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Risk Management in Complex Sociotechnical Systems: Early-Stage Contributions of the Change Laboratory to Radioactive Waste Operations at IPEN (Brazil)

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1. Introduction

Organizations engaged in radioactive materials management face a persistent challenge: ensuring that safety performance in actual operations matches what formal systems prescribe. Regulatory frameworks and engineered barriers are indispensable, yet they do not, by themselves, guarantee safe outcomes. System safety ultimately depends on the quality of coordination among technical resources, institutional arrangements, and human action in daily practice [1]. This challenge is especially sharp in radioactive waste management, where reliable performance depends on task division and coordination at the operational level, allocation of responsibilities among personnel, training continuity, and adequate institutional support. Leadership quality, management structures, and safety culture are as consequential here as the technical dimensions of the work [1,2].

Risk-management practices in these settings have progressively shifted toward more integrated frameworks, consistent with international guidance. Yet many analytical tools remain expert-centric and give limited weight to workers' situated knowledge. The Change Laboratory (CL) takes a different approach: a structured, formative intervention method developed within Cultural-Historical Activity Theory (CHAT) that brings workers, managers, and researchers together to collectively examine recurring tensions and breakdowns accumulated over time within a given workplace [3–5].

CHAT traces its roots to Vygotsky and Leont'ev and was systematically developed by Engeström into a framework for the analysis of collective work [4,11]. Its central claim is that human activity is mediated by tools, rules, and the shared object toward which a group directs its effort,By and that understanding how work actually happens requires examining the historically conditioned system as a whole, not only individual actions within it. Engeström formalized this claim in the activity system model [11], which maps any collective practice as a set of interrelated elements. The subject is the individual or group whose agency is under analysis. The object is what the activity is oriented toward and what gives it its motive. Mediating artifacts are the instruments and models through which work is performed; rules are the norms that regulate it; the community comprises all those who share the same object; and the division of labor describes how tasks and responsibilities are distributed. These elements are mutually constitutive; tensions among them generate the breakdowns that become the starting points for collective development. The cnonical representation of this model is shown in Figure 1.

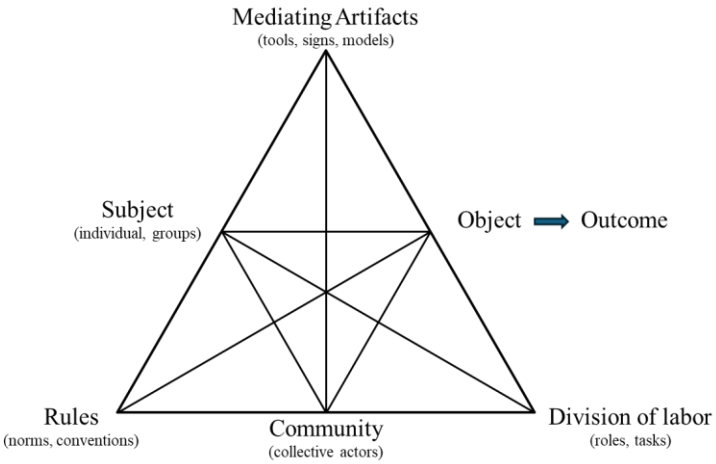


Figure 1: Adapted from Engeström as presented in Virkkunen & Newnham (2013, p. 34).

Within this framework, contradictions are not simply problems to be fixed. They are historically accumulated incompatibilities between elements of the activity system tensions that intensify as the object of the activity evolves while tools, rules, or organizational arrangements lag behind. Making these contradictions visible to practitioners, rather than diagnosing them from outside, is the defining purpose of the CL [4,5,11].

The CL is a formative intervention method developed by Virkkunen and colleagues at the University of Helsinki, operationalizing Engeström's theory of expansive learning learning [3–5]. Rather than observing work from the outside, it creates structured conditions for change from within: sessions bring workers, managers, and researchers together to reconstruct the system's history, surface its accumulated contradictions, and design new solutions collectively.

The method follows the logic of the expansive learning cycle (Figure 2), which describes how a group moves from a recognition that established practices are no longer adequate through historical analysis, identification of a zone of proximal development, and collaborative modeling to implementation and consolidation of new practices. In practice, groups move back and forth between these stages rather than linearly through them [4,5].

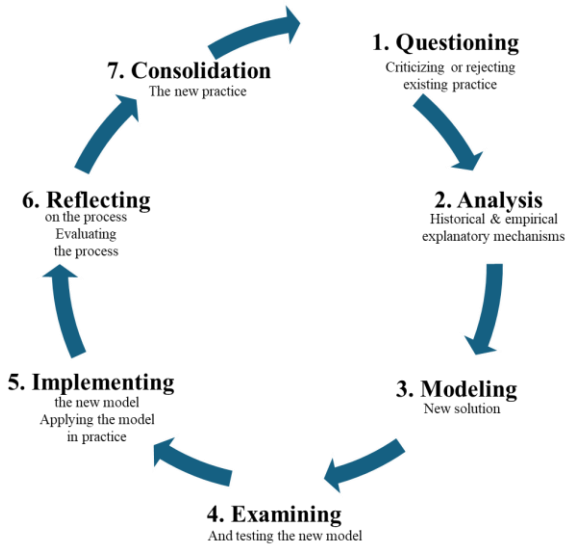


Figure 2: The expansive learning cycle as applied in the Change Laboratory. Adapted from Engeström as presented in Virkkunen & Newnham (2013, p. 51).

Central to every CL session is the use of mirror data: empirical material drawn from participants' own work, interview transcripts, incident records, workflow descriptions, historical documents selected by the research team and presented back to the group in the sessions. Mirror data serve a specific purpose:

they make recurring disturbances and systemic tensions visible as a collective pattern rather than as isolated individual problems. Once that pattern is shared, the group can begin to own the analysis of it [3,5].

The activity system model functions throughout the sessions as the primary mediating artifact, a conceptual scaffold that helps the group move from particular experiences to a systemic reading of the situation. Participants use it to locate where tensions are most acute and to begin reasoning about what a reconfigured system might look like. This paper reports on a CL intervention currently under way at the Radioactive Waste Management Service (Serviço de Gestão de Rejeitos Radioativos, SEGRR) of the Nuclear and Energy Research Institute (Instituto de Pesquisas Energéticas e Nucleares, IPEN) in São Paulo, Brazil. Two questions guide the work: (a) which historically rooted sources of risk and tension emerged during the intervention, and (b) how were these findings produced collaboratively through structured reflection and shared analytical tools?

2. Methodology

The study follows a qualitative, formative, and interventionist case-study design, conducted in the actual workplace where radioactive waste is handled at SEGRR/IPEN. Fieldwork spanned two main operational sectors. On the lower floor, the Integrated Unit for Treatment and Storage of Radioactive Waste (Unidade Integrada de Tratamento e Armazenamento de Rejeitos Radioativos, UITARR) carries out core operations: receipt, monitoring, characterization, treatment, segregation, and storage of radioactive waste. On the upper floor, four research laboratories conduct experimental and analytical work. The study was approved by the institutional Research Ethics Committee (Parecer nº 6.293.938), with all participants providing voluntary informed consent.

During the preparatory phase, the research team worked closely with local management to define the scope of the intervention and conducted preliminary interviews, on-site observations, and a review of internal documents. The empirical data-collection phase comprised 25 semi-structured interviews totaling approximately 50 hours of audio recording, subsequently transcribed and coded using a thematic approach guided by activity system categories. Participants were selected to represent the full range of roles, functions, and lengths of service at SEGRR, ensuring that the empirical material reflected the activity's heterogeneity.

From this corpus, the research team prepared mirror data packages combining the historical timeline of the service, illustrative interview excerpts, field observation notes, and relevant internal documents which were introduced into the CL sessions to stimulate collective analysis and discussion. To date, five CL sessions have been held, each bringing together operational staff, undergraduate and graduate students, research fellows, faculty members, and management representatives. The activity system model (Figure 1) functioned throughout as the shared conceptual tool for moving the conversation from particular complaints toward structural and historical patterns.

3. Results and Discussion

At this stage, the intervention has produced not a catalog of technical failures but a picture of tensions accumulated across five dimensions of the work, dimensions that participants themselves named and refined over the course of the sessions: physical infrastructure and material conditions; formal procedures, written records, and training practices; the organization and division of labor; the supply and management of individual and collective protective equipment; and the degree of institutional support and recognition the service receives within the broader organization. Different work logics operational, research, and educational coexist within the same unit, often competing for the same personnel, equipment, and working hours, a configuration that systemic approaches to safety recognize as structurally destabilizing [6,7].

The historical reconstruction of the service built collectively across the initial sessions using a timeline spanning several decades revealed two distinct yet overlapping lines of work. One centers on the routine handling and management of radioactive waste at UITARR. The other encompasses research and development activities in the upper-floor laboratories. Although physically separated, these two lines are not operationally independent: the same people, the same instruments, and the same working hours are regularly stretched across both, generating continuous and largely informal negotiation of competing priorities. In activity-theoretical terms, this configuration reflects two systems that share

portions of their object and resource base a condition that Engeström's framework identifies as a source of tertiary contradictions, arising between a historically established model of the work and one that has grown up alongside it [4,11].

The most striking finding of the historical analysis was an asymmetry between scope and support. Research activities grew substantially over the years and came to define much of the service's identity and output, yet this expansion was not accompanied by corresponding growth in staffing, infrastructure, formal procedures, or institutional recognition. The service continues to function largely through the personal commitment of its members with a resilience that is real, but fragile, and that tends to mask structural vulnerabilities rather than address them.

The five dimensions did not emerge from the research team's prior reading of the data. They were named, discussed, and verified over the course of several sessions, through sustained confrontation between documentary material and the participants' own accounts of daily work. When the research team presented, in one session, a timeline of critical events alongside interview excerpts describing recurring task interruptions, participants began recognizing patterns they had each experienced individually but had never collectively named. That moment of shared recognition, what the CL literature calls the beginning of questioning [3,5], was itself a methodological result: evidence that the mirror-data mechanism was functioning as intended.

Emergency preparedness and access-control procedures emerged as concerns that cut across all five tension dimensions. The sessions pointed to partially formalized routines, inconsistent training, and uncertainty about responses to abnormal events. Participants consistently reported that institutional responses to known safety problems tend to arrive late, and that the service is perceived as structurally undervalued within the institution a perception with direct consequences for safety culture and operational engagement.

As of the most recent session, the intervention had reached the transition between the analytical and modeling phases of the expansive learning cycle (Figure 2): contradictions had been collectively named and historicized, and the group was beginning to reason about what a reconfigured activity might look like. The next analytical stage of the study will draw on the Systems-Theoretic Accident Model and Processes (STAMP), specifically its System-Theoretic Process Analysis (STPA) variant, as a complementary instrument. This integration is designed to translate the contradictions identified through the CL into formal control-structure terms: hierarchical relationships, information flows, feedback mechanisms, and safety constraints within the sociotechnical system. It is conceived not as a replacement of the participatory process, but as a way of deepening what that process has produced.

Perhaps the most significant outcome of the sessions so far has been a change in how problems are framed. Frustrations that participants had long experienced in isolation were, through the sessions, reconstituted as shared historical problems — no longer attributed to persons but traceable to the longer organizational trajectory of the service. That reframing, from complaint to structural analysis, is not incidental to the method; it is precisely what the method is for [4,5,8–10].

4. Conclusions

This paper has reported on the early stages of a CL intervention into risk management in radioactive waste operations at SEGRR/IPEN. The vulnerabilities that have emerged are organizational and systemic in nature, traceable to the historical transformation and progressive hybridization of the service's activity: a growing research function was grafted onto an operational base that was never expanded to receive it. By demonstrating the practical viability of the CL in a high-stakes nuclear operational setting, this paper also shows that the approach reaches dimensions of the safety problem that normative audits and expert-driven tools are not designed to address the lived, historically accumulated, collectively produced texture of organizational risk. Rather than displacing technical or regulatory methods, the CL opens analytical access to a dimension of safety that falls outside their scope.

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