familiar situations. It is what people base most of their everyday decisions on, and a crucial part of human survival. System 2, on the other hand, is a slower, more analytical processor of information that employs rules of logic and Bayesian statistics if it is taught how to do so properly (Evans, 2008; Kahneman & Klein, 2009). This system is linked to the level of

general intelligence and the limits of the working memory (Evans, 2008). Some of the fundamental characteristics of the two systems are summarized in Table 7.

Table 7

Characteristics of System 1 and System 2 (Adapted from Evans, 2008)

	<u>System 1</u>	<u>System 2</u>
<u>Consciousness</u>	Unconscious	Conscious
	Implicit	Explicit
	Automatic	Controlled
	Low effort	High effort
	Rapid	Slow
	High capacity	Low capacity
	Default process	Inhibitory
	Holistic, perceptual	Analytic, reflective
<u>Functional characteristics</u>	Associative	Rule based
	Domain specific	Domain general
	Contextualized	Abstract
	Pragmatic	Logical
	Parallel	Sequential
	Stereotypical	Egalitarian
<u>Individual differences</u>	Universal	Heritable
	Independent of IQ	Linked to IQ
	Independent on working memory	Limited by working memory

The idea of dual systems, or at least dual processes, is by now central to most theories in a wide range of fields concerning human cognition, both in low-level tasks like motor skills and high-level tasks like reasoning and judgment (for a review, see Evans, 2008). The existence of two separate modes of processing has also gained some support empirical support from cognitive neuroscience (Evans, 2008; Fellows, 2004; Trepel, Fox, & Poldrack, 2005). Although the idea of competing systems is well established, both the fundamental attributes of these systems and the way they are employed in decision making are fiercely discussed.

Naturalistic decision making. At the time of writing, the world championships of chess just recently finished, with the aging (in chess terminology, at least) champion Viswanathan Anand losing out to the young starlet-turned-star, Magnus Carlsen. It has been pointed out that 22-year-old Carlsen is the first world champion to have had life-long access to high-level chess computers and databases, with combined analytical potential that far exceeds that of the dusty volumes former grand masters have mainly had to use to elaborate their strategies. The upshot of this is that many younger players have been accused of ‘playing machine-like’, using the computer aids to calculate odds, and practice detailed plans for an immense number of scenarios and board positions, and thereby beating older players by sheer procedural quality. Not so with Carlsen, according to former world champion Garry Kasparov, who claimed that “*Carlsen’s greatest chess strength is his remarkable intuitive grasp of simplified positions and his tremendous accuracy in them. (...) Computers have made players of Carlsen’s generation nearly machinelike in their objectivity at the board, so it is a pleasing irony that Carlsen himself is a very intuitive, very “human” player*” (Kasparov, 2013).

This view on the importance of intuition even in a game as analytical as that of chess does not really go well with judgmental decision theory, as the heuristic shortcuts commonly referred to as intuition surely would be the pitfall of the aspiring world champion? The tradition of *naturalistic decision making*, on the other hand, takes a different perspective on the way experts like Carlsen makes decisions in real-life settings.

Experts and expertise. Based on studies of chess players’ decision making (Kahneman & Klein, 2009; Klein, Wolf, Militello, & Zsombok, 1995), Naturalistic Decision Making, or NDM, started with a conference sponsored by the US Army Research Institute in 1989, discussing among other things the impact of the complexity, high stakes, time pressure, uncertainty and ill-defined goals of real-world settings on decision making, and the effect the expertise of the people working in these conditions had on the decision strategies in use (Lipshitz, Klein, Orasanu, & Salas, 2001). Rather typically for developments in the risk and safety community, this was spurred by the 1988 accidental shooting down of an Iranian commercial airline by the US battleship *Vincennes* (Cannon-Bowers & Salas, 1998a; Kahneman & Klein, 2009).

Joining ranks with the likes of Simon, Kahneman and Tversky in dismissing the classical decision-making model (Kahneman & Tversky, 1979; Simon, 1972; Tversky & Kahneman, 1974), the NDM framework took the critique one step further by replacing all of the four defining characteristics of classical decision making with new ones, placing at the center of their analysis what they referred to as the ‘*proficient decision maker*’ (Lipshitz et al.,

2001, p. 334), or *expert*, a professional with an extraordinary level of domain knowledge and experience (Phillips et al., 2004).

This subject matter expert does not make decisions in the way ‘normal’ subjects do in laboratory studies, and the difference starts as early as the option generation phase. Returning to the chess players, studies showed that they by no means consider all available moves when selecting a strategy, but instead generate a satisficing, if not optimal, move very early, and spent the time mentally simulating a small set of acceptable moves before choosing one (Klein et al., 1995; Simon, 1972). Experts have a number of advantages over mere ‘professionals’ when making decisions, as summarized by Phillips, Klein & Sieck (2004):

- Improved *perceptual skills*; especially making fine discriminations,
- Richer and more detailed *mental models*; a broader and deeper understanding of the problem context,
- Increased *pattern repertoire*; ability to recognize and interpret a greater number of, and more complex, patterns of information,
- *Routines*; a wider variety of courses of action and tactics,
- *Declarative knowledge*; more explicit knowledge to support the tacit knowledge (Alavi & Leidner, 2001),
- *Mental simulations*; using the more detailed mental models in superior mental simulations,
- *Anomaly detection*; typically spending more time on monitoring tasks, and being more able to spot ‘garden path’ traps in information,
- Finding *leverage points*; identifying opportunities for decisive action and improvisation through mental simulations,
- Managing *uncertainty*; using different strategies to manage uncertainty, discussed in further detail below, and
- Accounting for own *strengths and limitations*; checking own answers and judging and predicting own performance.

Looking back at the previous section about heuristics and biases, it should not be surprising, in light of the above list, that experts are considered to be more resistant to common decision biases, and so, the NDM view is that the uncertain process of debiasing and developing domain-general decision skills is not a worthwhile strategy for improving real-world decision making by experienced people (Phillips et al., 2004).

Recognition-primed decision making. The recognition-primed decision (RPD) model was based on cognitive task analyses of firefighters by Gary Klein and his associates

(Kahneman & Klein, 2009; Lipshitz et al., 2001), where the researchers expected simple comparisons between a favored and a back-up alternative by the commanders in time-critical situations, by the logic that the constraints on the situation would inhibit commanders from considering the wide range of options that would be expected from laboratory studies in the classical decision making tradition. Instead, researchers were forced to conclude that the experienced fire commanders rarely compared options at all, but instead just relied on their first thought of course of action to produce a satisficing decision, as described by Simon (Lipshitz et al., 2001; Phillips et al., 2004; Simon, 1972).

In the end, three variations of decision making was described in the RPD model:

- The simple variation where the initial option identified becomes the response,
- In unclear situations, story-building is used to mentally simulate what led to the situation, and
- A process of progressive deepening – evaluation of a planned course of action by mental simulation prior to execution.

The two latter strategies are examples of forward-directed reasoning; a trait also found more often in experts than in novices and journeymen, who to a greater degree work backwards from desired goal states (Lipshitz et al., 2001).

Adaptability and uncertainty in decision making. The conclusions from NDM and RPD research carry certain implications for training decision making; if even moderate levels of expertise means that the first option that comes to mind is about equally trustworthy as the end result of a complex analytical process (Klein et al., 1995; Lipshitz et al., 2001; Phillips et al., 2004), why bother learning complex analytical decision strategies? In attempt to reconcile the different takes on decision making held by the HB and the NDM research traditions, Kahneman & Klein (2009) described some characteristics of the decision making context that had significant bearing on the applicability of intuitive decision making.

The decisive situational qualities are the *validity* of the situation – the degree to which situational cues reliably predict an outcome – and the opportunity to *practice* and learn these relevant cues. While routine expertise is an obvious advantage in solving known and clearly defined problems, this static knowledge can be a hindrance for solving emerging and ill-defined challenges, with shifting and incompatible goals (Kozlowski, 1998). Algorithms can be expected to outperform human intuition at both ends of the scale: in low-validity situations where recognition-based decisions become increasingly heuristic, and in very high-validity situations where ceiling effects and attention lapses due to low workload may cause errors (Kahneman & Klein, 2009). High validity does not preclude high uncertainty, though, as seen

in the chess example; if expert intuitions are pattern recognition, a high number of possible, and valid, patterns does not mean the expert chess player cannot use intuitive, pattern-matching skills to handle the uncertainty created by the available moves (Kahneman & Klein, 2009; Klein et al., 1995). Uncertainty, in a RPD frame, affects experts' decision making in three ways; *inadequate understanding*, *lack of information*, and *conflicted alternatives*, issues that need to be addressed properly in order to reach satisfactory decisions (Lipshitz et al., 2001), and do not necessarily lend themselves to recognition-based decision making alone.

The recognition/metacognition model. This conflict between recognition-based “routine” expertise and metacognition-based “problem-solving” expertise is illustrated by models of training like Cohen, Freeman & Thompson’s (1998) *recognition/metacognition model* of decision making, trying to reconcile the main decision process of pattern recognition with problem solving and critical thinking by employing a series of discrete STEPs: Story, Test, Evaluate and Plan.

- In the *Story* phase, the expert tries to make the options generated through recognition available for analysis by constructing a story around it in past, present and future.
- The *Test* involves revising the stories by spotting and correcting gaps, and more experienced decision makers are more prone to seeing that no situation matches the pattern, or indeed any pattern, perfectly, and therefore often report more ambiguity in quick tests than less experienced decision makers.
- The *Evaluate* step means it is time to play the devil’s advocate by assuming an infallible ‘crystal ball’ has said that the story is wrong and an explanation for this needs to be given. This is comparable to the ‘premortem’ strategy employed by Klein (Kahneman & Klein, 2009).
- The final *Plan* step requires the decision maker to find the best available plan should the first option turn out to be wrong (Cohen et al., 1998; Lipshitz et al., 2001).

Metacognition – thinking about thinking, or awareness of one’s own cognitive processes – is regarded to be an important tool not only for learning purposes, but also during actual task performance. Through task-specific training of meta-cognitive skills, the operator could increase his or her ability to assess several aspects of the work at hand, including available decision time, decision biases, error reduction and own performance (Cannon-Bowers & Salas, 1998a).

Macro cognition. From a social psychological perspective, cognition is fundamentally a social process, the individual information processing notwithstanding (Thompson, Levine, & Messick, 1999). With the added use of problem solving teams in high risk industries, such as distributed teams of operators with differing domain expertise working together on joint projects, there is a need for a decision-making program that addresses such teams of experts (Klein et al., 2003; Letsky et al., 2007). One such framework is macrocognition, defined as “*the internalized and externalized high-level mental processes employed by teams to create new knowledge during complex, one-of-a-kind, collaborative problem solving*”(Letsky et al., 2007, p. 2).

Letsky et al. (2007) identified four dynamic stages that successful teams used in order to reach agreement on team decisions. *Knowledge construction* involves setting up the collaboration context, gathering information, and developing individual mental models, as well as building individual and team task knowledge; *collaborative problem solving* means developing viable solutions through team cooperation; *team consensus* is reaching team agreement among the solution alternatives; *outcome evaluation and revision* means analyzing and validating the chosen solution against goal requirements, and deciding when to go back one or two stages to find an alternate solution.

As these stages are dynamic, five major macrocognitive processes are identified, some of which appear sequential and linked to specific stages, others are more global and iterative processes that supersede the defined stages. *Individual knowledge building* includes improving information, knowledge and mental models on an individual level. *Team knowledge building* represents the main point of macrocognition, employing pattern recognition and trend analysis, developing team mental models in a converging activity, recognizing and utilizing expertise, sharing unique knowledge, and reducing uncertainty through a social process aiming to uncover and systematize all the diverse knowledge that the team possesses. *Developing shared problem conceptualization* is an operationalization of the former phase, making information accessible, sharing and transferring knowledge, building common ground and team shared understanding. *Team consensus development* is about making inferences from the shared problem conceptualization by critical thinking, mental simulation, and intuition, and evaluating these options through processes of storyboarding, group discussion and negotiation. Finally, *outcome appraisal* evaluates the fit of the final choice with goal trade-offs, and determines whether to go through with the selected option, to employ re-planning or to iterate another macrocognitive process (Letsky et al., 2007).

The theoretical connection to naturalistic decision making and recognition-primed decisions should be clear, as should the heritage from the recognition/metacognition methods, but what sets macrocognition apart is the attempt to lift the level of analysis from the individual to the team level (Klein et al., 2003). Still a young and relatively under-researched framework, it joins a number of efforts aiming for team-level analyses of workplace factors (e.g. Schaufeli & Taris, 2014), and as such may have a great potential.

Expert decision making and CRM training. Although several preconditions for good decision making may cause the recommendations based of this literature to bleed into all modules, this is mainly about the cognitive skills of situational awareness and decision making.

The novice-expert interval. The definition of expertise differs in the contrasting frameworks of research, and this is an important point in order to apply decision making theory to training recommendations. While the HB approach would use quantitative performance measures to identify expertise in comparison with an optimality criterion, the most common method in NDM research is by peer review (Kahneman & Klein, 2009). It is vital to realize that much of the decision making acumen described by the latter framework is actually founded on the assumption of extraordinary domain expertise, beyond that of the experienced professional (Lipshitz et al., 2001). With this in mind, it stands to reason that a training course designed for novices, journeymen and experts needs to cover more ground than that which is most crucial to domain experts.

Although both timeframes and repetition thresholds have been suggested for expertise or skill mastery, studies have shown that experience does not equal expertise; rather, experts make better use of their experience by employing different learning behaviors, notably; *practicing deliberately, compiling experience banks, diagnostic and timely feedback, and reviewing prior experiences* (Phillips et al., 2004). These are the processes that a training program for building expertise needs to address.

In my judgment, there is no real conflict between training to improve analytical decision-making skills by de-biasing and utilizing explicit knowledge, and that of strengthening expertise and expert decision making. Thus, a two-pronged approach of facilitating the building of expertise and improving analytical decision making, e.g. by use of the STEP framework suggested by the recognition/metacognition model (Cohen et al., 1998) could be a good way to train decision making. While, of course, the STEP framework spans over topics in both the situational awareness (M3) and decision making (M4) modules, the

key CRM modules of individual and shared mental models arguably warrant to be treated as their own topics under Situational Awareness (M3); from a pedagogical point of view, knowledge of mental models could facilitate learning of STEP and macrocognition.

Feedback. Giving and receiving proper feedback is widely regarded as a cornerstone in most training frameworks, and the utility of practice and feedback in order to train specific skills is unquestionable (Kluger & DeNisi, 1996; Phillips et al., 2004; Salas et al., 2001; Salas, Wilson, Burke, & Wightman, 2006). While traditional outcome feedback may not be conducive to learning in complex situations (Phillips et al., 2004), and traditionally is plagued by biases on the instructors' part (Kahneman & Klein, 2009), more process-related forms of feedback like cognitive feedback and process feedback may yield the desired improvement on judgment behaviors and judgment tasks (Phillips et al., 2004; Salas & Cannon-Bowers, 2001).

Also, since any integration of CRM training with on-the-job training requires that the operators are capable to give feedback to each other for effective learning to take place, practicing relevant feedback strategies as a topic under the Communications (M5) module should have positive effects on teamwork.

Macrocognition. While the macrocognition framework is still relatively unproven, the structured way of making decisions in a team certainly has potential for CRM application through practice-based modes of training delivery. However, this may demand a very comprehensive approach where this topic is delivered to all members of a distributed team, and as such not be of much specific use for a local introductory CRM course for participants in several time-constrained ad-hoc teams, as the specific collaborative method would not be employed in the actual work setting. Nevertheless, noting these limitations, using a macrocognition process to structure teamwork in a local, practice-based CRM course is very much in line with recommended course content, and should contribute to strengthening and encouraging good CRM behaviors.

Like the related STEP method, the macrocognition method spans Situational Awareness (M3) and Decision Making (M4), and for the same reason, it is grouped as a decision making topic. Additionally, the team decision making involved requires some negotiation skill, specifically the ability to reach consensus, and this could be a relevant topic for Communication (M5) training.

Critical thinking. As naturalistic decision making, in concert with added focus on the benefits of human performance variability, encourages more space for intuition and System 1-based thinking, knowledge and alertness to the most common pitfalls of intuitive decisions becomes even more important. As experts generally tend to assume expertise also outside

their specialty domains, i.e. they don't change decision strategies, awareness of the human fallacies of forecasting may help them see the use of reverting to a more analytical decision making mode when time allows it, or their understanding of the problem content is lacking.

Knowledge of heuristics and biases, then, along with other forms of metacognitive or critical thinking skills, should be supplied in training, and naturally belong to the Decision Making (M4) module.

Domain Adaptation

The International Space Station and Research in Space

The International Space Station (ISS) is a habitable research laboratory orbiting the Earth at between 330 and 435 km over the surface, serving as a unique microgravity environment - an environment where the effect of gravity is so low that it is mostly negligible, thus enabling researchers to control for the gravity factor in a number of ways. Scientific experiments are being conducted in a number of fields, including physics, biology, meteorology and astronomy. The ISS is a result of an initiative that was conceived as far back as 1984, as a pan-international collaborative effort. Since the arrival of the first crew in October 2000, the space station has been continuously manned by teams of astronauts and cosmonauts from the five participating space agencies: the American National Aeronautics and Space Administration (NASA), the Russian Federal Space Agency (Roscosmos), the Japan Aerospace Exploration Agency (JAXA), the European Space Agency (ESA) and the Canadian Space Agency (CSA), conducting experiments and servicing the space station. The ISS is currently funded until 2024, and may operate until 2028 (Achenbach, 2014; Coelho, Danielsen, & Stene, 2013; Danielsen & Stene, 2013; Fong, 2001).

The mission statement of the ISS program underscores the ambition in this undertaking: *“Safely build, operate, and utilize a permanent human outpost in space through an international partnership of government, industry, and academia to advance exploration of the solar system, scientific research, and enable commerce in space”* (Shireman, 2011).

The Columbus module. In February 2008, the space shuttle Atlantis took off carrying ESA’s ISS module Columbus in its cargo hold, a permanent laboratory for the study of gravitational effects on a range of phenomena (Schirber, 2008). The Columbus laboratory (Figure 6) was built to contain the bulk of the research equipment for the life sciences, like physiology, biology, behavioral science and space medicine, accommodating the racks – standardized



Figure 6: The Columbus module. 1:2 scale model, from the ESA facility in Oberpfaffenhofen, Germany. Photo: Private.

frames for mounting technical equipment modules – for experimental apparatus in combination with NASA’s Human Research Facility (Fong, 2001). Besides the rack, the module contains space for stowage of equipment necessary for the crew to perform experiment activities, but due to the small size of the Columbus module, there is very little redundant space, and stowage needs to be planned carefully. The payloads – the equipment necessary to conduct research – are attached to the rack, and can be seen covering the back wall of the Columbus in Figure 6.

Transporting crew and equipment. Ever since the final flight of the space shuttle Atlantis in July 2011 marked the end of the space shuttle era in American space transportation (Ryba, 2011), means of transporting scientific payloads and exchanging crew members have been mostly limited to the Russian Soyuz capsules atop the Korolev rockets fired from the Bajkonur Cosmodrome in Kazakhstan every six months (Jules, 2010). This six-month interval between Soyuz capsule dockings, the serving time of each shift of crew members, is defined as an increment in ISS terminology, and forms the basis of scheduling and planning of experiments and activities. This picture has changed somewhat in the last few years, as the private American initiative SpaceX – founded by Tesla and PayPal founder Elon Musk – with their Dragon spacecraft has provided additional capability for equipment transfer to and from the ISS, the previous launch as recently as April 18, 2014.

This means that the opportunity to address equipment malfunctions in the course of an experiment is mostly limited to the time and remedies available to the ISS crew at any given time. The upshot of these limitations is first, that extensive ground testing of every piece of equipment that is to be used in an experiment is absolutely necessary; second, that all equipment must comply with ISS standards in order for the crew to be able to interact with it, and third; that the experiment-specific crew training is so far back in time, and so basic, that very detailed procedures need to be made for the crew to be able to execute their actions correctly and timely (Hancock, 2014a; Jules, 2010).

The ground segment. In order to support the astronauts conducting research and maintenance tasks on-board the ISS, a large ground crew working as a multi-agency, multinational distributed team is necessary, creating a support network that spans the globe.

The ESA side. ESA has chosen a decentralized organization to provide ground support for the scientific payloads onboard the ISS, meaning that several geographically dispersed centers are responsible for specific payloads related to their field of expertise. These centers

are named User Support and Operations Centres, or USOCs, for short, and act as a link between the scientific communities and ESA's central Columbus Control Centre (Col-CC) in the south of Germany (Danielsen & Stene, 2013). There are currently seven USOCs across Europe, forming a payload operations network under the overall management of ESA. Each USOC is responsible for their own academic field of study in the Columbus module, consulting with and employing domain expertise in their organizations.

The NASA side. Due to the previously mentioned NASA involvement in the Columbus by the Human Research Center, Columbus operations are not necessarily limited to ESA personnel, but include involvement from the American counterparts at NASA, as some of the technical equipment is located in a NASA-controlled rack. This has some organizational consequences for the operation of the payloads, as the telemetry downloaded to the experiment conductors at the USOC involved passes through the NASA side, the USOC effectively a node in the American network. In these instances, the USOC operators have to comply with NASA, rather than ESA, regulations, and while these are very similar in many ways, other aspects are slightly different, meaning that operators may need to relate to a double set of standards.

The Norwegian User Support Operation Center

The high academic level in the early 1990s of the research group Plant Biocentre Group, working in the field of Space Biology under Professor Tor Henning Iversen, led to the Norwegian University of Science and Technology (NTNU) signing on in 1996 as a sub-contractor to the ESA-controlled development of a modular cultivation system for use in space. This role was continued until the completion and verification of the European Modular Cultivation System (EMCS) (N-USOC, 2006).

This led to the inauguration of the Norwegian User Support and Operations Centre, or N-USOC for short, in April 2006; a control center to support the operations of the EMCS, successfully put in operation aboard NASA's Destiny module on the ISS later the same year. Because of its science pedigree and excellent relations with the industry partners, the Norwegian control center was also designed by ESA as responsible for biological experiments on the ESA Columbus module when it was to be put into service (ESA, 2006; Larsen & Johansen, 2006).

N-USOC project organization. Currently, the N-USOC is organized as a long-term project run and staffed by the Center for Inter-disciplinary Research in Space (CIRiS), a

department of NTNU Social Research, a non-profit research foundation owned 100% by NTNU.

At this time, N-USOC is responsible for two payloads in the Columbus module, which can be remotely monitored and controlled from the designated control center. This responsibility entails many different tasks in different project phases, like integrated planning, testing, training, documenting, coordination with international partners and scientists, and work as console operators. In order to cover these tasks, the members of the project organization are assigned to one or several different roles (see Table 8). These roles are not static over time; there is an established practice of rotating roles across the team members depending on their interests, experience and overall workload (Coelho et al., 2013; Danielsen et al., 2014; N-USOC, 2010, 2013).

Table 8

Defined roles in the N-USOC project (Adapted from N-USOC, 2013)

<u>Role</u>	<u>Area of Responsibility</u>
<u>N-USOC Project Manager</u>	Contractual matters, budget and financial aspects, Point of Contact towards ESA USOC Technical Officer and ESA Contracts Officer, USOC Manager meetings participation, weekly internal progress meetings, Manpower and Activity Plan, Project Progress Report to Customer.
<u>Integration & Operations Manager</u>	Coordination and delivery of all operational products to the program, Generic Operational Procedures, Console coverage plan, Point of Contact towards ESA and NASA planning teams and ESA Project Integration Manager.
<u>Systems Manager</u>	N-USOC ground segment (Computer infrastructure, Networks, H/W and S/W, plan, coordinate and implement systems related tasks, N-USOC Flight H/W and Ground models configurations. Point of Contact towards ESA Payload Engineer Manager and ESA and NASA systems support.
<u>Security Manager</u>	Security systems; physical security and computer security, planning and implementation of security rules and standards, Security maintenance, contracts security requirements, security monitoring and logging, computer access control and authorization.

<u>Training Manager</u>	Coordinate training of new staff, recertification and refresher training of existing personnel. Point of Contact towards NASA SIM Coordinator and ESA USOC Training Coordinator.
<u>Experiment Activity Coordinators (EXAM)</u>	Experiment Integration & Test Schedule, coordinate experiment teams, Experiment design and safety reviews, experiment procedures development, experiment specific documents and tests. Point of Contact towards Principal Investigator-team.
<u>System Engineers</u>	Perform tasks under System Manager responsibilities.
<u>I & O Engineers</u>	Participate in experiment teams. Perform tasks during both Integration and Operation phase of the experiments.

Importantly, the N-USOC project organization is not the same as that of CIRiS, although most of the CIRiS staff are also N-USOC project team members (Danielsen et al., 2014; N-USOC, 2013). Although roles are rotated to a certain degree, this is not to say that the N-USOC team members are completely interchangeable in their contributions to the project. The team members come from different academic backgrounds, such as computer science, biology, physics, mathematics, psychology and sociology, and some of the core competencies are not readily replaceable, making the organization vulnerable to short- or long-term loss of their specific skills. In this scenario, the optimal utilization of the remaining resources would be very important.

N-USOC payloads. While both of the payloads assigned to N-USOC are important parts of the daily tasks and routines for N-USOC personnel, the most demanding and complex payload in terms of team collaboration and safety is the aforementioned EMCS, and this will be the main focus of analysis. Therefore, the second payload, named Vessel ID, will be described rather cursorily, while the EMCS payload will be described in more detail.

Vessel ID. The Vessel ID system monitors ship traffic from space through reception of Automated Identification System (AIS) messages containing information about several ship characteristics like position, heading, identity, and speed from an antenna mounted on the Columbus module. Monitoring ship traffic from the ISS gives access to a much larger area than ground antennas; the ISS orbit allowing coverage of the area between the latitudes of 67 degrees north and south. This project, also called the Columbus based AIS, is a joint venture between ESA and the Norwegian Defense Research Establishment (FFI), the day-to-day operation of which is monitored and controlled by the N-USOC project organization (Olsen & Eriksen, 2012).

The EMCS. Still the core of N-USOC activity, the European Modular Cultivation System, then, is an experiment facility that is designed for controlling atmospheric, gas and fluid exchange, light and gravity variables for microbiological investigations in up to eight experiment-unique cultivation chamber units. These are mounted on two separate rotors that enable scientists, through operator and crew involvement, to manipulate the factor of g between values very close to zero, called microgravity, and about 2 g. The EMCS provides both life support and observation capability for each of the experiment units.

The cultivation chambers are designed specifically and optimally for each experiment, depending on what the scientific goals and control variables are. Together, the EMCS and the experiment-unique equipment provide a unique capability for researching a wealth of topics in plant growth that is not feasible in facilities on Earth (Hancock, 2014a; Olsen & Eriksen, 2012).

There are currently two identical EMCS facilities to be found anywhere; the flight model located in the ISS (Figure 7), where the actual experiments take place, and the engineering model located adjacent to the N-USOC control center, where simulations and rigorous testing is done before each and any experiment is conducted in the flight model.



Figure 7: The EMCS. The flight module, right, mounted on a rack in the Columbus module (From Hancock, 2014a).

The EMCS is designed to fit the NASA-controlled express rack in the Columbus module, and as such, the operators involved in the monitoring and control of EMCS experiments function mainly as part of a NASA team. The main point of contact in the NASA organization is the Payload Operations and Integration Centre (POIC) in Huntsville, Alabama. Depending on the specific experiment-unique equipment that is to be used, the manufacturer is also regarded as a main contact point; mostly Airbus in Germany or the NASA-Ames research facility. Also part of the virtual project team at any time are the supervising controllers of NASA in Houston and ESA in Oberpfaffenhofen, Germany (Hauan, 2014a).

The duration of the actual experiment execution varies with the specific experiment content, but for the upcoming Gravi2 experiment, for example, five to six years of integration

and planning was needed to facilitate 4 days of experiment execution. This serves to underscore the importance and dominance of the integration and planning activities in the day-to-day activity of the N-USOC project, but also increases the stakes in the actual experiment execution (Mohammad, 2014a).

Preparation, integration and planning. As mentioned earlier, the planning and integration phase of the EMCS experiments is the part of the experiment activities that takes the lion's share of the time and energy of the project team. The process of taking the experiment from the early definition phase to the final execution phase is described as multi-phasic, multi-actor and non-linear, involving many stakeholders in different domains and agencies. N-USOC personnel is involved to a varying degree in every part of the process (Mohammad, 2014a).

Put simply, this process is about translating the wishes and requirements of the scientist(s) that were selected to perform their research project in the EMCS (dubbed the Principal Investigator, or PI) to the other stakeholders in the experiments, like the engineers designing and adapting equipment, the operators controlling and monitoring the experiments, the onboard crew performing the necessary handling, and the large team of system engineers designing procedures and parameters to make this complex system work. Also, vice versa, the constraints and boundaries given by the system need to be communicated to the principal investigator so that adaptations can be made to the scientific methodology (Jules, 2010; Mohammad, 2014a).

Levels of Risk and Science Mission Success. The European Cooperation for Space Standardization (ECSS) defines and develops the current set of standards for all participants in European space activities, and their definitions of dependability and safety thus provide direction for any intervention aiming to improve these areas. The ECSS, then, has defined four distinct levels of risk for ESA operations (Table 9) (Coelho et al., 2013).

Table 9

ESA risk categories (Adapted from Coelho et al., 2013).

<u>Severity</u>	<u>Level</u>	<u>Dependability</u>	<u>Safety</u>
Catastrophic	1	Failures propagation	Loss of life, life-threatening or permanently disabling injury or occupational illness; Loss of system; Loss of an interfacing manned flight system; Loss of launch site facilities; Severe detrimental environmental effects.
Critical	2	Loss of mission	Temporarily disabling but not life-threatening injury, or temporary occupational illness; Major damage to interfacing flight system; Major damage to ground facilities; Major damage to public or private property; Major detrimental environmental effects.
Major	3	Major mission degradation	---
Minor/negligible	4	Minor mission degradation or any other effect	---

NOTE: When several categories can be applied to the system or system component, the highest severity takes priority.

The experiments conducted at N-USOC are seldom assigned risk levels in the catastrophic or critical range, meaning that the focus of the operators in N-USOC missions is mostly to prevent loss of science. The upcoming “Gravi2” experiment, though, marks a step towards both higher complexity and higher risk, as the use of a toxic fixative to preserve the biological samples in desired states of growth awaiting space-to-ground transport has led to a level 2, or critical, risk assessment for the experiment. Moreover, because this operation requires use of another biology facility on-board the ISS, interaction and integration with another USOC is required to plan and conduct the experiment (Stene et al., 2014).

In order to cope with the workload and complexity, and reduce the risk of miscommunication and manual error, an operations support concept has been implemented for

this experiment that divides Gravi2-related control room tasks between two geographically collocated N-USOC operators (Mohammad, Johansen, & Almklov, 2014; Stene et al., 2014). While this is probably a necessary step for adequate workload management, it does add complexity to the teamwork situation, increasing demand for teamwork aspects to be addressed in training.

N-USOC tasks and tools.

The voicelink tool. The main tool used for communication between nodes in this distributed, ad-hoc team consists of an earpiece with a microphone, and a screen that enables the operator to choose to communicate on single loops with one or more other operators, and to listen in on several loops in parallel. The touchscreen allows operators to choose relevant loops to be visible in the display, and will show any communication between other nodes with indicator lights. This voicelink system, employed in such areas as air traffic control and the shuttle missions of old, is a good direct communication tool as it gives operators the power to contact any relevant node in the network at any given time if need be. This mode of communication is at the heart of the strict and coherent communication procedures surrounding ISS, and indeed space, operations in general (Danielsen, 2014; Hauan, 2014a).

The true power, though, lies in its potential for contributing to situational awareness by giving an overview of the goings-on of the system without taxing the operator in his or her tasks (Patterson, Watts-Perotti, & Woods, 1999). By discriminately selecting relevant loops to monitor in the event of a system disturbance or off-nominal situation, the operator may gain important insights to specific causes and impacts located in other parts of the system, and a more global sense of the strain on the system may be gained by simply watching the voicelink screen for sudden spikes in activity (Patterson et al., 1999).

Graphical user interfaces. Ground segment operators use a range of context- and equipment-specific computerized tools that allow simultaneous monitoring of a host of parameters, describing both general system states and equipment-specific values, a few of which will be described here.

The main tool used by N-USOC operators during EMCS experiments is the “EMCS Displays” tool. This provides a graphical representation of the key indicators of the flight model EMCS, over a number of thematically arranged information windows that are, typically, spread over the three large computer screens available to the N-USOC operator. A system of color codes indicate key states for parameters, such as ON/OFF, Loss of signal, or a threshold violation for a specific variable, facilitating anomaly detection for the operator.

Although the EMCS Displays tool is very flexible, allowing the operator to select his or her own configuration of open windows – and even including an alphanumerical view of many simultaneous indicators for expert use – there is a strong sense of agreement over which windows go where in the N-USOC control room. This is important for other team members to be able to support console personnel easily upon request (Hancock, 2014b).

Another tool that is used by all involved parties in the distributed team surrounding ISS operations is the On-Board Short-Term Plan Viewer, or OSTPV. This is a real-time timeline that shows any planned crew (astronaut) activity on-board the ISS, including mundane activities like eating or sleeping. The working days of ISS crew are planned down to the last detail, and the OSTPV contributes to the situational awareness of the ground support personnel by showing who does what at any point. This is also a source of redundancy in off-nominal situations; the OSTPV can theoretically be used to re-plan in unexpected circumstances, ensuring that planned crew activities can be completed. Realistically, there is usually no such redundancy on short notice, and so the OSTPV is mostly used for planning and re-planning in the long and medium term (Danielsen, 2014).

Cognitive tasks. The main responsibility of N-USOC personnel consists of monitoring the parameters of the EMCS and the telemetry, making sure the equipment works nominally throughout the experiment cycle, and that all collected data is being transferred and stored correctly from space to ground (Hauan, 2014a). Aside from that, the operation requires the operators to perform some routine tasks connected to the experiment, and to stand by in the event of off-nominal, unexpected events arising from the experiment execution or from the surroundings. There are various examples of such critical incidents leading to an unexpected need for operator involvement, joining the distributed team in order to find and perform a work-around.

Technical tasks. Although the main role of the N-USOC operator is acting as a node in a distributed network, employing cognitive skills and equipment expertise to aid the experiment execution, there is also a hands-on technical side to the operation at the local level, with equipment designed for retrieving and storing data. While intimate knowledge of the local technical systems is not required by all operators, principal knowledge of the role these systems play in the N-USOC operation is.

For simple local actions, then, all operators should know the basics of the technical systems, but the domain experts state that they would like to be kept in the loop when such actions are to be performed, and consulted for more complicated procedures (Hauan, 2014a).

N-USOC operator training. Due to the small size of the N-USOC organization, the console personnel during experiments are not full-time, dedicated operators, rather the console duties are part of the job descriptions of most of the scientists and technical personnel employed by CIRiS. As these employees have very different fields of academic expertise, console operations need to be taught as a specific skill, and trainees need to complete one or more training courses to be considered certified operators by NASA and ESA. Danielsen & Stene (2013) compiled a list of the required knowledge and skills trainees need to acquire in order to be formally certified N-USOC operators (Table 10).

Table 10

Required knowledge for N-USOC operators (Adapted from Danielsen & Stene, 2013).

<u>Topic</u>	<u>Content</u>
Payload knowledge	Technical, operational and scientific knowledge that pertains to specific payloads.
Display knowledge	Monitor and understand the information in the computer displays that show telemetry from the payload.
Handling digital and auditory tools	Use the different operations support tools efficiently and correctly.
Procedure knowledge	Follow the established rules in the operations environment, voice loop protocol, flight rules and formal procedures.
Planning	Understand the information in the Onboard Short Term Plan Viewer that displays the real-time plan for the ISS, and be able to plan and re-plan.
Anomaly handling	Be able to handle anomalies and unforeseen events, knowledge about ESA and NASA anomaly reporting systems, previous anomaly signatures, and involving appropriate engineering support.
Communication	Be able to communicate well with the distributed team; other control centers, engineering support and scientists.
Situational awareness	Awareness and understanding of the operational

	situation in the distributed team.
Workload and stress	Be able to multitask and handle stressful situations.

Internal training. In order to achieve these goals, new console personnel need to complete a dedicated training program of eight modules, starting with the background of ISS and N-USOC, and ending with a final multi-actor and cross-agency certification simulation. The N-USOC training manager monitors the progress of the trainee in the course of the training program, and a pass/fail grade is given after the final simulation (Danielsen & Stene, 2013).

The operator training course is inspired by what NASA refers to as ‘the art and science of systems engineering’ (Mohammad, 2014a), which was compiled in a monograph by Ryschkewitsch, Schaible & Larson (2009). The systems engineer must combine a high level of technical proficiency and understanding with the non-technical team qualities of leadership, communication, and planning in a complex, multidisciplinary setting. These behavioral characteristics need to be adopted by the systems engineer through all project phases; design, planning, operation and evaluation (Ryschkewitsch et al., 2009).

Experiment-specific training. Prior to each experiment, the involved actors of all affected organizations and agencies need to go through payload-specific training in order to be optimally prepared for the real-time event. These NASA-controlled simulator training sessions, called Joint Multi-Segment Training (JMST), are designed to cover routine operations – a walk-through of the planned execution starring all actors – but they also require operators to handle off-nominal situations: deviations from normal procedures somewhere in the collaborated team effort, and assess and address the eventual impact for their specific payload. Vice versa, operators may also need to assess the impact an off-nominal situation in their payload may have on the operation of other parts of the network. For some of the participants, these training sessions serve as the certification step of operator training, and so, there is bound to be some complications added to the simulation ‘script’ (Stene et al., 2014).

This is an important opportunity for the trainees to practice the skills of problem solving and situational awareness in a safe environment, yet having a realistic and lifelike experience (Coelho et al., 2013), but the effect of training is reduced somewhat by the arising complications being mainly known and previously encountered errors uncovered through NASA’s Payload Anomaly Reports, or PARs. A report has to be submitted every time an off-nominal situation is encountered during experiments or testing, and the recurring or unsolved

issues are used to create “What-if”-scenarios that are brought to the attention of operators in experiment preparations, and used in simulator sessions.

There is a danger that these ‘known dangers’ may cause the operators to lock on to these specific errors, ignoring new and unexpected situations if they should arise due to too much attention being spent monitoring for the expected “what ifs” (Pariès, 2011b).

A call for CRM training. While the current operator training gives a thorough overview of the technical and functional aspects of the operator role, the training does not really cover enough ground on the desired non-technical behaviors that contribute to the ‘art’ of systems engineering, in NASA terminology.

Also, the team dynamics of the N-USOC project organization and its regular partners may be subject to change. The first ‘generation’ of N-USOC team members had been in the organization since the start-up, and had contributed to the development of both the technical systems and the collaboration procedures they were supposed to mind. The familiarity within the small group of operators, and with their counterparts at the equipment manufacturers and at the two space agencies was a main success factor in the early years, along with a highly motivated young group. While this in many ways still is the case, there is some concern that the collaborations will not be as smooth when key personnel is changed both in-house and in the connected organizations.

Human Dependability in the Space Domain

There is not a lot of published work on the human contribution to safety, or indeed safety-related crew training, from the space domain, despite the fact that both of the major Western space agencies, at least, have adopted Crew Resource Management-inspired training programs for some of the involved interfaces (Rogers et al., 2002; Stene et al., 2013). NASA’s Space Flight Resource Management is now required for all ISS control room operators, but the benefits of this training is not offered to the more peripheral nodes of the network, like Payload Developers (Kanki et al., 2010). There is some evidence that this should be addressed.

The HuDeM project. The Human Dependability Model (HuDeM) project, a collaborative effort between NTNU Social Research, the research foundation SINTEF and the ESA safety contractor Argotec conducted in the course of 2012 and 2013, analyzed the User Support and Operations Centers in particular, and N-USOC in particular, with an aim of developing a human dependability model for space operations (Johnsen et al., 2013). In doing

so, both quantitative and qualitative research was conducted both on the blunt and the sharp end, some of the conclusions of which are informative to this study.

The first activity carried out in the HuDeM project was a survey, designed for the *"identification, survey and evaluation of the most meaningful domains for deriving a consistent human dependability model applicable to space projects and activities"* (Johnsen et al., 2013, p. 82). Using 11 root causes of human error derived from existing anomaly reports as a basis, the 'state-of-the-art' survey was designed by Argotec to validate these root causes. The survey consisted of 23 main questions, some of which had sub-questions, in total 94 items rated mostly on a 6-point Likert scale, and was submitted electronically to operators with at least one increment (6 months) of on-console experience. Additionally, some interviews with astronauts were conducted in order to gain a different perspective. The survey uncovered a list of 6 validated root causes of human error in ISS operations (Johnsen et al., 2013):

- *Workload due to parallel tasks*; both in the general sense and specifically due to cross-talk on the voice loops.
- *Simple, repetitious tasks*; following procedures closely leads to lack of situational awareness.
- *Lack of domain knowledge on support systems*; Activities that impact other systems reveal problems sharing information across domains.
- *Long hours, similarity in the tasks or distractions in the environment*; Too short breaks and teleconferences are reported as key causes.
- *Lack of team support*; Many operators report that support is not available to them on console, leading among other things to cross-talk.
- *Procedures*; astronauts reported inability to read procedures and perform activities at the same time.

This list of concerns was, at least for the purposes of this study, replicated in a subsequent workshop with N-USOC personnel, prioritizing and elaborating key safety issues in the local context (Ophof et al., 2013). In response to this and other aspects, one of the recommendations from the HuDeM project was that the N-USOC operators should be subjected to the same non-technical training course along the lines of Crew Resource Management that ESA astronauts and control room personnel employ (Rogers et al., 2002; Stene et al., 2013). This call has subsequently been repeated in several articles analyzing different aspects of the N-USOC organization (Coelho et al., 2013; Danielsen & Stene, 2013; Danielsen et al., 2014).

Problem solving for NASA control room operators. In a rare, domain relevant study of control room personnel in the space domain, Martin, O’Keefe, Schmidt, Barshi & Mauro (2012) underlined the need for expanding the toolkit of decision making strategies in use by the heavily procedure-based and time-constrained NASA organization, recognizing that no one decision making strategy works for all instances and all levels of skill. In their aptly named article “Houston, We Have a Problem Solving Method for Training”, they identified six key problem solving skills used by NASA control room operators (Martin et al., 2012, p. 60):

- Recognizing and confirming the situation
- Determining indirect and direct impacts to the system, vehicle, crew and mission
- Determining time constraints
- Determining goals
- Developing and evaluating options
- Planning and implementing a plan.

These key skills were used to create a verbal description and a rather complicated flowchart model of the decision making process, called Solving Problems In Complex Environment, or SPICE. While this chart arguably does not really address the question of rule-based versus intuitive problem solving, and might be wrongly construed as normative by users in training – a point the authors concede themselves – it also led to a list of 17 relevant questions that could aid decision making for ISS control room operators, grouped in the same way existing NASA communication practices recommend for transferring relevant information across interfaces (Table 11).

Table 11

The '17 questions' (Adapted from Martin et al., 2012, p. 64).

<u>Group</u>	<u>No.</u>	<u>Question</u>
Failure	1	Can you recognize and (dis)confirm the failure?
Impact	2	Any immediate crew actions required for safety?
	3	What functionality/capability has been affected?
	4	What are the immediate impacts?
	5	What are the near-future impacts?

	6	What are the times to effect?
	7	What are the critical circumstances?
	8	How have you checked your assessment?
	9	What is your immediate goal?
Workarounds	10	Is there an existing course of action?
	11	What are the options?
	12	What are the risks of each option?
	13	What are the benefit/cost/risk trades?
	14	What is your contingency plan?
	15	What is your plan of action?
	16	How have you checked your plan?
	17	What is your next goal?

The basic principles of this approach should be well known to N-USOC operators as tacit knowledge, but explicating this approach through training may aid the distributed teamwork as well as the individual decision making by adding to the sharedness of mental models across organizations.

Contextual Evidence

Advocate for science success. As the ESA definition of risk levels clearly states, the success or failure of the various scientific endeavors are actually regarded as a safety concern, albeit low-level (Coelho et al., 2013), which is not surprising, taking into consideration the mission statement's focus on science. With the risk levels of EMCS experiments rarely tipping the fourth level of risk, science mission success usually becomes the main safety-related focus of N-USOC operations. This has some implications for the skills required of the operators, one of which is communication-based. With the principal investigators reduced to a consulting capacity, the N-USOC operator may be the only member of the distributed experiment team that has science success as the highest priority.

The classic CRM module of assertiveness, then, could be a helpful tool in order to protect the interests of science mission success against marginalization from higher-order decision makers with more abstract concerns and procedures to follow. Skillfully advocating the case of prioritizing the on-going science mission could prove useful in the long run. For this reason, the specific skill of issue selling should be addressed along with the trait of assertiveness in the Communication (M5) module.

Utilizing domain expertise. As noted by the aforementioned survey of ISS operators, a lack of domain expertise on unfamiliar systems could pose a rare, but serious threat to safety, and contribute to anomalies taking place (Johnsen et al., 2013). As the wealth of specific knowledge required for a deep understanding of all aspects of the experiment execution makes such unrealistic to achieve, systematically consulting with domain expertise throughout the process is crucial to decision making in the face of off-nominal events. It is also a question of uncovering hidden knowledge within the team; knowing who knows what. The workshop with N-USOC staff from the same project revealed some uncertainty regarding when and how to utilize such expertise (Ophof et al., 2013), a concern that needs dealing with both on an organizational and a teamwork level. The teamwork (M1) processes of mutual performance monitoring and backup behaviors could be helpful for local console support, while processes of self-monitoring under Personal limitations (M6) may be useful for early identification of such demand. In addition, the positive action of actively seeking and utilizing domain expertise could be addressed as a training objective in its own right under Teamwork (M1).

Taking advantage of groupware. The voice-link tool is a powerful aid for situational awareness, and the ways in which this tool can be optimally utilized should be made explicit and subsequently internalized through training. In unison with the communication protocol that follows the technology, and is already taught in operator training, this tool provides a basis for good monitoring and communication practices in the control room. While already addressed in technical training, this should also be clarified and reinforced in the Communication (M5) module of CRM training, focusing on the clarity and timing required to follow protocol, and explicating the benefits of the closed-loop nature of the recommended interchanges.

Standard Operating Procedures. The space domain is very proceduralized, putting a lot of effort into discovering and systematizing past events in order to optimize these procedures. N-USOC operators face a host of these SOPs every day, and for the most part, they are very helpful for safe operations, and a vital part of both ESA and NASA's safety management systems. This explicit knowledge is important both for situational awareness (M3) and for leadership skills (M2), as managing the flexibility trade-off between the expected and unexpected is important for both functions.

SPICE. While the decision flowchart of the SPICE model does not really bring any new information on the table for the purposes of this thesis, the 17 questions recommended by the model may be very useful and domain-relevant for the operators, and could aid the

development of good analytical decision skills as they lend themselves well to practice-based training of decision making (M4).

Planning. Space activities are plagued by the inertia of risk – the time elapsed between action and consequences – and the immense planning that is needed in order to prepare for an experiment therefore needs to pay close attention to detail, especially the issues of sequencing and timing, as ISS operations are extremely time-pressured (Mohammad, 2014b). On a local level, the planning of available resources for the operator: decision support, redundancy or workload sharing, is important for good CRM behaviors and mission success. These issues need to be covered as a leadership (M2) issue in training.

Overload. The very cyclical nature of the workload in the control room outside and during experiment execution poses a few challenges to team and project performance. Workload issues are widely reported in control room work (Flin et al., 2008), and are also highly rated by operators in the space domain (Johnsen et al., 2013; Ophof et al., 2013). The small N-USOC organization makes them especially vulnerable to large increases in workload, or unplanned short-term staffing problems, the consequences being that the shifts in the control room may be substantially longer than planned or recommended (Stene et al., 2013). While this is obviously a case for organizational level change, the effects of stress and fatigue can be somewhat ameliorated by CRM training in the Personal Limitations (M6) category, as well Teamwork (M1) topics.

Also connected to an overload issue is the risk of being overwhelmed by the complexity of the domain when monitoring or problem solving during operations, the working memory capacity being depleted. This cognitive overload is also an issue that can be addressed through CRM training, by self-monitoring skills in the individual (M6), and team support skills on the part of the team members (M1).

Underload. While not as widely studied as the overload threat, underload and its effects on attention has been identified as a root cause of anomalies (Johnsen et al., 2013; Ophof et al., 2013), the heavy focus on procedures in the domain exposing the operators to a host of simple, repetitive tasks. Addressing the dangers of boredom and attention lapses, as well as the virtues and costs of vigilance, in CRM training under Personal Limitation (M6) may help give operators awareness of the issue, and possibly introduce some helpful tools.

Results & Discussion

Stand-Alone Initial Course

Although much is written about the benefits of integrating training into the every-day activities of work and existing training, as this would be the first introduction to CRM training for N-USOC, it should be taught as a separate, stand-alone course (Flin et al., 2014). This is desirable for two reasons; first, it is an easy way to emphasize the importance of non-technical skills, second, the very process of full participation with all members of the small organization should be conducive to good CRM behaviors by building common ground. Considering the latter statement, as far as realistically possible, the initial CRM course should be mandatory for all team members, and later for any new additions to the team. The course is conceived as a three-day course of about 8 hours each; Flin et al. (2014) recommend a minimum of two days, but the intent to employ practice-based delivery modes for much of the training had led me to conclude that another day is necessary.

Final CRM Modules

The following 41 CRM training objectives, divided by 14 topics as described throughout this thesis, were finally prioritized as part of the first prototype of crew resource management training for the N-USOC control room operators. In line with the recommendations for initial course delivery, and adjusting for delivery modes, they are presented as three working days. As the helpful numbers in front of the module titles illuminate, the ordering of the topics has been moved around a bit for practical reasons, so that, for example, the most simulation-relevant topics are presented in the same sitting, and the ‘defining margins’ topic is presented before managing margins is addressed in the next sitting.

Table 12

Day 1: Leading self and monitoring others (4 hours)

M2: Leadership		M6: Personal Limitations	
<u>Coordination</u>	<u>SOPs</u>	<u>Overload</u>	<u>Underload</u>
Sequencing and timing	Flexibility	Stress	Boredom

Redundancy	Reporting	Fatigue	Attention lapses
Resource management	<u>Risk management</u>	Cognitive overload	Vigilance
Knowledge management	Defining margins		

The first day of training (Table 12) contains mainly classroom-based modules, and as such place little demand for training supplies. The main mode of delivery is probably an individual, information-based approach, aiming to produce knowledge and attitude effects, although group discussion is desirable and exercises a possible option. It is also, due to its lecture style, the shortest of the three course days; therefore it is well suited to be combined with a general introduction to Crew resource management as the first part of the course.

Table 13

Day 2: Cognitive skills (8 hours)

M3: Situational Awareness		M4: Decision Making	
<u>Anticipation</u>	<u>Monitoring</u>	<u>Evaluating options</u>	<u>Responding</u>
Tight coupling	Leading indicators	Heuristics and biases	Graceful recovery
Complexity	Lagging indicators	STEP	Sacrificial decisions
Explicit knowledge	<u>Sensemaking</u>	Macro cognition	Loosen couplings
	Individual mental models	SPICE	Reduce complexity
	Shared mental models		

The second day of training (Table 13) involves a lot of cognitive work, most likely delivered as a mixture of an information-based approach and a practice-based approach. The use of scenarios is recommended especially for decision making training, individual and group exercises are a must, and simulator use is an option. This course day is much more resource demanding, as a lot of work needs to be put into developing credible and pedagogic scenarios.

Table 14

Day 3: Positive team behaviors (8 hours)

M1: Teamwork		M5: Communication	
<u>Teamwork</u>	<u>Support</u>	<u>Skills & Practices</u>	<u>Negotiation</u>
Mutual performance monitoring	Utilizing domain expertise	Voicelink protocol	Assertiveness
Backup behaviors	Considering others	Timing	Advocacy
Role clarity		Closed-loop	Consensus seeking
		Feedback	

The third day of training (Table 14) addresses the social elements of team collaboration, and consists mainly of team-based, rather than individually based, learning.

Recurrent Refiller

Although an initial course of CRM training does produce positive effects for a while, the attitudes, knowledge and skills need to be continuously reinforced and practiced at regular intervals for this explicit knowledge to be internalized into the tacit routines of the team. Refiller training sessions of a more limited scope are regarded as necessary, although the recommended frequency of refiller trainings is very variable. From an expertise building point of view, though, the general recommendation is to choose shorter, more specific courses more often rather than comprehensive courses more rarely (Phillips et al., 2004).

The current low frequency of experiments, combined with the access to the Engineering Model of the EMCS and simulation equipment makes more frequent simulations a good candidate as the main medium for refresher training, at least from a purely learning point of view, as simulation is regarded to have positive effects on building expertise. From a resource perspective, of course, arranging for designated simulator sessions is a more challenging undertaking, and so the prospect of building training into the predictable low-workload periods in the control room should be seriously considered.

Simulations

Real-World Context. One of the basic tenets of naturalistic decision making is that the decision cannot be taken out of the real-world context in which it is embedded. This

carries some implications for training decision making, favoring practice-based interventions such as exercise- and simulation-based training set as closely as possible to the real-world work context (Cannon-Bowers & Salas, 1998a). Training for a simplistic view of the operational context may even do more harm than good, from a resilience perspective. The way many simulation training courses have been undertaken, the possible adverse situations are anticipated to the point of being pre-briefed (not a new situation for N-USOC), thus effectively eliminating several important real-world skills, like risk assessment, margin management, and decision mode switching from training, but also cognitively ‘closing the mind’ to the occurrence of unplanned system behaviors (Pariès, 2011a).

Scenario development. This means that more effort needs to be put into developing credible, challenging and unexpected scenarios for problem-solving and simulator use, both in a stand-alone CRM course and in on-the-job training. Using the STEP framework to practice scenario-based decision making is not only a good way to practice judgment techniques, but also an excellent generator of hypothetical scenarios and what-if situations, as the domain expert operator generates solutions, backup solutions, stories and devil’s advocate counterarguments. This, of course, would demand a structured approach to documenting and information-gathering during training sessions; e.g. by “stream-of-consciousness”-type running commentary from trainees collected and analyzed in order to improve and generate training scenarios. In the event that more frequent simulator training is a viable option for operator training and refiller practice, using this kind of information to create variety in the simulated scenarios and generate pattern repertoires in the operators could prove very valuable. Operators need to be exposed to the uncertainty of the real-world setting if CRM training is to address uncertainty management.

Differentiating Training

Already a major issue in CRM training design, and one which only gets more salient with increasingly multidisciplinary teams, such as that of N-USOC, and increasing importance of the domain expertise of the trainee, is the differentiation of training. Two dimensions are identified for differentiation: team versus individual orientation, and expert versus beginner.

Team perspective. There are a number of reasons to put a special focus on the team aspects of operator training, rather than the individual non-technical ability of each operator. As the environment grows more complex, and the safety envelope gets constrained by the

various trade-offs, taking advantage of the added response variety of the controller team will at some point become necessary for sustaining safe operations. As work in high-risk industries progresses on identifying and synthesizing sets of indicators, the number of available cues may become too large to be comprehended by the pattern recognition skills of a single expert.

This is not to say, however, that the individual perspective of CRM training should be abandoned. Successful team training rests on individual training, too (Kozlowski, 1998), and individual team skill and attitude learning is surely helpful as a foundation for effective team-based learning.

Training for experts vs. training for new recruits. There is arguably a sort of balance point where the level of expertise is high enough that using expert heuristic strategies in decision making leads to higher instead of lower human dependability, whether this is on a continuum or exhibiting threshold behavior, cf. Kahneman & Klein's (Kahneman & Klein, 2009) discussions of the level of complexity. Given the infrequency of experiments and simulations: is it at all feasible to maintain a level of expertise in all the operators over this theoretical balance point? Should CRM training be delivered in two or more separate courses, depending on operator experience?

This need is partly addressed through the pragmatic inclusion of both analytic and heuristic elements in decision making. It is safe to say that not all operators would regard themselves as experts in the 'Klein-ian' definition (Phillips et al., 2004), mostly due to lack of practice, and the view of training decision making in a CRM course, then, needs to address both the fast, expert ways of the most experienced operators and the more analytical needs of the less experienced. The meta-cognitive process of knowing when to do what should be accentuated. The N-USOC organization is small, too small to warrant the development of two separate CRM courses, and anyway this would compromise some of the teamwork improving potential of an integrated, all-hands approach.

Other control centers, even in the space domain, have integrated simulations as part of their daily routine for full-time operators. Even if this may seem optimistic with regard to available resources – both personnel and financial – a limited scale and recurrence integrated training simulation is not a complete impossibility.

Evaluating CRM Training

A major challenge for CRM practitioners is the evaluation of CRM training, as the effectiveness of the training courses are frequently hard to verify sufficiently. A proposed

framework for evaluating training is that of Kirkpatrick, specifying four levels that needs to be addressed in evaluations; attitudes, knowledge, skills and organization (Salas et al., 2001; Salas, Wilson, Burke, & Wightman, 2006). For a domain with established models of CRM training, tools for the evaluation of the first three levels are generally well developed. Taking aviation, again, as an example, the attitudinal dimension is usually measured by a questionnaire such as the Cockpit Management Attitudes Questionnaire (CMAQ) developed by Helmreich (Helmreich, 1984, in Gregorich, Helmreich, & Wilhelm, 1990). Knowledge, in Kirkpatrick's definition, is quite simply measured by a written test, while the behavioral level requires the development of a behavioral marker tool such as NOTECHS (Flin et al., 2003). The organizational level poses something of a challenge even in aviation, as the number of yearly accidents and incidents is just not big enough to accommodate quantitative analysis – a “problem” aviation shares with other high-reliability industries. Incident reporting has been suggested as a proxy for accidents; however this potentially ignores the reason why the incident did not turn out an accident (Cox & Flin, 1998). This remains a source of uncertainty, and a potentially fatal one for the implementation of CRM training, as the organizational impact is just what tends to lead to financing.

In a new domain like this one, the wish to perform a pre- and post-test to validate CRM training from the start poses something of a chicken-and-egg problem, as the process of developing training for all intents and purposes is the very process needed to obtain data for developing or adapting valid scales of attitudes, knowledge and behavior. Still this speaks for the preservation of the knowledge gained in adapting the framework and performing crew training for later use in evaluating training outcomes.

Limitations of the Study

Some limitations of this study will be discussed, regarding the validity of the work performed. In a sense, with the premium that is put on context specificity in CRM training design, the discussion of transferability is close to meaningless at this point – halfway through the development of a CRM course – and so validity will be the topic of interest here.

Bias and preconceptions. There are two confessions I would like to make that pertain to the validity of this work. First: in the course of my stay with this small organization, I have become personally acquainted to some degree with all of its members, interacting with them every day and so I cannot say with any sort of certainty that this absolutely does not unduly affect my conclusion. Second: when I started this research project in August 2013, I

had already written a shorter report on distributed teams and CRM training, which was what initially awoke my interest in the topic; therefore I cannot claim to have adhered to what some qualitative researchers refer to as *epoché*, being a pre-conception-free ‘blank slate’ prior to entering the research setting.

While these are certainly limitations that are worthy of mention, I have a few points to make to defend my scientific honor. The question is really an epistemological one, regarding the validity of action research. Starting with the second question, regarding the question of preconceptions; in an action research framework, a broad pre-understanding is not only acceptable, but required to perform research, as a necessary precondition to understand and externalize the tacit dimension of the knowledge elicited (Coughlan & Coughlan, 2002; Nonaka, 1994).

The first question is another matter altogether, as the reason why a participant observer, with no pretense of being unbiased beyond the level which can be accomplished simply by critical thinking, can produce valid interpretations of the knowledge gained in the socializing process is by repeated cycles of member evaluations and analyses until theoretical saturation is achieved (Coughlan & Coughlan, 2002). While member checks of my suppositions about the context have been supplied, the scope of my work with regard to the final result has prevented me from obtaining the cycles of evaluation that would make my findings more credible.

In other words, the prototypical phase of CRM course building that represents the end state of my involvement in the action research project cannot be claimed as a valid selection of CRM topics and objectives, nor can it be described as a completed instance of action research. This objection pertains not only to the contextual evidence, since the member evaluations are the main way of validating the theoretical selection as well. This is a serious limitation of my study, but at least one that was clear from the outset. The goal of this thesis was never to develop a valid, full-scale CRM training course; however I hope to have contributed to a future continuation and completion of the course by the co-workers that have participated in this groundwork. The findings of this thesis, at least, will be presented to the staff in the near future, and then time will show to what degree they find it valid or valuable in its present form.

The dynamic context in action. The second limitation was less predictable, and has to do with triangulation of the research data. The opportunity to perform real-time observation of a major experiment was sadly missed, due to an unforeseen and repeated six-week delay of

the scheduled launch of the SpaceX vessel, moving the long anticipated Gravi2 experiment observation out of the time limit for this thesis (Barstein & Holmlund, 2014). This was very unfortunate for my planned data collection and analysis, since observing crew behavior through the unexpected events that are, according to the N-USOC team, bound to happen in any experiment could potentially be a rich source of data, enabling several forms of task and team analysis that could enrich, inform and validate the proposed topics for training through triangulation.

Ironically, for a freshly forged resilience nerd, this was experienced as an emergent adverse event, causing an unrecoverable delay in my data collection due to tight coupling and time dependency between this equipment launch and the experiment execution. Also, there was little redundancy for this data collection in my schedule, and so I had to make a sacrificial decision between two evils: having my thesis delayed while gathering and analyzing the new information, or excluding the post-experiment analyses as a source of information.

While the first, rather unsafe option of taking my chances with a late delivery and possibly improving my data was certainly appealing in the circumstances, in an action research framework such as this it is not uncommon at all to have to make do with another approach than the preferred one. Therefore, I let Kahneman & Tversky (1974) lead my way across the chasms of my heuristic wish to take the rocky road in the face of two evils, and chose to trust the strength of the evidence I had gathered, and the perspectives gained from the operators themselves regarding the nature of their control room work.

It means, in other words, that more emphasis was put on the evidence from other sources, like the HuDeM project and the knowledge acquired in and around the operator training in particular. While this, of course, may contribute to a tendency to find exactly what is expected in the context, it should also be subject to correction and validation through an eventual evaluation.

Conclusions

Research Questions

In the beginning of this project, I set out to investigate two complex questions, though briefly and succinctly framed. The answers to, or rather contributions to answering, these questions have thus far been stated rather verbosely, and it might be prudent to offer a short summary; answers that match the modest framing of the questions.

Research question 1: How can the recent systemic approaches to safety management be translated into CRM training?

The increased focus on beneficial human functioning has made the human response variety, exemplified by the uniqueness of human decision making ability, be regarded as a coveted asset instead of a hindrance to safe operations. The skills demanded by the increased focus on managing the overall system level of risk through monitoring patterns of indicators place pattern recognition and human expertise in the center of attention. These assets are in turn compounded and magnified by the instances of human expertise in effective teams.

Research question 2: How does the specific context of control room support for ISS operations guide the recommended syllabus for CRM training?

The N-USOC operators work in a very time-constrained environment characterized by a strong focus on procedures and very variable workload. However, the complex-dynamic nature of the work means that the principles of resilience should apply to the risk picture, and so CRM training should focus on utilizing team resources and advocating science success, while building both expert and analytical decision-making skill.

Future Directions

The next major project for N-USOC is due to be executed this summer – barring any additional delay – and in conjunction with this, researchers wishing to complete the development of an N-USOC CRM course should take advantage of the opportunity to gather task- and teamwork-relevant data for analysis. Also, the preliminary conclusions supplied by this thesis should be evaluated and elaborated by the control room crew, in line with the recommendations of Salas et al. (2006) and the action research perspective. Successive cycles of evaluation and development should be performed, refining the prototype, identifying specific work content to be improved from training, and developing themes and scenarios for problem solving and simulation training before starting the implementation.

The penultimate goal of conducting and completing research work on CRM training for the N-USOC team is, of course, to state an example that the other USOCs can learn from, and as part of a research foundation, CIRiS is in a unique position to do just that. By taking the opportunity to valid develop evaluation criteria and performance indicators from the

course content and proceedings, the best possible groundwork can be laid for a common training platform that would benefit USOCs, ESA and the space domain alike.

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Appendix A: Popular CRM Topics

<u>Core CRM modules</u>	<u>Detailed topics</u>
Team Work	<p>Backup behavior (Flin et al., 2014; Salas, Wilson, Burke, Wightman, et al., 2006).</p> <p>Mutual performance monitoring (Salas, Wilson, Burke, Wightman, et al., 2006).</p> <p>Culture: National, Professional, Organizational (Heemstra, 2013).</p> <p>Role clarity (Flin et al., 2014).</p> <p>Considering and supporting others (Flin et al., 2014; O'Connor & Flin, 2003).</p>
Leadership	<p>Conflict management (Flin et al., 2014; Heemstra, 2013; O'Connor & Flin, 2003).</p> <p>Team leadership (Heemstra, 2013; Salas, Wilson, Burke, Wightman, et al., 2006).</p> <p>Risk management (Heemstra, 2013).</p> <p>Standard operating procedures (Heemstra, 2013).</p> <p>Planning/coordination (Flin et al., 2014; O'Connor & Flin, 2003; Salas, Wilson, Burke, Wightman, et al., 2006).</p>
Situational awareness	<p>Shared mental models (O'Connor & Flin, 2003; Salas, Wilson, Burke, Wightman, et al., 2006).</p> <p>Cognition-memory (Heemstra, 2013).</p> <p>Understanding risk status (Flin et al., 2014).</p> <p>Anticipation (Flin et al., 2014; O'Connor & Flin, 2003).</p> <p>Gathering information (Flin et al., 2014).</p>
Decision making	<p>Judgment (Heemstra, 2013).</p> <p>Problem definition (O'Connor & Flin, 2003).</p> <p>Risk and time assessment (O'Connor & Flin, 2003).</p> <p>Recognition/Analytical/Procedures (O'Connor & Flin, 2003).</p> <p>Option generation/choice (Flin et al., 2014; O'Connor</p>

	& Flin, 2003).
	Team decision making (O'Connor & Flin, 2003)
	Flexibility (Salas, Wilson, Burke, Wightman, et al., 2006).
Communication	Assertiveness (Flin et al., 2014; Heemstra, 2013; O'Connor & Flin, 2003; Salas, Wilson, Burke, Wightman, et al., 2006).
	Asking/listening (Flin et al., 2014; O'Connor & Flin, 2003).
	Feedback (Flin et al., 2014; O'Connor & Flin, 2003)
	Closed-loop communication (Salas, Wilson, Burke, Wightman, et al., 2006).
Personal limitations	Distractions (Heemstra, 2013; O'Connor & Flin, 2003).
	Automation (Heemstra, 2013).
	Stress management (Flin et al., 2014; O'Connor & Flin, 2003).
	Workload management (Heemstra, 2013; O'Connor & Flin, 2003).