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Victor Nikolaus Bistritzki

PRACTICING THE UNKNOWN:
organizational practices to cope with uncertainty and develop competences for innovation

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Victor Nikolaus Bistritzki

Practicing the unknown:
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Versão final

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Orientadora: Professora Ana Valéria Carneiro Dias

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ATA DA SESSÃO DE DEFESA DA 17ª TESE DO PROGRAMA DE PÓS-GRADUAÇÃO EM INOVAÇÃO TECNOLÓGICA E BIOFARMACÊUTICA DA UNIVERSIDADE FEDERAL DE MINAS GERAIS, DO DISCENTE VICTOR NIKOLAUS BISTRITZKI, Nº DE REGISTRO 2017714563.

Aos 15 (quinze) dias do mês de setembro de 2021, às 08 horas, na plataforma on-line Microsoft Teams, reuniu-se a Comissão Examinadora composta pelos Professores Doutores: Ana Valéria Carneiro Dias do Programa de Pós-graduação em Inovação Tecnológica e Biofarmacêutica da UFMG (Orientadora), Mônica de Fátima Bianco da Universidade Federal do Espírito Santo - Departamento de Administração, Mario Sergio Salerno da Universidade de São Paulo (USP) - Departamento de Engenharia de Produção, Maria Cecília Pereira do Programa de Pós-graduação em Inovação Tecnológica e Biofarmacêutica da UFMG e Francisco de Paula Antunes Lima do Programa de Pós-graduação em Inovação Tecnológica e Biofarmacêutica da UFMG para julgamento da Tese de Doutorado em Inovação Tecnológica e Biofarmacêutica - Área de Concentração: Gestão da Inovação, Propriedade Intelectual e Empreendedorismo do discente Victor Nikolaus Bistritzki, Tese intitulada: **"Practicing the unknown: Organizational practices to cope with uncertainty and develop competences for innovation."** A Presidente da Banca abriu a sessão e apresentou a Comissão Examinadora, bem como esclareceu sobre os procedimentos que regem da defesa pública de tese. Após a exposição oral do trabalho pelo discente e arguição pelos membros da Banca Examinadora na ordem registrada acima, com a respectiva defesa do candidato. Finda a arguição, a Banca Examinadora se reuniu, sem a presença do discente e do público, tendo deliberado unanimemente pela sua **APROVAÇÃO**. Nada mais havendo para constar, lavrou-se e fez a leitura pública da presente Ata que segue assinada por mim e pelos membros da Comissão Examinadora e pela Coordenadora Pró-tempore do Programa (via Sistema Eletrônico de Informações – SEI). Belo Horizonte, 15 de setembro de 2021.

Professora Doutora Ana Valéria Carneiro Dias (Orientadora)

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UNIVERSIDADE FEDERAL DE MINAS GERAIS
Programa de Pós Graduação em Inovação Tecnológica e Biofarmacêutica da UFMG

"PRACTICING THE UNKNOWN: ORGANIZATIONAL PRACTICES TO COPE WITH UNCERTAINTY AND DEVELOP COMPETENCES FOR INNOVATION."

VICTOR NIKOLAUS BISTRITZKI, N° DE REGISTRO 2017714563.

Tese **Aprovada** pela Banca Examinadora constituída pelos Professores Doutores:

Professora Doutora Ana Valéria Carneiro Dias (Orientadora)
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Belo Horizonte, 15 de setembro de 2021.

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"Change is not something that happens to things, but the way in which reality is brought into being in every instant"

Ann Langley & Haridimos Tsoukas, The SAGE Handbook of Process Organization Studies, 2016

Resumo

Na busca pela inovação as organizações se deparam constantemente com a incerteza inerente aos processos devido à falta de conhecimento. Diversas ferramentas e estruturas tentam controlar, limitar ou prever incertezas, mas a noção de prever algo incerto permanece um oxímoro. Prever o momento exato ou a configuração de uma solução dentro do ambiente incerto que cerca o surgimento da novidade é simplesmente impossível.

Esta pesquisa aborda tal problema por meio da análise de práticas que foram identificadas ao lidar com a incerteza no processo de inovação e como contribuíram para formação de competências. O método é um estudo de caso descritivo e explicativo que foi escolhido para investigar um grupo de pesquisa envolvido em dois projetos de P&D de células a combustível em um laboratório de uma universidade federal brasileira. Para descrever o processo de inovação, incertezas e práticas dentro do desenvolvimento dos projetos de células a combustível, foram utilizadas documentações do projeto e entrevistas.

Esta tese investiga a dinâmica entre incertezas, dualidades, complexidades, práticas e desenvolvimento de competências no contexto de um complexo processo de inovação. Este estudo identifica práticas que surgiram e se desenvolveram ao serem confrontadas com a incerteza ao longo do processo de inovação e analisa como elas utilizam dualidades, lidam com complexidades e com eventos imprevistos. Além disso, ao analisar as práticas, seu surgimento e desenvolvimento ao longo do processo de inovação, são identificadas as competências relacionais e seu desenvolvimento, que por sua vez se aproximam da incerteza e contribuem para lidar com imprevistos, resultando em um modelo circular de prática do desconhecido.

Os resultados sugerem que, ao centralizar as práticas no processo de inovação performativa, as organizações têm a oportunidade de enfrentá-las com imprevistos e, simultaneamente, apoiar o desenvolvimento de competências no trabalho.

Palavras-chave: Processo de inovação, teoria da prática, competência, performatividade, complexidade, dualidade

Abstract

Due to the lack of knowledge, organizations are constantly faced with uncertainty while pursuing innovation. Several tools and frameworks attempt to control, limit, or foresee uncertainties, however, the notion of predicting something uncertain remains an oxymoron. To predict the exact timing or configuration of a solution within the uncertain environment that surrounds the emergence of novelty is merely impossible.

This research approaches the problem by analyzing practices that were identified by dealing with uncertainty within the innovation process and how they turned into competences. A descriptive and explanatory case study method was chosen to investigate a research group, which was involved in two fuel cell R&D projects in a Brazilian federal university laboratory. To describe the innovation process, uncertainties, and practices along with the development of the fuel cell projects, project documentation and interviews were used.

This thesis investigates the dynamics among uncertainty, dualities, complexities, practices, and competence development within the context of a complex innovation process. This study identifies practices that emerged and developed by being confronted with uncertainty throughout the innovation process and analyzes how they synergize dualities, deal with complexities, and cope with unforeseen events. Furthermore, by analyzing the practices, their emergence and development throughout the innovation process, relational competences, and their development are identified, which in turn approach uncertainty and contributed to deal with unforeseen events, resulting in a circular model of practicing the unknown.

The results suggest that when we centralize practices within the performative innovation process, organizations have the opportunity to cope through them with unforeseen events and simultaneously support the development of competence at work.

Keywords: Innovation process, practice theory, competence, performativity, complexity, duality

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List of Abbreviations

ANEEL	Agência Nacional de Energia Elétrica
CEMIG	Companhia Energética de Minas Gerais S.A.
IC	Iniciação Científica
LaMPaC	Laboratório de Materiais e Pilhas a Combustível
PEM	Proton-exchange membrane
POP	Procedimentos Operacionais Padrão
RQ	Research question
SOFC	Solid Oxide Fuel Sell
UFMG	Universidade Federal de Minas Gerais

Summary

1 INTRODUCTION

This thesis is devoted to organizational practices and how they emerge and transform by being confronted with unforeseen events within a complex innovation process. This work discusses how practices embrace duality and complexity within such processes and are a source of competence development within uncertain environments. A research group from the *Universidade Federal de Minas Gerais* (UFMG) and their engagement in two fuel cell development projects that they conducted together with the Electric power distribution company CEMIG[1] over ten years, were chosen as a case.

For a long time, the complexity of the innovation process has been recognized and researchers are trying to open this black box, aiming to better understand the emergence of new technologies. Traditional research on the innovation process aims at investigating the antecedents and consequences of innovation and subsequently creating links between the registered events (Cooper, 1990; Pavitt, 2004; Utterback, 1971). When process theory was introduced to the study of innovation in the late 1980s (Van De Ven & Angel, 1989) a new stream of research investigated innovation by focusing on how the sequence of events unfolds over time (Dougherty, 2008; Garud et al., 2013, 2015; Garud, Gehman, et al., 2017; Van de Ven & Poole, 2005). This process perspective on innovation highlights the events and changes within the process, distancing itself from established definitions of innovation that often imply the concrete functionalistic concern about commercialization (Van de Ven & Poole, 1989). Within the research on innovation from a process theory perspective, two ontologically different streams evolved into a synoptic and a performative view (Langley & Tsoukas, 2016). When applying a synoptic perspective to the temporal evolution of elements, the sequential events are perceived as stable entities and change is something that happens to organizational structures. This thesis takes on a performative perspective on innovation processes, in which entities become secondary and the process becomes the ontological basis. Entities are never stable and are constituted by changes as they are becoming something else through processes. The concept of performativity is based on relational, co-constituted entanglements of social and material entities within the "sayings and doings of multiple actors", avoiding dualism by embracing a complex network of social and material elements (Garud, Gehman, & Giuliani, 2018, p. 5; Garud, Gehman, & Tharchen, 2018).

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[1] Name changed

When addressing innovation processes, we need to recognize that they are constituted and driven by multifaceted relational, temporal, and contextual dynamics of our world (Tsoukas, 2017). The constant interaction and combination among heterogeneous elements, humans, and artifacts within a social setting are catalysts for complexity (Garud et al., 2011; Petzold et al., 2019). The emergence of novelty is, therefore, associated with adaptive, relational, and temporal complexities and their presence suggests not to control, but to harness the innovation process (Garud et al., 2011, 2013; Garud, Gehman, et al., 2017). Such increased complexities within innovation processes impact practices and uncover challenges and opportunities within opposing organizational elements (Smith et al., 2017). Being confronted with the tension between elements, or duality, like autonomy and control, personal autonomy and professional commitment (Mazmanian et al., 2013), social constraint and social action (Dougherty, 2008), and most famously within innovation research: exploitation and exploration (Raisch et al., 2009) or stability and change (Farjoun, 2010). By managing paradoxes or dualities, within innovation processes and across the entire organizational structure, responsibilities are distributed, which intensifies the importance of paying attention to established knowledge and the creation of new knowledge (Andriopoulos & Lewis, 2009).

The degree of technological complexity or newness is intricately linked with the limited access to available knowledge and influences the number of uncertain elements within the innovation process. The innovation process of complex technologies is confronted with a much higher degree of uncertainty than the development of complementary product improvements, preventing firms to fully explain and accurately predict possible outcomes (Pavitt, 2004). Several tools and frameworks attempt to control, limit, or foresee uncertainties, however, the notion of predicting something uncertain remains an oxymoron (Loch et al., 2007). To foresee or even predict the exact timing or configuration of a solution within the uncertain environment that surrounds the emergence of novelty is merely impossible (Garud, Gehman, et al., 2017). In development projects, deviations might occur in project steps that were not included in the initial scope of the project (Munthe et al., 2014) and managerial approaches for such development projects might have several shortcomings when confronted with unexpected problems (Aggeri & Segrestin, 2007).

This thesis approaches the process of innovation with a practice perspective and recognizes this process as the holistic coming-together of all practices of its participants, knotted together by their social and material interactions (Jörgen Sandberg & Tsoukas, 2011). Practice theory centralizes practices as a point of departure - not practitioners (C. Nicolini, 2012). In a very holistic way, practices can be defined as "historically and geographically recurring localized occurrences" (C. Nicolini, 2012, p. 10) or several elements of doings and sayings that are spatially and temporally dispersed and organized by a context (D. Nicolini, 2017).

When applying a practice perspective to the concept of competence, we challenge the entity-based perspectives. Those entity-based perspectives focus on individual knowledge or skills in a static, analytical model and assume context independence, whereas a relational practice view proposes that a human and the world are inseparable and cannot be divided into two entities and, therefore, unifies worker and work. Scholars that approach competence with practice theory argue that competence includes not merely knowledge, knowing-in-action, or the understanding of work, but comprises social and non-social interactions embedded in practice (Lindberg & Rantatalo, 2015; Jörgen Sandberg & Pinnington, 2009). According to competence as practice, competence can only manifest in practice as practical understanding of situations, mobilization of networks, or taking initiative and assuming responsibility (Zarifian, 2001, 2003)

From a performative and practice perspective, this thesis uncovers how organizational practices deal with unforeseen events, which are inevitable in any development process, especially innovation processes. Throughout this contribution, I will shed light on the temporal, relational, and contextual complexities of the innovation process that contribute to the emergence of unforeseen uncertainties. I propose a practice approach that reveals the creation of practices as a response to uncertainty. This thesis uncovers how such practices embrace unforeseen events and how they utilize them as a source of competence development. This work also contributes by identifying dualities within the organizational processes and by providing insight into how they were managed through practices.

Current managerial frameworks have been focusing on minimizing uncertainty in project execution to improve firm performance. To lower uncertainty and control development processes, various tools like the Stage-Gate-System (Cooper, 1990), milestone planning, discovery-driven planning, or diagnostic tools are implemented (Loch et al., 2007; Rice et al., 2008). In organizations, managers can prepare to a certain degree for uncertainties, however, they hinder the systematization of managerial practices, making it impossible to completely plan contingencies (Brasil et al., 2018; De Meyer et al., 2002; O'Connor & Rice, 2013; Rice et al., 2008). Hence, planning for uncertainty might be necessary but is not sufficient for managing risks (Perminova et al., 2008) and management needs to distance itself from predicting the unknown and to embrace the unknown when it becomes known so organizations can move from "troubleshooting to opportunistic orchestrating and networking" (De Meyer et al., 2002).

This stresses the importance of developing different approaches that can embrace uncertainty and deal with it during project execution, ergo, when we actually do things within practice. This thesis aims at contributing with a novel approach to deal with uncertainty within innovation processes, by introducing practice theory and justifying why organizational practices can confront uncertainty and develop competences that ultimately support dealing with unforeseen events.

A qualitative case study research method was chosen to investigate the innovation process and its complexities and dualities, the established practices, and the developed competences. A Brazilian fuel cell R&D project was selected as the case of this work. The project resulted in the first national Solid Oxide Fuel Cell (SOFC) prototype and was initiated by individual effort, supported through an academy-industry interaction, and executed by constructing an R&D laboratory in a national public university and financing a 10-year prototype development of a university research group. Interviews with project participants and internal and external project documentation provide qualitative data for the analysis. The research question of this thesis is: "How do practices emerge from uncertainty to engage with unforeseen events and how does this engagement stimulate the development of competences?". To investigate this research question, the general objective of the research was to **analyze practices that are identified by dealing with uncertainty within the innovation process and how they turned into competences.** More specific objectives of this research include:

- Mapping the innovation process of the case chosen
- Detecting and categorizing uncertainties that emerged during the innovation process
- Identifying and categorizing practices that contributed to deal with uncertainties
- Analyzing how practices, when confronting uncertainty, can turn into competences

The following work is separated into six chapters. Following this introduction (Chapter 1) I will elaborate on the theoretical background of the research (Chapter 2), which includes innovation theory, the synoptic and performative innovation process including its complexities, duality, uncertainty and unknown unknowns, practice theory, and competence at work comprising rationalistic and relational perspectives. Chapter 3 is dedicated to the methodology of this work and aims at locating the study and provides insight into data collection and analysis. The fourth chapter introduces the adopted case, the complexity of fuel cell technologies, and provides the setting of the prototype development projects. The fifth chapter presents the findings of this work. It entails the set-up within the project group, elaborates on the identified uncertainties, discusses the identified practices and how they confront unforeseen events, presents a discussion on how duality within practice was managed within the innovation process, and analyses how competences were developed through practices. The chapter finishes with a dynamic model on how practices confront uncertainty and develop competences within the context of a complex, relational, and temporal innovation process. The thesis closes with the conclusion in chapter six.

2 THEORETICAL BACKGROUND

This chapter will create a foundation to approach the research question and the objectives of this thesis. It entails the theory on the innovation process with different ontological perspectives. Furthermore, complexity, duality, and uncertainty within such processes will be addressed. Subsequently, I will give insights on practice theory and competence as practice.

2.1 Innovation and its process

Innovation has been associated with being a decisive driver for economic growth. It is central in the continuous vitalization of organizations, regions, and nations, and in recent decades the term innovation has been more popularized by managers, policymakers, and academics by associating it with the creation of something new that solves problems and can eventually provide a competitive advantage. Originally envisioned as a source of profit generation, Schumpeter (1911) explicates innovation as the enforcement of new combinations into reality that can transform into products, processes, markets, or sources of resources.

This chapter will introduce innovation and its process, its definitions, and research areas, followed by a theoretical elaboration of synoptic and performative process perspectives and performative emergence. The chapter will move to implications of the innovation process which includes its complexity and duality and finish with theoretical concepts on uncertainty.

2.1.1 Defining innovation

Innovation is more than just a new product or process that is introduced to the markets to be consumed or applied. It is a meandering process that emerges out of constantly changing situations and reconfigurations of structures and is confronted with conceptualizations, concretizations, failure, and reevaluations to pervade and change organizations and society. The complex and unpredictable - though conceivably rewarding - nature of innovation has been attracting a constantly growing number of scholars from different disciplines that dedicated their research to diverse elements of the innovation phenomenon. After Schumpeter, innovation emerged as fundamental in economic development research, was adopted by sociologists and anthropologists, concerned with the effect of innovation on society, and later on investigated by management and organizational studies (Martin, 2012).

The accumulated organizational research over the last decades offers continuously deepening insights on topics concerned with, for example, types of innovation (Damanpour, 1991; Utterback & Abernathy, 1975), uncertainty management (Brasil et al., 2018; De Meyer et al., 2002; Munthe et al., 2014; O'Connor & Rice, 2013), organizational competitiveness (Prahalad & Hamell, 1990; Raisch et al., 2009; Teece et al., 1997), the innovation process (Cooper, 1990; Garud, Gehman, et al., 2017; Pavitt, 2004; Salerno et al., 2015; Utterback, 1971; Wheelwright & Clark, 1992) and innovation networks (Dias et al., 2012; Powell, 1990; Powell & Grodal, 2006; Tidd & Bessant, 2013).

With innovation studies spreading to several academic disciplines, it created commotion around its definition (Baregheh et al., 2009). Innovation is commonly recognized to be central in elaborating economic and technological change and in creating value and sustainable competitive advantage for countries and organizations, however, due to its widespread adoption and use, it is impossible to arrive at a definition that reconciles and accommodates all perceptions and uses of the term. This might relate to the deviation of research on the several stages of innovation. As innovation research ranges from its emergence, process, establishment, organization to its implementation and impact, innovation can be explored from diverse angles, which leads to diverse definitions.

Innovation is commonly separated from invention. Fagerberg (2009) defines invention as the first occurrence of an idea for either a product or a process and innovation as a first attempt to commercialize the inventions. He highlights the nature of a continuous innovation process that relies on the combination of knowledge, capabilities, skills, and resources with considerable time lags between invention and innovation. Utterback (1971) follows Schmookler's definition of an invention as an original solution that is derived from the combination of information and is related to a specific need or aspiration and its technical means. Accordingly, innovation is an invention that was introduced into the market (in the case of a product) or the first use of a production process (in the case of a process). Therefore, Utterback advocates the well-established dichotomy between product and process innovation. Unlike Fagerberg and Utterback, Pavitt (1984) introduces a social aspect by including not only a market entrance but successful commercialization or usage into his definition of innovation, thereby acknowledging that a product or process needs to be socially accepted or implemented to be termed as innovation.

Due to the increasingly interconnecting worlds of business and research, Baregheh and colleagues (2009) propose a multidisciplinary definition, building upon extensive literature research on innovation definitions, which they identified in various research fields. The research group calls for a more integrative definition and sees innovation as a multi-stage process, resulting in new products, services, or processes with the organizational aim to achieve competitive advantage. The authors argue that the approach to find a generic definition is to develop a shared understanding and meaning of the innovation concept. However, some alternative definitions of innovation refer merely to the introduction of a new idea (Van de Ven & Poole, 1989), distancing themselves from terms such as market implementation or commercialization and therefore from a functionalistic ideology.

Indeed, if the definition of innovation implies product or process commercialization or adoption, it means that innovation can only be defined as such ex-post; and that innovation studies can only be developed ex-post as well. In some cases, however, the innovation process can be interrupted and then restarted, for several reasons, within years or decades. As Usher (1954, p. 46) noted: “We must presume that all particular systems of events are finite, but we cannot assume that any given moment constitutes their ‘end’”. If we adopt a performative and complex perspective towards innovation, we must admit that due to temporal complexity an invention might ultimately turn into an innovation. Therefore, within this non-functionalistic perspective, it is not easy, if not impossible, to distinguish a priori between what is invention from what will be innovation. To dive deeper into the emergence of innovation, a recent trend in organizational research deals with the process of innovation (Garud, Berends, et al., 2017; Garud, Gehman, et al., 2017; Garud & Turunen, 2020; Matitz & Chaerki, 2018), and to define innovation for this thesis, we need to dive deeper into the theories on the different perspectives of this process.

2.1.2 Perspectives on the innovation process

Before elaborating on the innovation process, we need to define ‘process’. A process can be distinguished from variance. In the case of variance (Garud, Berends, et al., 2017), “the precursor (X) is a necessary and sufficient condition for the outcome (Y)” and a process being “a series of occurrences in a sequence over time so as to explain how some phenomenon comes about” (Mohr, 1982 *apud* Garud, Berends, et al., 2017: 227). According to this definition of a process as a sequence, we understand a phenomenon if we arrange the sequence of events in chronological order - or *chronos*. For example, Person A can only pass on knowledge to person B if person A had previously acquired that knowledge. But if person A meets with person B before acquiring that knowledge, the knowledge would not be passed on. In short – the chain of events is important (Garud, Berends, et al., 2017; Garud & Turunen, 2020). This chronological, synoptic perspective of the process serves predominantly as a process definition in management, new product development, and organization literature, however, an alternative view is emerging that perceives the process as performative and as a dynamic, temporal, and relational construct without chronological sequences.

Research on the innovation process was initially aimed at investigating the antecedents and consequences of innovation and subsequently creating links between the registered events (Garud et al., 2013). In the late 1980s, the Minnesota Innovation Research Program introduced process theory to the innovation process (Van De Ven & Angel, 1989) what lead to a stream of research, that investigated innovation by focusing on how the sequence of events unfolds over time (Dougherty, 2008; Garud et al., 2013, 2015; Garud, Gehman, et al., 2017; Van de Ven & Poole, 1989, 2005). From a process perspective, Van de Ven and Poole (1989, p. 32) define innovation as "the temporal sequence of events that occur as people interact with others to develop and implement their innovation ideas within an institutional context". Therefore, such a perspective on the innovation process highlights the events and changes within the process, distancing itself from established definitions on innovation that often imply the concrete functionalistic concern about commercialization. Within the research on innovation from a process theory perspective, two ontologically different streams evolved into a synoptic and a performative view (Langley & Tsoukas, 2016).

2.1.2.1 Synoptic process perspective

When trying to understand the temporal evolution of elements by perceiving the sequential events as stable entities, researchers refer to a synoptic or 'weak process' view. Within this view, time moves chronologically and change is "something that *happens*" to the stable organizational structure (Langley & Tsoukas, 2016, p. 3 authors' emphasis). This perspective focuses not on the process but on entities such as organizations or individuals, advocating a substance ontology (Jörgen Sandberg et al., 2015). The synoptic view, also referred to as the unitary sequence model (Van de Ven, 1992; Van de Ven & Poole, 1989), allows identifying familiar types of innovation processes and facilitates the comparison of different situations in the innovation processes (Gopalakrishnan & Damanpour, 1997).

When considering the example: 'the chemist is doing an experiment', the synoptic view perceives that the 'doing-an-experiment' process *is happening* to the 'chemist' entity. Along with 'doing-an-experiment', other processes like reading, writing, measuring, etc. are happening to the entity across the timeline. The chemist is seen as a stable entity that is not changed by the process but rather diversified.

Utterback (1971) separates the stages of the innovation process into idea generation, problem-solving, implementation, and diffusion, chronologically evolving in sequence. This view of a rational, linear progression with separable stages and transitions is predominant in process research (Van de Ven, 1992) and has been adopted to develop models with predefined sequences and phases. Infamous examples are Wheelwright and Clark's development funnel that "takes an idea from concept to reality" by generating and reviewing development options along the process (1992, p. 111) and Cooper's Stage-Gate System that was conceptualized to move a new product "from idea to launch" by assigning gatekeepers that review and assess each stage of the predefined development process (Cooper, 1990, p. 44). With having clear start (idea/concept) and end (reality/launch) points (Van de Ven & Poole, 2005), those models imply temporal and process linearity (Salerno et al., 2015), driven by fixed events, exogenous contexts, and unequivocally defined success and failure (Garud, Gehman, et al., 2017).

Although the traditional development models are widely recognized and implemented in organizations, they are increasingly criticized for their linearity that neglect the dynamic nature of the innovation process with its "multiple, cumulative and conjunctive progressions of convergent, parallel and divergent activities" (Gopalakrishnan & Damanpour, 1997, p. 16). Researchers increasingly move away from the perspective that innovation is an outcome and recognize the dynamic complexities surrounding the innovation process (Garud et al., 2013) that incorporate temporal and relational process determinants (Garud et al., 2015; Kumaraswamy et al., 2018; Langley et al., 2013). Those complex processes (Garud, Gehman, et al., 2017) focus on nonlinear interaction and recombination of existing entities.

2.1.2.2 Performative process perspective

The performative, or 'strong process' view abandons the notion of rigid entities and builds on process-relational thinking which moves 'constantly becoming' in the spotlight (Langley & Tsoukas, 2016). Within the performative view, the entity becomes secondary and the process is proposed to be the ontological basis (Jörgen Sandberg et al., 2015). Organizations and individuals are therefore characterized by change and 'constantly becoming' as they are constituted by their process. Let us reflect on the example given before, 'the chemist is doing an experience', with a strong process (or performative) view the chemist is constituted by changes that he/she experiences and is *becoming* something else through processes like doing an experiment, reading, or writing. The entity is therefore never stable and continuously evolving. Through change, the actor is constantly experiencing the world differently. “Change is not something that happens to things, but the way in which reality is brought into being in every instant” (Langley & Tsoukas, 2016, p. 4).

The concept of performativity is based on relational, co-constituted entanglements of social and material entities within the “sayings and doings of multiple actors”, which avoids dualism by embracing a complex network of social and material elements (Garud, Gehman, & Giuliani, 2018, p. 5; Garud, Gehman, & Tharchen, 2018). Performativity is emphasizing that new realities are constructed through the sayings and doings around them (Garud & Gehman, 2019). The concept argues that the act of speaking is more than just words but implies a meaning, such as a command, request, or warning, and carries therefore an illocutionary force (Garud, Gehman, & Tharchen, 2018; Garud & Gehman, 2019). The utterance “I cannot do this task alone” might have the illocutionary force of requesting for help and the utterance “The traffic light is red” might have the illocutionary force of a warning. The intended action (asking for help or warning), is therefore brought about by the act of speaking, having the effect of change, and making it performative. Just like an utterance, a process, from a performative view, is comprised of multiple dynamic actions and elements that are interwoven to form a holistic unit.

The philosophy of reality of Alfred North Whitehead (1861–1947) can help us understand the performative view of constantly becoming processes. Whitehead’s process-relational philosophy opposes the ‘weak process’ perspective, substance thinking, and substance metaphysics and, therefore, rejects the claim that elements in our world remain unchanged and are disconnected from “the processes which actually constitute the self” (Mesle & Dibben, 2016, p. 4). To understand the process-relational philosophy, Mesle and Dibben (2016) point out that we have to be aware of some difficulties that impede this understanding, like our language. The authors argue that the grammar and phrasing of the English language, and other Germanic languages, centralize around substance thinking, making it difficult to perceive reality as a process rather than substance. Nouns dominate the spoken language and verbs which incorporate action and change are taking a secondary role (Langley et al., 2013). This is well exemplified by Mesle and Dibben (2016, p. 3):

> “The fire burns. The river flows. Rain falls. A smile appeared on her lips. Substance thinking is especially deep when merged with Cartesian philosophy, treating the mind as a mental substance: I think. She felt. He experienced. Am ‘I’ not the thinking; is ‘she’ not the feeling; is ‘he’ not the experiencing, just as surely as the wind is the blowing, the fire the burning, the river the flowing of the water?”

We can transpose this thought onto the example of ‘the organization’ that treats the actually highly relational, interactive and continuously changing and becoming *organization* as a static, unalterable construct. This promotes research on a rigid organization rather than on “*how* settings of interaction *become* organized” and, therefore, how an organization, as a process, emerges (Langley & Tsoukas, 2016, p. 3 emphasis original).

In romance languages like Portuguese or Spanish, the example of *ser* and *estar* helps us to understand how language can give a different sensation and relation to a substance. Schmitt and Miller (2007) use the Spanish sentence ‘*Manolo es/está flaco’* to exemplify the variance in discourse. In the case of *es*, Manolo *is* thin; in the case of *está*, Manolo is thin *right now*. This changes our perception of discourse. Putting aside the obvious difference in the meaning of the two phrases, *ser* promotes a stable characteristic or attribute of the subject, whereas *estar* gives us the impression of a fluid element that is not chronologically stable but continually changes with each moment. When bringing it into an organizational context, we can use the Portuguese phrase ‘*A organização é/está inovadora'*. Depending on the verb, we are talking about an innovative organization (*é*) or an organization that is innovative but only due to the arrangements that are present at the current, ever-changing moment (*está*).

Whitehead frames his process philosophy around the experiencing subject rather than the passive object and argues, that subjectivity is inherent in nature (Mesle & Dibben, 2016). Every human being collects unique experiences and, therefore, is interpreting everything differently. Experiences can only be formed by having relationships with social and material elements, making it a relational process. According to Whitehead, experience is simply defined as ‘constantly becoming’. Any process is constantly moving and is never standing still. And every organization is constituted by the experience of its actors and, therefore, constantly changing and evolving (Mesle & Dibben, 2016). “The entire cosmos, including our own lives, communities, and organizations, are constructed out of momentary events of experience – out of a flow of relational processes” (Mesle & Dibben, 2016, p. 8).

In Whitehead’s philosophy, the process of experience is penetrated by relationships, making any process subject to relational power. Relational power opposes unilateral power and advocates the assumption that actors have the capacity to be open towards the changing world, absorb and integrate experiences and sustain relationships to deepen the exchange of experience (Mesle & Dibben, 2016).

This notion of performativity can bring us closer to understanding innovation as a process. It distances our thinking from innovation as something that occurs within organizations and towards a perception "where organizing occurs *around* innovation"(Garud & Turunen, 2020, p. 35, author's emphasis). For this work, my definition of the innovation process is based on a performative perspective, adopting a process-relational philosophy. In this work, the innovation process is <u>not</u> defined as a linear, chronologically evolving sequence, constituted by stable entities that are subject to change **but** refers to a highly dynamic structure that is constantly becoming and is being transformed through the assumption of context-dependency without any temporal timestamps. Garud and colleagues (2017) present a summary of the synoptic and performative perspectives which is shown in Table 1.

Table 1 Synoptic and performative perspective

Synoptic View	Performative View
Contexts are exogenous, with actors adapting and then getting locked into a path.	Actors contextualize their initiatives by actively reinforcing or de-coupling links and continually re-drawing their relational boundaries.
The beginning, the middle and the end are fixed events between which innovations are refined.	The beginning, the middle, and the end are mobilized and modified by actors to constitute innovation journeys in-the-making.
Over all perspective is one of the processes of innovation, driven by linear stage-gates with success and failure defined unequivocally	Overall perspective is one of innovation as process, driven by non-linear, ongoing translations between multiple social and material elements, remembered, experienced, and imagined.

Source: Garud, Gehman, et al., 2017

2.1.3 Performative emergence of novelty

Research on innovation often addresses its emergence and process as it is key to understand how to sustain it (Dougherty, 2008). As the innovation process can generate non-linear temporal dynamics (Garud et al., 2011), research on how something emerges, develops, and grows, by incorporating relationality and temporality, can contribute to the understanding of the evolvement of innovation (Langley et al., 2013). By endogenizing context and time, the innovation process shifts from synoptic linearity to performative emergence of novelty (Garud, Gehman, et al., 2017).

Garud and colleagues (2015) identify three contemporary research perspectives (or lenses) that adopt a process perspective towards the emergence of novelty and are based on underlying assumptions about the nature of space and time, guided by specific epistemological and ontological viewpoints. The lens of *spatial* emergence implies that the process unfolds unpredictably and chronologically within a systemic structure. The system, within which novelty emerges, exists independently of spatialized (clock) time and independently of the actor's knowledge of it. This perspective views emergence as the changes that occur between two points of observation on a timeline that moves incessantly.

The *relational* perspective perceives emergences as a dynamic process that unfolds across a "pervasive and intricate network", challenged by serendipity and disruption (Garud et al., 2015, p. 7). Knowledge is gathered through the actor's interaction with social and material elements. This lens assumes an endogenous network that emerges through the interaction between actors and space, however, like in the perspective of spatial emergence, independently from time. This line of thought moves away from individualism and towards a non-dualistic ontology that implies embedding the relationships of actors into the context and not merely their isolated behaviors or attributes.

Within the third lens, *temporal* emergence, the process is open-ended and continuous, constantly reacting to the interactions with social and material elements. Advocates of this perspective perceive emergence as a relational process that is inextricably linked to not only space but also to temporal experience that is continuously constructing and reshaping the process. Actors perceive the present differently because of differently perceived memories and imaginations. Temporal emergence is "concerned more with different ways of participating in an ongoing, unfinished world than with discovering the realities of an already complete and stable world" (Garud et al., 2015, p. 9).

In this study, the innovation process will be observed through the lenses of relational and temporal emergence, which embraces the context-dependency and the individual, continuously unfolding experiences of involved actors, which are inseparably linked to space and time. In this thesis, innovation is considered as a collective accomplishment, which unfolds progressively within organizational settings, however, it also considers the individual contribution of involved actors. As Garud and Turunen (2020, p. 18) put it:

> "[…] [D]ifferent aspirations for the future by actors ends up mobilizing the past in different ways for them. And, these visions of the future and mobilizations of the past will galvanize specific initiatives by the actors in the present. Such plasticity of temporal experiences implies that it is up to the actors to work with enacted memories and anticipations at any given moment of their innovation project as they try and give it meaning"

2.1.4 Complexities of innovation processes

Our reality is too complex, holistic, and ambiguous to be entirely incorporated into theories without simplification. However, this profound complexity should promote researchers to develop even more complex theories (Tsoukas, 2017) instead of generalizing and oversimplifying the multifaceted relational, temporal, and contextual dynamics of our world. In this work, I lean on Garud et al. (2011) that attribute the emergence of complexity to the "combinations or interactions among heterogeneous elements […] or between humans and artifacts in social settings". The elements that make up a practice, project, organization, country, or world are intertwined through relational and temporal dynamics which drive innovation as a distributed process.

To continuously open up the black box of innovation and gain more insights into its unfolding manner it is inevitable to *complexify* the concept of innovation processes (Petzold et al., 2019; Tsoukas, 2017). Independently of a synoptic or performative perspective, the innovation process is exposed to and constructed through an interplay of variables and relationships (Utterback, 1971), confronting researchers with complex arrangements embedded in the process that need to be addressed. By advocating not to control, but to harness the innovation process, Garud and colleagues (2011, 2013; 2017) shed light on complexities that are associated with the emergence of novelty from a nonlinear, performative view.

The *evolutionary* or *adaptive complexity* refers to path dependency, however, the path creation does not merely depend on the emergence of the technology in question. The authors (Garud et al., 2013) bring attention to the fact that the emergence of innovation in one field is influenced by other fields and vice-versa, spreading across multiple levels (technologies, industrial structures, and societies) and, therefore, leading to a co-evolutionary process. This interaction of many social and material entities makes the innovation process a *complex adaptive process*, that emphasizes nonlinear recombination that distances itself from the linear and synoptic "vestiges of determinism" (Garud, Gehman, et al., 2017, p. 457).

As continuous interacting relationships among actors and between social and material elements are very present in the innovation process, a *relational complexity* arises from such ambiguity of inputs (Garud et al., 2013). Within the complex relational process, the actors are translating their efforts by interacting and associating with social and material elements (Garud, Gehman, et al., 2017). This creates a relational dynamic emergence pulled by a process that unfolds across a network of entanglements (Garud et al., 2015).

Innovation unfolds over time, characterized by "multiple temporal rhythms and experiences rather than by a single linear conception of time" (Garud et al., 2013, p. 795), generating *temporal complexity.* Such asynchronies can be observed in several technological innovations such as the video cassette recorder, which was only possible after several technological advances developed across different periods of time (Garud, Gehman, et al., 2017). The same ideas, materials, or social elements can be useless or valuable depending on the point in time but can only be evaluated as such after being applied. On the flipside, however, a suitable solution right now might generate problems in the future (Garud et al., 2011). Therefore, when applying linear mechanisms that disregard temporal dynamics, such as the Stage-Gate-System (Cooper, 1990), social or material elements could be discarded that could have been valuable at some point.

> "The achievement of a solution cannot be presumed at any particular time, and it is an abuse of language to represent it as certain and "necessary" irrespective of a determinate time of accomplishment." (Usher, 1954, p. 66)

Garud and colleagues (2017) highlight the three complexities within the innovation process as an ontological evolution from a synoptic view towards a performative perspective of innovation. First, the adaptive complexity adds nonlinear dynamics to the linear, deterministic understanding of the innovation process. Second, by introducing a context-dependent relational ontology, the adaptive process shifts to a relational perspective, and third, by endogenizing time, a temporal perspective is introduced to deal with continuity and change.

2.1.5 Duality not dualism

Such increased complexities within innovation processes impact practices and uncover challenges and opportunities within opposing organizational elements (Smith et al., 2017). Organizations are constantly confronted with tensions between extremes like autonomy and control, personal autonomy and professional commitment (Mazmanian et al., 2013), social constraint and social action (Dougherty, 2008), and most famously within innovation research:

exploitation and exploration (Raisch et al., 2009) or stability and change (Farjoun, 2010). Those paradoxes (Papachroni & Heracleous, 2020) might be seen as a source of conflict but can also be perceived as an opportunity for finding innovative solutions and organizational development (Hargrave & Van de Ven, 2017).

Opposing elements in organizational research often lead to duality and dualism. Dualism reveals the world as a construction made of separate and contrasting entities, whereas duality recognizes the distinction of elements without clearly separating them (Farjoun, 2010; Tsoukas, 2017). Approaching innovation, or management in general, with a more holistic and paradoxical perspective seems to be more effective as it does not validate one of the contradicting elements but embraces their coexistence and sees their tension as synergetic (Andriopoulos & Lewis, 2009).

Papachroni and Heracleous (2020) elaborate on the duality of *ambidexterity as practice* in which certain practices act like 'hybrid tasks' to solve the contradictory tension between exploration and exploitation with synergetic effect. In their study, they utilize "paradox theory and the interdependent nature of dualities that views them as dynamic polarities rather than static contradictions" (Papachroni & Heracleous, 2020, p. 17). Duality research portrays contradictory elements as generally distinct, while at the same time enabling each other. For example, diversity often leads to innovation and change within organizational structures but can also confirm stability (Smith et al., 2017). By managing paradoxes or dualities within innovation processes and across the entire organizational structure, responsibilities are distributed, which increases the attention towards established knowledge and the creation of new knowledge (Andriopoulos & Lewis, 2009).

This subsection brought attention to innovation as a process. It highlights that innovation, and therefore change, does occur through the continuous development of individuals and organizations. Change, however, does also arise through unpredictable events, or discontinuities, and acts of insight while being immersed in context. This ongoing process is constantly transforming individuals but also entire organizations and their knowledge structures (Garud & Turunen, 2020; Usher, 1954), which brings our attention to unpredictability and the emergence of such discontinuities – or unforeseen events.

2.1.6 Innovation and uncertainty

There are recurrent factors related to the success or failure of the innovation process that tends to vary according to the degree of change and the impact they have on organizational structures and practices (Damanpour, 1991). Over the decades, a typology has emerged in organizational science that differentiates incremental from radical innovation (Damanpour, 1991; Ettlie et al., 1984; Gopalakrishnan & Damanpour, 1997).

Incremental innovations are product or process improvements introduced into the market with low uncertainty, contrary to radical innovations that come with a great impact on organizational structures and high market uncertainty. Incremental innovation implementation does not require large changes in the organization structure, and it relates to exploiting existing technologies. Exploring new opportunities often leads to radical innovation and its implementation entails drastic changes in the organization structure. The purpose of incremental innovation is mainly to stay competitive in the current market. Radical innovation on the other hand disrupts and transforms the current market or even creates a new, uncontested market space without competition. (Tushman & O'Reilly III, 1996).

As radical innovation is a catalyst for disruption (Kim & Mauborgne, 2004), it usually generates much higher rewards than incremental innovation, however, with more uncertainty and risks involved (Gopalakrishnan & Damanpour, 1997; McDermott & O'Connor, 2002; O' Conner & DeMartino, 2006). Radical innovation projects that originate from R&D phases correlate with greater technological uncertainty as those projects attempt to cover a scientific gap of a less developed and advanced research field (Green et al., 1995). Green and colleagues (1995, p. 7) identified that "the greater the technological uncertainty, the greater the business inexperience, and the costlier the technology, the longer the life span of the project."

Such characteristics of radical innovation intertwine with each other. Because of its novel aspect, there is little scientific, technological, tacit, and explicit knowledge available. Especially, but not exclusively, in the early phases, new products or processes are more likely to depend on the previous technology path that is strongly associated with the accumulated knowledge necessary for technological development. When it is hard to transmit knowledge, testing and experimenting become determinant for progressing.

The development of new technologies is constantly confronted with uncertain events within the process of rearranging established configurations. Those uncertain elements arise due to a lack of knowledge as the product or process is new to the organization, the country, or the world. The degree of technological complexity or newness is intricately linked with the limited access to available knowledge and influences the number of uncertain elements within the innovation process comprising all parts from research and development to commercialization. The innovation process of complex technologies is confronted with a much higher degree of uncertainty than the development of complementary product improvements, preventing firms to fully explain and accurately predict possible outcomes (Pavitt, 2004).

As uncertainty arises due to the lack of knowledge within an environment, we must acknowledge not all individuals within an organization have access to the entire accumulated knowledge of the organization. This implies that environmental uncertainty cannot be used interchangeably as a descriptor for the state of organizations and the state of actors within the organization. To clarify, Milliken (1987) differentiates three types of uncertainties that occur in the environment, experienced by project management: The uncertainty of changing environments and the unpredictability of the ever-changing world (state uncertainty); The uncertainty that arises when environmental change might affect the organization (effect uncertainty) and; The uncertainty that comes with the decision-making process in which the organization needs to respond to an environmental change (response uncertainty).

The multifaceted uncertainty intensifies the complexity of dealing with uncertainty in innovation processes and, simultaneously, uncertainty increases with higher levels of complexity (Loch et al., 2007). Although a certain degree of uncertainty might be healthy for an organization’s creativity and long-run viability (Van de Ven, 1986), handling uncertainties is seen as essential in managing risks in innovation projects. Therefore, current managerial frameworks have been focusing on minimizing uncertainty in project execution to improve firm performance. To lower uncertainty and control development processes, various tools like the Stage-Gate-System (Cooper, 1990), milestone planning, or discovery-driven planning are implemented (Rice et al., 2008).

In the need to reduce risks for organizations, some contributions provide diagnostic tools that support managers in the search for unpredictable events, or unknown unknowns (Loch et al., 2007). In organizations, managers can prepare to a certain degree for uncertainties, however, they hinder the systematization of managerial practices, making it impossible to completely plan contingencies (Brasil et al., 2018; De Meyer et al., 2002; O’Connor & Rice, 2013; Rice et al., 2008). Hence, planning for uncertainty might be necessary but is not sufficient for managing risks (Perminova et al., 2008) and management needs to distance itself from trying to predict the unknown and to embrace the unknown when it becomes known so organizations can move from “troubleshooting to opportunistic orchestrating and networking” (De Meyer et al., 2002).

Perminova and colleagues (2008) adapt the relativistic view of uncertainty and recognize that different beliefs and experiences lead to a different perception of uncertainty. Their definition embraces a dualistic nature of uncertainty, as its appearance might have a negative or positive outcome. According to Perminova and colleagues (2008, p. 76), uncertainty is ”a context for risks as events having a negative impact on the project’s outcomes, or opportunities, as events that have beneficial impact on project performance.” The group turns away from planning for uncertainty as we can only plan what we know, which is termed as risks. However, ”[u]ncertainty, in contrast, is an event or a situation, which was not expected to happen, regardless of whether it could have been possible to consider it in advance” (Perminova et al., 2008, p. 77). If by definition, an uncertain event was not expected to happen, it cannot be identified a priori and the organization was either unaware of the possibility of the emerged event or did not consider it as likely to happen and, therefore, did not include it in the project plans (De Meyer et al., 2002). Such unforeseen uncertainty is termed as unknown unknowns or ”unk-unks”.

The origin of unknown unknowns is attributed to the two psychologists Joseph Luft and Harrington Ingham that created a model of awareness in interpersonal relations in 1955 and defined unknown unknowns as an activity that is neither know to self nor others (Luft, 1982). However, the term became widely known when the United States Secretary of Defense Donald Rumsfeld used it during a press conference in 2002 in which he described the lack of evidence that could link the supply of weapons of mass destruction to terrorist groups by the government of Iraq (Rumsfeld, 2002, emphasis added):

> Reports that say that something hasn't happened are always interesting to me, because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. **But there are also unknown unknowns -- the ones we don't know we don't know.** And if one looks throughout the history of our country and other free countries, it is the latter category that tend to be the difficult ones.

The concept of unknown unknowns, or unforeseen uncertainty, was adopted by social scientists to describe the planning difficulties with limited access to or availability of knowledge within projects, organizations, or economies. The less knowledge available, the more unpredictable the process, however, if “we don’t know we don’t know” (Rumsfeld, 2002), there are no predictions to be made and organizations can only deal with the unknown when it appears.

The term “unknown unknowns” was adopted by engineering and project management professionals to express that “important parameters and possible outcomes are not known; some things out there are not on the horizon at all” and are referred to as “unawareness” or “unforeseen contingencies” by economists and “wicked problems” by public policy scholars (Loch et al., 2007, p. 4).

According to De Meyer and colleagues (2002), unk-unks can emerge “out of the blue” from single, unanticipated events, but might as well arise due to the accumulation of several unanticipated events, which, investigated individually, might have been foreseeable, but when those events interact, they lead to unk-unks. Therefore, we can derive that even though events or management tools might have been known, the necessity of acting only emerges out of context, which highlights a process philosophy. The authors further advocate that the appearance of unk-unks calls for flexibility, iterative planning, mobilization of networks to solve challenges and flexible relationships, and strong communication with stakeholders. Such unk-unks introduce new challenges and to advance the development, project plans must be adapted constantly along the process. Planning is possible and favorable in stable projects that are confronted with foreseeable uncertainty, however, projects with a high level of unk-unks need to emphasize learning and parallel execution of several tasks while the process evolves (De Meyer et al., 2002; Loch et al., 2007).

Several tools and frameworks attempt to control, limit, or foresee uncertainties, however, the notion of predicting something uncertain remains an oxymoron. To foresee or even predict the exact timing or configuration of a solution within the uncertain environment that surrounds the emergence of novelty is merely impossible (Garud, Gehman, et al., 2017). In development projects, deviations might occur in project steps that were not included in the initial scope of the project (Munthe et al., 2014) and managerial approaches for such development projects might have several shortcomings when confronted with unexpected problems (Aggeri & Segrestin, 2007). This stresses the importance of developing different approaches that can embrace uncertainty and cope with it during project execution, ergo, when we actually do things within practice, which I shall discuss in this thesis.

2.2 Practice theory and competence

Just like process research, practice theory is based upon the philosophical perspectives of Wittgenstein and Heidegger, who elaborate the notion of society and culture being constituted by an amalgamation of actions and institutions, constituted by meaningful performance, instead of limiting it to physical and biological processes (Rouse, 2007). Practice theory challenges individualism and system theory and is seeking out “the middle-ground between structural determinism and deconstructive nihilism” (Whittington, 2011, p. 183).

2.2.1 Practice definitions and ontology

When applying practice theory to an organizational context, we try to shed light not only on what people actually “do” when they are part of an organizational construct but on the holistic embeddedness of their actions (D. Nicolini & Monteiro, 2016). Although we observe those “doings and sayings”, we consider them how they are involved with any kind of practice that constantly shapes and reshapes an organization. Calling to our minds the infamous box-and-arrow figures within organizational literature, in which boxes are extensively described as some state of the organization and process arrows are often neglected. Practice theory shifts our attention to the arrows and through its procedural nature, it enables us to “theorize the arrows [, or processes,] to understand how actions produce outcomes” (Feldman & Orlikowski, 2011, p. 1249). Unfamiliarity with practice theory might lead to confusion as it does not treat the rationalistic questions about what knowledge, skill, or new organizational state was acquired but rather *how* they were achieved (Feldman & Orlikowski, 2011).

The theory attempts to describe elements of the world around us as something “that is routinely made and re-made in practice using tools, discourse, and our bodies.” (C. Nicolini, 2012, p. 2). Practice is constituted by the interwoven interactions and entanglements of social and material entities. The practice idiom views the world and its elements as a fluid scene that unfolds while interacting with it and social life emerges through our recurring actions (Feldman & Orlikowski, 2011). Practice theory considers the organization as the place and the result of work activities, making the organization a construct that is constituted of practices and that embodies these work activities (C. Nicolini, 2012).

Applying a practice lens will ultimately lead us to a processual and relational worldview. It highlights the importance of activity, performativity, and work in the creating of everything. (C. Nicolini, 2012). As our actions are relational and context-dependent, they are also consequential, meaning that any activity can become a practice as "the action of engaging in it is consequential for the development of the activity" (Feldman & Orlikowski, 2011, p. 1242). We can, therefore, state that some practices can only be identified as such ex-post. The performativity and contextuality of practice reinforce the holistic standpoint that we need to take when researching organizational practice. Practice theory observes interconnected actors and objects and their relational experience instead of selected and isolated entities and, therefore, rejecting dualism in favor of dualities (Feldman & Orlikowski, 2011; Jörgen Sandberg & Tsoukas, 2011; Tsoukas, 2017).

If we look at the process of innovation from a practice perspective, we need to recognize this process as the holistic coming together of all practices of its participants, knotted together by their social and material interactions. Sandberg and Tsoukas (2011) elaborate that when analyzing the intertwinement of socio-material practices we need to distance ourselves from the scientific rationality, which is introduced by prevalent organizational and management theories as they do not capture the onto-epistemological assumptions of practice. Scientific rationality focuses on the subject-object relation, which in turn will stir research to a dualistic perspective that investigates separate entities and, therefore, failing to grasp the logic of practice. The authors advocate practical rationality and argue that we can only grasp the logic of practice by ontologically prioritizing the intertwinement with the world over epistemological relation between the social and material entities.

Practice theory centralizes practices as a point of departure - not practitioners (C. Nicolini, 2012) – and, therefore, we need to approach the definition of practices. For this work, I will differentiate between 'practice' and 'practices' (the German language uses two distinguishable words that facilitate the understanding: *Praxis* and *Praktiken,* respectively). The term 'practice' (*Praxis*) represents the whole of human action and 'a practice' (*Praktik*) can be framed as a routinized activity, which consists of several interconnected elements - physical and mental activities and social and material interactions (Reckwitz, 2002). Practices are routines: "routines of moving the body, of understanding and wanting, of using things, interconnected in a practice." (Reckwitz, 2002, p. 255).

In a very holistic way, practices can be defined as "historically and geographically recurring localized occurrences" (C. Nicolini, 2012, p. 10) or several elements of doings and sayings that are spatially and temporally dispersed and organized by a context (D. Nicolini, 2017). Nicolini and Monteiro (2016) put together an extensive literature review on the definition of practices and extracted similarities among them. According to their review, practices are constituted by several sub-components, are only meaningful when performed in a context, and are happening simultaneously and harmoniously with other practices. Practices are of social and material nature and are constituted by the intertwinement of those elements. Exemplifying those smaller elements that constitute practice varies across theories and can range from "sitting correctly at a table" to "science as a whole field itself" and, therefore, "[n]aming, defining, and exemplifying practices is already theorizing them" (C. Nicolini, 2012, p. 10).

Cook and Brown (1999, pp. 386–387) define practices as "the coordinated activities of individuals and groups in doing their 'real work' as it is informed by a particular organizational or group context." Such meaningful, coordinated activities can manifest in the work context and consequently become a component of a practice (C. Nicolini, 2012). A practice is, therefore, a meaningful activity, with the meaning drawn from a particular group or work context. Transposing this thought to the environment of the innovation process, "doing their real work, informed by context" relates to any coordinated activities that are being pursued to advance the innovation process by a person embedded in the context of that process.

The notion of practice theory lies in describing key moments of the world we live in as routinely enacted and re-made in practice through social and material elements like artifacts, language, or our bodies (C. Nicolini, 2012). When applying practice theory to research, there are common themes, elaborated by Rouse (2007) and Whittington (2011), which we need to acknowledge: Focusing on practices needs to imply that they are part of a larger structure; the existence of an individual that influences practices and shapes and reshapes them through improvisation actions; practice is enacted through the interaction of artifacts and bodily actions; the importance of discursive practice but also tacit elements which are not possible to express through language. Those themes, among others, are essential to practice theory, but not all need to be applied to scientific research simultaneously (Whittington, 2011).

For this work, I recognize Reckwitz's (2002) differentiation between practice (*Praxis*) and practices (*Praktiken*) and advocate the viewpoint of Praxis being the whole of all actions within the organizational context. This study is focusing on practices (*Praktiken*) and approaches them by advocating Nicolini's notion that defines them as routinely enacted and constantly re-made interactions of interconnected social and material elements in form of discourse and bodily actions. "[A practice is a] coherent and complex form of socially established co-operative human activities" (MacIntyre 1981, p. 187) in (C. Nicolini, 2012, p. 9).

2.2.2 Terminologies and ontological perspectives of competence at work

The definitions, concepts, and typologies surrounding competence have been discussed, opposed, and expanded for many decades. The wide range of stakeholders of the term that investigate the competence concept include psychologists, organizational and management theorists, human resource managers, educationalists, and politicians, each approaching the definition and framing of the term differently (Burgoyne, 1993). Adapting competence as a concept to organizational and management literature and comparing and differentiating it to terms such as skills, attributes, knowledge or traits lead to various typologies and taxonomies, making it impossible to find a coherent theory, capable of enclosing and considering all different ways that competence is being referred to (Winterton et al., 2005).

The ontological perspective plays a big role when defining competence. Depending on how we perceive the relation between worker and work, we create different concepts and methods surrounding competence and ultimately interpret the practices at work. This has further implications for competence development as the worker's development is inseparably linked to how we think competence is constituted. To clarify the concepts and define the term for this present work, I will provide an overview of current approaches and introduce literature that attempts to define and categorize competence at work. Originally used in the educational literature to investigate the behaviors of trainers and teachers, the competence concept became widely known through the work of Boyatzis (1982) in the management field (Hoffmann, 1999), dealing with professional competence at work from an individual perspective and Prahalad and Hammel (1990), who outlined competences' strong relation to organizational effectiveness and argue that competence is the root of competitive advantage, adopting a collective perspective.

To advance on the clarification of competence at work, I follow the literature stream portrayed by Dall'Alba (1996), Hoffmann (1999), Velde (1999), Sandberg (1994, 2000; 2009), Winterton et. al. (2005), Håland and Tjora (2006) and Lindberg and Rantatalo (2015) that contrasts a rationalistic (generic, entity-based, descriptive, positivistic) with a relational (interpretative, non-entity-based, constructivist, phenomenological) approach to competence. This opposition represents a longstanding discussion between the generic view that believes in certain attributes of individual competence being transferable, and the context-dependent view that assumes that individual competence inseparably linked with professional work practice and goes beyond individual attributes.

Rationalistic approaches focus on individual knowledge or skills in a static, analytical model, that assumes context independence and therefore, advocates that a competent practitioner can perform well in any situation or workplace (McMullan et al., 2003). As this rationalistic approach serves the "operationalizations" of individual attributes into quantifiable measurements it tends to be narrow and limited and might not fully comprise complex professional practices (J Sandberg, 2000; Velde, 1999). Such entity-based approaches to professional competence are rooted in a traditional ontology that assumes a primarily disconnected link between human and world that only connects when we pursue different activities (Dall'Alba & Sandberg, 1996; Jörgen Sandberg & Pinnington, 2009). This view allows organizations to categorize competence (Boyatzis, 1982; Ellström, 1998; Veres III et al., 1990) and to approach competence with a utilitarian instrumentalist philosophy, advocating that rational management of individuals eventually leads to competitive advantage (McGuire & Garavan, 2001).

Although this traditional approach is considered to be quite narrow (Velde, 1999), scholars believe that it allows to development of highly transferable generic skills that might not apply to context-dependent tasks but to the general execution of jobs (Winterton et al., 2005). The main criticism of the rationalistic approach is its disconnected view on worker and work tasks, therefore, a lack of contextualization. Some scholars empirically identified that technical expertise and skills do not differentiate between more or less competent professionals but the contextual and interpretative relation to the task (Dreyfus & Dreyfus, 2005; Kosmala, 2013; Lindberg & Rantatalo, 2015) and use relational approaches to explain the phenomenon of competence. The rationalistic competence perspective is being challenged by relational approaches that assume that person and world are inextricably related through practice (Dall'Alba & Sandberg, 1996).

2.2.3 Relational competence approach - as practice

The contextual-relational paradigm to professional competence challenges the entity-based perspectives and proposes that human and world are inseparable and cannot be divided into two entities and, therefore, unifies worker and work. Several scholars adapted a relational perspective to research professional competence at work, like understanding-based and practice approaches. The understanding-based approach defines competence through the meaning a professional gives her work (J Sandberg, 1994, 2000). This interpretative concept of professional competence is based on Heidegger's existential ontology that assumes that the world we live in is not a combination of entities but one "meaningful whole". This thesis, however, will deal with the practice-based approach, which assumes that competence is formed around practice and becomes an indistinguishable part of it.

If we apply practice theory to the relational approach of competence, we recognize the interwoven socio-material relationship that constitutes practice and acknowledge that competence emerges out of routinized activities within a work context. To investigate competence as practice we cannot focus on the individual nor the organization separately with a dualistic perspective, but need to incorporate the individual and its activities within the organizational context that emerged in practice (Bramming, 2004). Lindberg and Rantatalo (2015, p. 565) view human activities as practice and transpose this line of thought onto the concept of competence where "a competent professional is […] able to anticipate what is regarded as a good and favorable activity in a certain practice and to act accordingly". They define competence as "the inferred potential for desirable activity within a professional practice", therefore advocating and contributing to the relational perspective that centralize context-dependency. Lindberg and Rantatalo suggest competence as balance between social and performance orientation. Those social abilities relate to being flexible, cooperative, socially competent, and humble whereas task-related abilities comprise ambition, leadership, and autonomy. They termed this balance between self-knowledge and responsibility *logic of excellence*.

Scholars that approach competence with practice theory, such as Lindberg and Rantatalo, argue that competence includes not merely knowledge, knowing-in-action, or the understanding of work, but comprises social and non-social interactions embedded in practice and might therefore be the most comprehensive concept of what constitutes professional competence at work (Jörgen Sandberg & Pinnington, 2009).

Zarifian (2001, 2003) argues that competence can only manifest in practice and proposes the definition of competence as being a practical understanding of situations that are based on previously acquired knowledge and transforms together with the diversification of the situation. The person's interaction with her surroundings is a central element of Zarifian's definition of competence. He emphasizes the relational aspect by viewing competence as the ability to mobilize networks of actors that are involved in the same situations as the worker himself and the faculty to make these actors share the implications of their actions and assumes co-responsibility (Zarifian, 2001, p. 74). He argues that competence includes the actor's consciousness when being in complex situations that exceed his individual skills and engaging in collective work inside the network. By adopting this social constructivist perspective, he advocates that competence is constructed not only by engaging with the assigned tasks but also by being immersed in an interactive environment.

In agreement with this observation of Zarifian, Le Boterf (2003) recognizes that competence develops through the performance of individuals by engaging with the professional context, ultimately advocating a constructivist philosophy. He suggests that professionals should access, mobilizes, combine and transpose previous knowledge, obtained from personal and mean resources. The adaptability of the worker to different tasks is related to the learning process of the individual (Le Boterf, 2003; Zarifian, 2001). This relates to the worker's capability of using their knowledge in different situations. Both, Zarifian and Le Boterf use the term competence concerning the personal achievements within a given context, in other words, what is produced or realized by an individual at work or in practice (Lima & Brito, 2017).

The relational perspective of competence exposes a highly dynamic and context-dependent construct (McMullan et al., 2003) that incorporates the interaction with practice and other individuals along with the awareness of particular faculties and how to apply them to ever-changing situations in an intelligent way. In this work, competence is defined through a relational approach, in which competence is formed through practice within a highly dynamic and context-dependent construct. This definition is, however, not limited to the application of attributes, skills, and experience and is not trying to define what is a competent worker or work. Competence, according to this study, embraces the relational interaction among actors and practices within ever-changing situations, making it impossible to separate the worker from its work. Competence will therefore be defined through the actor's interaction with its practice, making it inseparable.

When considering relational competence definitions, we always must be aware of the current practical situation the actor is immersed in. Competence as practice can have many facets and includes the inferred potential for desirable activity within a professional practice; taking initiative & assuming responsibility; practical understanding of situations based on previously acquired knowledge and transforming the knowledge to the extent that it increases the diversification of situations and; the faculty to mobilize networks of actors around the same situations, to make those actors share the implications of the actions and to make them assume co-responsibility (Zarifian, 2001, 2003).

Table 2 presents an overview of the theoretical models and concepts elaborated in this section on the theoretical background of this study.

Table 2 Theoretical background reference list

Themes and dimensions	Discussed topics	Authors
Innovation	Concept and definition	Martin, 2012 Baregheh et al., 2009 Fagerberg, 2009 Utterback, 1971
	As a process	Van de Ven and Poole, 1989, 2005 Garud et al., 2017b, 2017a Garud et al., 2013, 2015 Dougherty, 2008 Sandberg et al., 2015 Gopalakrishnan and Damanpour, 1997 Van de Ven, 1992
	Performativity & Emergence of novelty	Langley et al., 2013 Langley and Tsoukas, 2016 Garud et al., 2015, 2017, 2018b, 2018c Garud and Gehman, 2019 Mesle and Dibben, 2016: 4 Schmitt and Miller, 2007
Complexity & duality	Complexities	Tsoukas, 2017 Petzold et al., 2019 Garud et al., 2011, 2013, 2017b
	Duality, contradictions, and paradox	Smith et al., 2017 Hargrave and Van de Ven, 2017 Andriopoulos and Lewis, 2009 Mazmanian et al., 2013 Farjoun, 2010 Papachroni and Heracleous, 2020 Tsoukas, 2017 Dougherty, 2008
Uncertainty		Pavitt, 2004

	Concepts and traditional management tools	Milliken, 1987 Loch et al., 2007 Van de Ven, 1986 Rice et al., 2008 Loch et al., 2007 De Meyer et al., 2002 O'Connor and Rice, 2013 Brasil et al., 2018
	Relativistic perspective	Perminova et al., 2008 De Meyer et al., 2002
	unknown unknowns or unforeseen uncertainty	Loch et al., 2007
		De Meyer et al., 2002 Garud et al., 2017b Aggeri and Segrestin, 2007
Practice theory	Concepts and definitions	Nicolini and Monteiro, 2016 Feldman and Orlikowski, 2011 Nicolini, 2012 Sandberg and Tsoukas, 2011 Reckwitz, 2002 Cook and Brown, 1999 Rouse, 2007 Whittington, 2011
Competence	Concept and definition	Winterton et al., 2005 Burgoyne, 1993 Sandberg and Pinnington, 2009
	Rationalistic perspectives	Boyatzis, 1982 Veres III et al., 1990 Ellström, 1998 McGuire and Garavan, 2001
	Relational perspective	Velde, 1999 Sandberg, 1994, 2000 Dall'Alba and Sandberg, 1996
	Competence as practice	Zarifian, 2008 Le Boterf, 2003 Lima and Brito, 2017 Lindberg and Rantatalo, 2015

Source: Own table

3 METHODOLOGY

3.1 Locating the study

The primary objective of this thesis was to **analyze practices that were identified by dealing with uncertainty within the innovation process and how they turned into competences.** Additionally, secondary objectives that are treated in this work include:

- Mapping the innovation process of the chosen case
- Detecting and categorizing uncertainties that emerged during the innovation process
- Identifying and categorizing practices that contributed to deal with uncertainties
- Analyzing how practices, when confronted with uncertainty, can turn into competences

To reach the research objectives, this thesis used extended case methods (Burawoy, 1998), which are characterized by researchers engaging with the subject he or she is researching in a sensible and respectful dialog. Instead of imposing theories and concepts a priori on the investigated constructs, the extended case method approaches the development of the research flexible and the researcher must, therefore, be willing to extend his viewpoint with the unfolding of events and collection of experiences (Cock, 2010). Due to the nature of the research method, due to the performative perspective of this work, and in the spirit of transparency, I want to guide the reader through the development process of the research question, before presenting it. This controversial approach is inspired by Anonymous (2015) and Raguh Garud (2015), who brought attention to the ethical discussion of "presenting hypotheses as if they were known a priori but, in fact, generated after data analyses." (Garud, 2015, p. 1). Researchers who adopt methods with an open-minded perspective towards their experience with the investigated study need to adapt their research to wherever the path leads them. This includes hypotheses and, in the case of this thesis, the research question and objectives. The reason behind presenting the research question as evolution instead of a rigid, unchanged, *a priori* starting point is based on the ethical convincement of advocating research transparency.

This contribution is concerned with the development of organizational practices and competences within complex innovation processes as a response to unforeseen events. The initial research question (RQ) was inspired by the complex innovation process and the arrangement of players, their interaction, and relationships to investigate their competence (development) at work.

Initial RQ: **“How do competences emerge from innovation processes?”**

This initial setup led my research to the different concepts of competences including the duality of rational and performative perspectives within competence theory. The investigation of innovation processes introduced me to performativity and complexity. Performative innovation processes and relational competence approaches are based upon similar context-dependent concepts of reality, which focus on change and the notion of ‘constantly becoming’ instead of on stable structures that are disconnected from its process. This led me to investigate the notion of change and unforeseen events – or in a more general vein: uncertainty. I adapted the research question due to new theoretical insights:

Transition RQ: **“How does competence development, conceptualized from a perspective of complexity, help to deal with the uncertainties that emerge during the performative innovation process?”**

This transition research question guided me through the initial phases of the data collection and analysis, however, a missing link between uncertainty and competence became evident. This made me extend my research by including the concept of organizational practices which became a bridge between the emergence of unforeseen events and competence development and shaped the final research question.

Final RQ: **“How do practices emerge from uncertainty to engage with unforeseen events and how does this engagement stimulate the development of competences?”**

Due to the explanatory nature of social phenomena that emerged from the formulation of the research question, a descriptive and explanatory case study method was chosen (Eisenhardt, 2021; Yin, 2018) to investigate a research group, which was involved in two fuel cell R&D projects in a Brazilian federal university laboratory and financed by an energy distribution company. To describe the innovation process, uncertainties, and practices along with the development of the fuel cell projects, I used project documentation and interviews. Exploring the case with those methods makes it possible to explain the intertwinement of practices, unforeseen events, and complexities that emerged from the performative innovation process. Theory building was done prior to the data collection, however, was revised and extended throughout data collection and analysis (Burawoy, 1998; Cock, 2010).

The aim of applying a qualitative method was to analyze practices within the innovation process, how they emerged from unforeseen events, and how competence developed through the engagement of participants with practice (Garud, Berends, et al., 2017). Qualitative research uses an interpretative and naturalistic approach to the analyzed subject (Deniz & Lincoln, 1994), which is especially important when applying process philosophy and practice thinking. Qualitative research values the description and understanding of human actions and interactions as well as meanings and social processes in an organizational setting as it focuses on unfolding events over time making it the most suitable method to investigate relational, contextual, and temporal processes (Gephart, 2004). Furthermore, qualitative research is often designed parallel with its execution and makes it therefore open for unanticipated events also due to its holistic perspective towards reality (Gephart, 2004).

At the time of the research, the projects were already concluded for several years, which created the possibility of a retrospective research method. Practices can only be identified as such ex-post as they developed over time and are often within construction when the organizational processes are still in development (Feldman & Orlikowski, 2011; Orlikowski, 2002). This facilitates an ex-post reflection of the interviewees on the development process, and practices are more structured, which enabled interviewees to describe developments in the past ‘at that time’. In this methodology section, I will first introduce the investigated case, follow with the data collection, which was done via interviews and the collection of secondary data, and then continue to the analysis.

The theoretical concepts, presented in the previous section, can be approached with diverse ontological lenses. In this work, the innovation process is defined as a performative and highly dynamic structure that is constantly becoming and is being transformed through the assumption of context-dependency without any temporal timestamps. Additionally, relational and temporal complexities within the innovation processes are being thematized and I recognize the distinction of elements without clearly separating them by adopting duality instead of dualism.

Uncertainty, in this study, relates to unexpected/unforeseen events or situations, regardless of whether they could have been possible to consider before or not. If by definition, an uncertain event was not expected to happen, it cannot be identified a priori and the organization was either unaware of the possibility of the emergent event or did not consider it unlikely to happen and, therefore, did not include them in the project plans. Unforeseen uncertainties can emerge “out of the blue” from a single, unanticipated event, but might as well arise due to the accumulation of several events, which, investigated individually, might have been foreseeable, but when those events interact, they lead to unk-unks. Therefore, we assume that even though events or management tools might have been known, the necessity of acting only emerges out of context, which advocates a process philosophy.

For this work, I differentiate between practice (*Praxis*), as in ‘the practice of chemistry’ and practices (*Praktiken*), as in organizational practices, and advocate the viewpoint of *Praxis* being the whole of all actions within the organizational context. Practices (*Praktiken*) are defined as routinely enacted and constantly re-made interactions of interconnected social and material elements in form of discourse and bodily actions and are the focus of this thesis.

Within the vast possibilities of locating a definition of competence, in this study, competence is defined through the actor’s interaction with practice. I adopt a relational approach to competence, which is formed through practice and is, therefore, a highly dynamic and context-dependent construct. This definition is therefore not limited to the application of attributes, skills, and experience and is not trying to define what is a competent worker or work. Competence, according to this study, embraces the relational interaction among actors and practice within ever-changing situations, making it impossible to separate the worker from its work.

3.2 **The case**

The case chosen for this thesis is a Brazilian research and development project, created and supported by the Brazilian federal university UFMG and the national energy distribution company CEMIG to develop the first national SOFC prototype. The prototype development aimed at using merely national products and resources. The project was divided into two parts over ten years and comprised the construction of an R&D laboratory, the development of two SOFC prototypes (50W and 1kW), the education and training of human resources, the establishment of national and international research collaborations and the production of scientific and technological knowledge on hydrogen technologies. This thesis is investigating both projects, however, it focuses on the first SOFC prototype development project from 2009 to 2014. The uncertainties and practices, presented later in this thesis, are extracted from the first prototype project.

Two project leaders maintained in charge of the projects throughout all phases. The team was composed of research scientists, research coordinators, bachelor, master, Ph.D., and post-Ph.D. students, who were responsible for research monitoring and measuring, and technical support staff, students from *iniciação científica* (IC), and interns who were assisting with the process scale-up, purchases, and cell production. A complete list of all participants can be found in Appendix 5.

After ten years of R&D and roughly R$ 7.7 million in investments, the project resulted in nine completed master dissertations, six completed Ph.D. thesis, 14 published articles, 50 congress presentations (oral and poster), and two functioning SOFC systems of 50W and 1kW power including more than 30 technical and financial reports.

The project group aimed to develop two full functioning prototypes throughout two projects which received the internal classification of high risk and low probability of commercialization (internal CEMIG report). The common notion of innovation comprises the aspect of commercialization. However, this work is concerned with the innovation process and focuses on the sequence of events and changes of interactions, and contexts, all during the development of a new idea. This case can, therefore, be classified as a development process of innovation and can be studied within the context of innovation processes.

The case study was chosen due to several factors: (a) Data accessibility: The two research leaders showed their cooperation by sharing data and agreed to be accessible for several interviews as well as establishing links to other participants of the two projects; (b) Geographical proximity: As the projects were conducted within a laboratory of UFMG, frequent visits to the laboratory could have been conducted; (c) Grade of innovation: Any development project contains uncertain elements that must be challenged, however, uncertain elements in more complex innovation processes and smaller organizations, such as in this case, might be more frequent, easier to detect, and with a higher impact on further steps; (d) Special case: Being the first SOFC development project in Brazil, makes this case a special case (Siggelkow, 2007), not comparable to other cases or events. It offers the opportunity to research this unique innovation process without the need to be representative nor to increase the sample size. I justify using a singular case study, as process research breaks down the event that is a case into many smaller events (Langley et al., 2013). This case study is, therefore, constituted of several unforeseen events and identified practices that will be examined in this work.

3.3 Data collection

To approach the objectives of this research, I carried out several rounds of interviews and studied archival sources like project contracts, formal reviews, and reports, 'best practice' manuals, technical documents, academic memoirs, financial records, communication records between the project team and other organizations, meeting notes and other internal records, formulated or collected by the project team and the client. Such archival data add significantly to the analysis of the case as they are suitable for recording events and chronological processes over a long period of time (Langley et al., 2013). The relational aspect of competence and the dynamic and temporal innovation process call for a processed orientated research (Garud, Berends, et al., 2017) to incorporate these temporal progressions of events, recognizing that "practices are continually questioned and reinterpreted, even as they are performed" (Langley et al., 2013, p. 10). As the development projects were concluded in 2014, this research was not executed in parallel but retrospectively and, therefore, relies on interviews, formal records, and informal notes and documents.

The collected data enabled approaching the research objectives. To identify unforeseen events, analyze practices, and determine the chronological development of the case, interviews were introduced. Secondary data was consulted to map the innovation process and to identify practices.

3.3.1 Interviews

For the interviews, all project participants were identified and a total of ten were selected, who varied in their academic degrees and responsibilities within the project. In total, 17 interviews were carried out with the participants. I conducted between one and two rounds of interviews with each interviewee, focusing on the participants of the first project due to their availability. The formal and semi-structured interviews were conducted in person, via telephone, or through diverse online communication software[2], had an average time of 1 hour and 10 minutes, and were afterward transcribed manually. Each round of interviews was handled with a different set of scripts. Table 3 presents the participants interviewed. Throughout the analysis, I refer to and cite the transcribed interviews in the following format: (Participant Interview timestamp:hhmmss). For example: (RC I2 2340) refers to timestamp 23 minutes and 40 seconds (2340) of the second round of interviews (I2) with the research coordinator (RC).

[2] Following software was used: Skype, Zoom, Whatsapp, Google Meet

Some interviews were interrupted due to connectivity issues and, therefore, some references have additions like ‘p1’ or ‘p2’ (parts).

Table 3 Interview list

Dummy	Role	Project	Round 1	Round 2
RL1	Research leader	1 & 2	✓	✓
RL2	Research leader	1 & 2	✓	
RC	Research coordinator	1	✓	✓
Part1	Ph.D., post-Ph.D.	1	✓	✓
Part2	Master, Ph.D., post-Ph.D.	1	✓	✓
Part3	Ph.D., post-PhD.	1	✓	✓
Part4	Ph.D.	2	✓	
Part5	Master, Ph.D.	2	✓	
Tech	Technician	1	✓	✓
Intern1	Internship	1	✓	✓

Source: Own table

The first interview was conducted with RL1 with the primary objective to get an initial overview of the project and its timeline. The script for this interview “pre” is disclosed in Appendix 2. The first round of interviews was also the first contact with most participants[3]. Date and time were arranged via e-mail or Messenger and the interviewee received an introduction page to the research, including several topics of the interview. The introduction page is added to Appendix 1. The goal of this document was to give the interviewee a first impression of the research, to define some of the terms (e.g., ‘practice’, ‘organization’) as they often differ from the definitions of hard science research, to clarify that the questions would not focus on the technology but the development process and to remember the participants of the project and its timeline. The page also served to create a basis so the interview could build upon this timeline.

The interview was an open-ended conversation and covered a broad array of predefined questions. The interview started with a basic introduction and then with a questioning about the interviewees' first confrontation with the project. The participant was asked to recollect the beginnings of the projects and how they evolved. The goal was to objectively record the course of the case and to comprehend the personal perception and development of the individual.

[3] Except RL1, RL2 and Intern

Besides getting a general overview of the organization's activities and timeline, a particular interest of this round was to identify practices and unforeseen events that might have been established during the project. When I noticed practices, difficulties, or unforeseen events within the conversation, I asked the participants to elaborate on them. A questionnaire script was developed for the student participants and the research leaders and coordinator for the first interview round and can be found in Appendix 3.

The second round was initiated after interviewing eight participants from the first project and two from the second. The objective of the second round was to investigate the before-mentioned topics, difficulties, unknown-unknowns, and practices. This was done by drafting a new script (Appendix 4) that would assist in questioning the participants about the discourse of other participants from the first round and to intensify certain articulations that the interviewee elaborated on in the first round. By interviewing participants, a second time, I was able to add questions about their previous responses and cross-checking the answers of different participants with each other, which reduced the hindsight bias.

This second round was designed to intensify the questioning on practices, unforeseen events, and other difficulties that were identified in the first round and documents and reports. An objective was to cross-reference the responses of all interviewees to then gain insights on the topics, practices, difficulties, and unforeseen events across the entire organization. After the second round was completed, I followed up with some interviewees via email or messenger to resolve some newly emerged questions. To indicate additional questioning beyond the interviews, citations in this thesis include the communication channel, for example, 'RC, WhatsApp' references a communication with the research coordinator through the platform *WhatsApp*.

3.3.2 Secondary data

As an additional source of data, I gathered several physical and digital documents that were accumulated or drafted by the project group. I was granted access to the web storage folder and the laboratory and accumulated several different types of documentation, which surrounded the two projects. Due to laboratory reorganizations and relocation of other project groups, some of the physical documentation was not findable, but many files were still stored in the laboratory. Table 4 lists secondary data that was available:

Table 4 Secondary data overview

Administration	Research and lab	Other
Spending reports	Planned activities and phases	Travel tickets to conferences
Repair and order request	Reports for CEMIG	CV's of participants
Salary slips	Produced articles and research	e-mail exchanges
Internship contract	Material list and costs	Product catalogs
CEMIG-UFMG partnership agreement	Notebooks and memoirs of research leader with notes on meetings and research	Information sheet on how to clean the laboratory incl. responsible participants and signing boxes.
Architectural plans & sketches of lab	List to reserve equipment and to sign after using equipment	Several organizers with daily memos and activities entries

Source: Own table

Additionally, I consulted an expert in the field of social science fuel cell research who passively observing the project planning and execution since the beginning but was not part of the organizational structure of the projects nor its execution. This provided useful insights and information for this study and was considered secondary data. The data were merely used for the description of the case and its chronological development, but not for the data analysis.

3.4 **Data analysis**

The data analysis started with predefined categories that were selected in accordance with the research questions and the theoretical basis, developed at that time. By continuously intensifying the data analysis and further elaborating the literature review additional categories emerged from the search for repetitions and dualities within the interviews (Bardin, 2011). This research design demanded a constant switch between data collection, data analysis, and theoretical elaboration (Burawoy, 1998). New insights on data needed to be reflected in the theory and vice versa. The analysis unfolded in stages. An extensive interview with one of the project leaders (Appendix 2), several informal follow-up conversations, and the study of the research leader's academic memoirs contributed to a first analysis of the project design and process. This first research gave grounds to the development of the questionnaire script for the first round of interviews, which can be accessed in Appendix 3.

During the first interview round, secondary data was constantly consulted. After executing and transcribing the first round of interviews, I reread all transcriptions and registered recurrent themes. I then mounted a spreadsheet with the following categories: "topics, difficulties, unk-unks, practices, and competences" and started filling out the categories with the data extracted from the transcriptions, while cross-referencing the data with each participant to be able to determine who said what, in which interview with what timestamp. If the interviewee agreed with the occurrence of a certain matter, the cell that links the participant with the subject was filled out with '1', and if she disagreed with a '0'. If no data was collected on the theme, the cell was left empty. Each filled-out cell received a note in which I cross-reference the datapoint with its discourse from the interview and the timestamp of the transcription. I extracted data from the interviews, which seemed to be important at that time to answer the research question and objectives but also added repetitive themes across the interviewees. Furthermore, I added themes that were not added a priori but were repetitively addressed by more than one interviewee. This was done to stay receptive to practices, unforeseen events, and other difficulties that were not predefined and could enrich the research analysis. Table 5 is a simplified extract of the construction of the datasheet.

After collecting and categorizing the data from the first round of interviews, I returned to the theoretical part of my thesis, intensifying the elaboration of the innovation process theory, on practice theory, and uncertainty. Additionally, more secondary data was collected and the previously collected one was revisited. In the subsequent phase, I designed scripts for the second interview and included previously identified events, practices, and difficulties to understand their emergence and transformation and possible competence development. I included several new insights from the theoretical research into the new script and drafted follow-up questions on the previous responses but also excluded some themes that did not seem to be as relevant anymore as initially expected. The 'second round' scripts also included individually shaped questions. This was due to the objective of cross-referencing certain themes among the participants and, therefore, each script for each interview had to be customized. If in one interview, 'Interviewee A' commented on a certain topic that was considered as important according to the research question and objectives, a follow-up question was included in the second script to investigate more on that topic. To cross-reference that topic with the experiences of other interviewees, that topic was included in the second scripts of other interviewees, hence, resulting in personalized second-round scrips.

To understand the implications of the events, I investigated how events appeared, how they were detected, how they affected the group, how they handled the events and how practices might have contributed to finding a suitable solution or might have emerged to deal with those events. This questioning provides me with information on, inter alia, the degree of uncertainty,

Table 5 Simplified datasheet extract.

				Participant 1	P2	P3	P4	P5	P*n
		Interview 1 (I1)		20.05.2020	13.05.2020	15.05.2020	13.05.2020	16.05.2020	06.05.2020
		Interview 2 (I2)		14.09.2020	23.10.2020	21.08.2020		16.10.2020	09.10.2020
Topic	t1	Time pressure	I1	1	1	0	0	1	1
			I2	1	1	0			1
	t2	Project responsibility	I1	0	1	0		1	1
			I2	0		0			
	t3	External help	I1	1	1		1		1
			I2			1		1	
	t4	Rede Pacos	I1	1	1	1	1		
			I2		1	1			0
	t*n	etc.	I1	1		1		1	1
			I2						1
Difficulties	d1	Starting from zero	I1	1	1	1	1	1	1
			I2		1/0	1			
	d2	Order process	I1	0		1		1	1
			I2	0	0	1		0	1
	d3	Broken equipment	I1			1		1	1
			I2	1	1	1			1
	d4	Equipment use	I1	1	1	1	1	1	
			I2	1	1	1		1	1
	d'n	etc.	I1	1					
			I2	1	1	0			0
unk-unk	u1	Interconnector	I1		1	1			
			I2			1			1
	u2	German oven and connection	I1						
			I2		0			1	
	u*n	etc.	I1	1					
			I2	1	1			1	
Practices	p1	Pass it on	I1			1			
			I2	1	1	1		0	
	p2	Equipment responsibility	I1	1		1			
			I2	1	1	1		1	1
	p3	New entrants	I1	1		1		1	1
			I2	1	1	1			1
	p4	Notebook checking	I1					1	
			I2			0			
	p5	Repair equipment	I1			1		1	
			I2			1			
	p6	Meetings	I1	1	1	1		1	
			I2	1		1		1	1
	p*n	etc.	I1	1					
			I2	1	1			1	1

Source: Own table

the chronological interception of unforeseen events, applied, implemented, and developed practices, and how competence developed in practice.

The customized scrips guided me through the second round of interviews, however, with each new interview, new experiences and information were transmitted. This meant that the personalized scrips of interviewees, who were not yet questioned had to be adapted with each interview conducted to utilize all data possible for upcoming interviews. During and after the second round of interviews, some categories were excluded, added, or merged. Some previously categorized unk-unks were rejected, and some difficulties were considered as unk-unks. Similarly with some topics and practices. Some topics were considered less relevant, and others turned out to be practice, and through the course of the data analysis, some previously defined practices were later not considered as such anymore.

This performative data analysis provided a holistic representation of events and practices. Previously categorized elements were being constantly revisited and modified when new information was introduced to the research and predefined themes were reshaped. Continuously revisiting secondary data and transcriptions was an essential part of the analysis as some data might have been considered less important at first, but through the performative development of this thesis, it sometimes became valuable. Due to this temporal construction of data analysis, some interviewees had to be contacted after the two interview rounds to collect more information on certain subjects.

4 THE TECHNOLOGY AND CASE SET-UP

In this section, I will describe fuel cell technologies and introduce the case of a research group at UFMG which was involved in two fuel cell development projects with CEMIG over 10 years and I will present the context the projects were embedded in. At first, I will present the complexity and composition of the technology itself and then present the larger context in which the case is embedded, including the historical unfolding of the case and the organizational process of the two projects.

4.1 Contextualization of the prototype development

To comprehend the innovation process of the prototype development, it is beneficial to outline the context in which the development took place. This subsection will describe the emergence of the project, the project group, and the environment in which it was embedded.

4.1.1 Background of fuel cell development in Brazil

Since 1995, the Brazilian government has promoted initiatives that have aimed at stimulating the production of fuel cell technologies. By fostering research from universities and other institutions such as CEMIG, the government reduced the uncertainty regarding technological obstacles by indicating its interest in participating in the technology development and including hydrogen technologies in the Brazilian energy matrix (Raffi et al., 2013). A few years later, in 1999, the government created an instrument for public policies to designate funds for science and technology in strategic areas. With this, the government became more ambitious to allocate a greater flow of resources to the energy sector that benefited SOFCs science and technology programs. As a result, private and international partnerships were intensified, enabling projects such as ethanol reforming for hydrogen production (MCT, 2002).

In addition, in 2001, Brazil faced an energy crisis, driven by the lack of planning in the energy sector, the dependence on hydroelectricity, the low investment in energy transmission, and low rainfall. The electric power cuts in 2001 highlighted the need for greater investments in alternative energy sources in the country. In the following year, the government prospected national technological competencies to develop fuel cell systems in several Brazilian states. Most of the identified competencies were at research groups in federal universities, which had previous experience in researching materials necessary for cell fabrication or on the phenomenon behind the technology. The government selected companies and researchers with expertise in components related to fuel cell development to participate in the most influential worldwide fuel cell conferences to create the first group committed to fuel cell development in the country. These conferences and initial networks were decisive for the technology path in Brazil as many of the decisions that guided the technology development were orientated by information extracted at these places. Each of the researchers identified the equipment used, the dominant materials and techniques, resources, and measurements for the cell performance, and potential international partners. These researchers have visited national industries with industrial processes on ceramic and metallurgic niches. However, at the time, the technology was far from the commercialization phase and the industries had their business in applications distance of energy generation.

The Brazilian government emphasized the need to stimulate the development of a national prototype through coordination and collaboration among different research groups, by creating research networks, intensifying the training of human resources, encouraging the participation of Brazilian companies, and consolidating a new concept for the fuel cell development, which would identify the national research efforts and connect the involved actors. For these purposes, the government, together with the researchers, implemented the Brazilian Program for Fuel Cell Systems in 2002, which allowed integrated and collaborative actions for the development of national fuel cell technology (Tarôco et al., 2009). The program supported and financed R&D activities for fuel cell development and promoted a network among the research groups.

Despite the favorable environment, which propitiated with the creation of fuel cell programs, many managerial challenges have partially limited the success of national collaborative system development. Gradually, individual projects prevailed instead of integrated ones, as they were less bureaucratic than the national projects and provided faster responses to operational processes (such as the acquisition of equipment and materials). The specific case of a federal university research program in cooperation with CEMIG stands out as it resulted in the first national SOFC prototypes.

4.1.2 Cooperation of CEMIG and UFMG

CEMIG, an open capital company controlled by one of the state governments, is a stakeholder in around 200 companies and is globally recognized for its sustainable practices. CEMIG operates in 22 out of 26 Brazilian states, in addition to the Federal District. The company is responsible for 96% of the electric energy supply in its home state and recently assumed control of the energy distribution in other major Brazilian states, investing through spin-offs in natural gas, telecommunications, renewable energy, and energy efficiency.

In cooperation with UFMG, CEMIG launched projects to promote the R&D of SOFC technology. A selected research group from the university carried out those projects, which resulted in a 50W and 1kW fuel cell in 2009 and 2014 respectively, after around 10 years of R&D. The rapid global development of fuel cell technologies and the success of several prototypes and demonstration projects at the beginning of the 2000s led to high expectations worldwide and pushed many countries to catch up and advance the technology development to be prepared for a potential shift in energy generation (Behling, 2013). Several countries like the U.S., Japan, and Germany pushed the technological and scientific borders of the technology further. In Brazil, however, the motivation behind CEMIG's investment was to keep up with those world advances, without the explicit intention of contributing to the scientific progress (internal report). When the UFMG projects were initiated, they received a classification of high risk and low probability of commercialization.

The case of the SOFC research program is a university-industry interaction enabled by public policies promoted to enhance innovation in Brazil. The partnership lasted for over 10 years, leading to a better understanding of the technology, the training and education of professionals, and the development of the first national SOFC prototype.

4.1.3 Emergence and concretization of prototype project

In December 2001 through an initiative of the *Ministério da Ciência, Tecnologia* and the *Centro de Gestão e Estudos Estratégicos* (CGEE), the *Fundo Setorial de Energia* invited a representative of the American National Renewable Energy Laboratory[4] together with four Brazilian researchers[5] to map and visit Brazilian institutions to organize national fuel cell R&D capabilities (Cgee, 2002). At first, the initiative did not identify the research group around the two electrochemical scientists of UFMG, with years of experience in fuel cell research

[4] American National Renewable Energy Laboratory is a subdivision of the American Department of Energy (DOE)

[5] from the Research Center Leopoldo Américo Miguez de Mello (CEPES), the *Instituto de Tecnologia para o Desenvolvimento* (Lactec), the *Centro Nacional de Referência em Energia do Hidrogênio* (CENEH) and the *Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia* (COPPE) of the Federal University of Rio de Janeiro (UFRJ)

(Research Leader 1 [RL1], and Research Leader 2 [RL2]), as the initiative did not search for fuel cell competences at UFMG or in Minas Gerais in general.

Through RL1's routine in scanning through governmental programs, calls, and reports related to her area of expertise, she came across the notice that the Brazilian government was prospecting national competences related to fuel cell technologies. By going through the list of participants she notices that UFMG was not listed and mainly universities, research centers, and companies from São Paulo and Rio de Janeiro were included in the prospection.

> "Eu olhei, consultei alguma coisa [governmental programs, calls, and reports] e tinha lá falando o que o governo estava mexendo com isso [national fuel cell capability mapping]. Aí eu falei: "Como sim?". E a gente nem sabendo!? A gente quer entrar! Já estava Campinas, Rio, todo mundo menos nós. Aí, quando falou que era pilhas a combustível eu falei: "Não. A gente tem que ir lá". Então eu fui pra FAPEMIG e pedi um recurso pra ir pra Brasília. [...] Aí eu fui lá para Brasília, conversei com uma pessoa, que não era ainda do evento, do workshop, fui lá e conversei com essa pessoa. E ela falou "Nossa que coisa, que bom, vamos colocar vocês também nos lugares que foram visitados". E aí, eles vieram visitar a gente e ficaram muito impressionados com que viram" (RL1 I1 0830).

Not being part of the prospection as being one of the most specialized researchers in her area in Brazil was unacceptable to her as she was working with the technology already for decades and built extensive knowledge around it. She immediately contacted the initiative in Brasilia and told them about her research. They invited her to present the UFMG research to them in Brasilia and RL1 requested financial support from the *Fundação de Amparo a Pesquisa do Estado de Minas Gerais* to travel to the capital and present the research group's scientific advances. After the meeting, the initiative was convinced by the group's effort and included them in the technology mapping.

After the mapping of national fuel cell technology competencies, the initiative visited the identified sources. For that visit, RL1 and RL2 invited two representatives of regional research centers *Centro de Desenvolvimento da Tecnologia Nuclear* and the company CellTech that had certain knowledge on the use of equipment, which would be necessary for the fuel cell development. RL1 never directly engaged in research collaborations with those organizations before but had students and colleagues that used their equipment for their R&D. As being one of two research groups in Brazil that already worked with materials specifically used for fuel cells, the initiative was impressed by the advances of the group.

The initiative published the results of the competency mapping in a national fuel cell report (Cgee, 2002) and the UFMG group was invited to participate in a fuel cell seminar in

Brasilia in July 2002 that was organized to present the findings of the mapping. This seminar was attended by representatives of various national research institutes involved in fuel cell development as well as national regulatory and financial organizations like the *Agência Nacional de Energia Elétrica* (ANEEL), the *Financiadora de Estudos e Projetos* and the *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq) and organizations involved in energy technologies. The effort from the seminar resulted in the creation of the 'Brazilian Fuel Cell Program'. The fact that the group was mentioned during the event as one of the universities with the greatest instrumental and human resources in SOFC technologies has given them visibility. At the seminar, RL1 got to talk with representatives of CEMIG and ANEEL and arranged a meeting with CEMIG to talk about project collaborations in the area of SOFC technology development.

Fuel cell technology research was not new to CEMIG. The energy company previously bought a Canadian SOFC system intending to include it in the energy grid of a regional municipality as a backup energy generator. As no competencies in SOFCs and only little in fuel cell technologies existed in Brazil at that time, the acquisition of the system generated several problems from its installation to operation. At this point, the company was already involved in a fuel cell project with the *Universidade Federal de São Carlos* for the development of Proton-exchange membrane (PEM) cells, however, the expertise of the group was not enough as the assembly, materials, climate control and requirements of the high-temperature SOFC are fundamentally different to the characteristics of a low-temperature PEM fuel cell.

Finding a national research group in SOFC technologies to collaborate with was, therefore, a special interest of CEMIG, however, the company had a bigger objective. At that time, the technology showed promising results and acceptance worldwide and was seen to be on the edge of being the "next big thing" (Behling, 2013). The goal was to create a center of excellence for fuel cell development. Uniting as many national competencies in fuel cell development as possible and advancing the technology development to a certain point, could give CEMIG an advantage if the technology would reach global acceptance. Creating this network would have the advantage of contacting and mobilizing the members rapidly to accelerate the development of fuel cell technologies fast and coordinated when needed. According to internal reports, CEMIGs focus was on electricity generation through hydropower, however, they did not want to fall behind in global development. It was said that fuel cell systems could be a big advantage to use for electricity generation for inner-city buildings that are heavily dependent on energy like banks or hospitals (Behling, 2013).

In 2002, CEMIG expressed interest in developing a SOFC prototype with the research group around RL1 and RL2 and offered funds for a research project. It took, however, two years until the group was accepted for the call of CEMIG/ANEEL to develop an R&D project to produce a 50W fuel cell system with technologies, primarily developed in Brazil. To carry out the project, CEMIG, in partnership with UFMG, planned to construct the 200m2 *Laboratório de Materiais e Pilhas a Combustível* (LaMPaC) at the university campus with the most modern equipment needed for the research in different areas of knowledge. This included, inter alia, several ovens with varying capacity and temperature ranges, a screen-printing machine, a tape caster, an electrical measurement instrument, a printing press, and spraying systems for coating. According to internal reports, the main research focus for the group was on the influence of the chemical composition of materials on fuel cell performance.

During the two years before the project was signed in 2004, RL1 and RL2 promoted the technology and as the knowledge on fuel cell development in Brazil was almost non-existing, they mobilized UFMG researchers from various areas of expertise to join the project preparation. Material chemistry was only one part of the fuel cell system and therefore, the group needed specialists from other areas e.g., electrical, and mechanical engineering.

> "CEMIG queria esse projeto. Queria saber quanto fica. Aí a gente não tinha competência dentro da química pra fazer protótipos. Eu falei, não, a gente precisava se juntar com um engenheiro. Não é um projeto da química. A química, sozinha, fazia materiais. Mas pra o protótipo eu precisava de mais gente. Aí a gente foi montando. Eu chamei o pessoal da elétrica, da mecânica, da engenharia. Dentro da universidade" (RL I1 1840).

At that time, there was no student or researcher educated to work with fuel cell development what was one of the key issues of the project. Chemists are more used to work with solutions and powders than with ceramic plates. Therefore, the research leaders promoted the upcoming project through seminars and workshops and involved more and more graduate, master, and Ph.D. students in their preexisting research group to study the stages and materials of fuel cell development. The goal was to train them for the upcoming prototype development as the main obstacle of the project at that time was, according to RL1, qualified human resources. As the first part of the project would be focusing on the development of chemical expertise and advances, most of the participants were chemical students and graduates but she also needed mechanical competencies for the subsequent cell integration and modeling. As electrochemistry is a specific niche of chemistry, the participants had to be trained to gather those types of competencies.

> "O nosso grupo já trabalhava com isso, os materiais. Nós continuamos a trabalhar dentro do departamento de química como a gente sempre tinha feito. Só que aí, como eu sabia que lá na frente eu precisava o anodo e catodo, em vez de colocar só gente pra trabalhar em eletrólito, que era minha expertise, eu comecei juntar a gente pra trabalhar em anodo e catodo. Então já selecionei alunos pra começar os mestrados dessa área de catodo e anodo" (RL1 I1 2815).

RL1 invited a previous post-Ph.D. student of hers (RC), who would become the future research coordinator of the first project, to join the pre-project, to help with defining the project and to prospect necessary resources. During the two years from the first meeting with CEMIG in 2002 until the contract for the project was finally signed by all involved parties, in 2004, the research leaders and the coordinator were involved in diverse activities to prepare and plan for the development of the SOFC prototype – a technology that did not exist until then in Brazil. Two or three times a month, the three scientists met with CEMIG to shape the project proposal, so all involved parties would accept the terms and objectives. Besides their liabilities as professors and researchers at UFMG, RL1 and RL2 visited various international conferences, seminars, laboratories, universities, research centers, and groups to understand what would be needed to build the first Brazilian SOFC system. They prospected the technology development, created links, and contacted researchers worldwide to learn what would be needed for the project execution.

> "Fomos nos congressos, e lá a gente viu: "Olha, Fulana está fazendo. Eu fui lá perto do Canada". E essa rede [*Rede Pacos*[6]], que foi criada, foi boa também pra isso. Além do dinheiro da CEMIG, pra fazer o laboratório, pagar os técnicos e tal, essa outra rede nos possibilitava ir pra congressos. Eu podia ir para congressos, eu pedia dinheiro extra pro CNPq pra apresentar nossos trabalhos. [...] Durante todo projeto. Hora nenhuma a gente parou de visitar ... a compra dos grandes equipamentos foi feita com o que a gente via nos congressos lá fora" (RL1 I1 3835).

> "Não [sabia se isso iria dar certo]. Foi um pouco de estatística. Eu assistia tanta palestra... eu via que o pessoal lá já tava com protótipo, com horas de treinamento, com horas de demonstração, em Julich. Principalmente em Julich, porque eles eram muito abertos pra conversar com a gente. Então a gente foi, conversou com eles, e eles falaram: "Olha, aqui a gente faz é assim, nós vamos mostrar os vídeos para vocês". Eles vieram pra Brasil. Chamados pelo *Rede Pacos*. Nós ficamos 4 dias na Bahia. E eles dando curso pra gente" (RL1 I1 4140).

The pre-group was also involved in the architectural model of the new laboratory, LaMPaC, the administrative, financial, and legal issues that arose through the collaboration between CEMIG and UFMG, and the preparation of all necessary technical documents for the technology development.

[6] *Rede Pacos* is a national SOFC technology network, which was created to connect knowledge on SOFC within the country.

Due to the divergent overall objectives of all participants, the creation of the project proposal became increasingly complex. At that time, the international energy community believed that the fuel cell revolution would arrive soon and CEMIG felt pressure to catching up with the technology development as fast as possible. Their project interest was driven by future commercialization opportunities; the university on the other hand was concerned about intellectual property and educational purposes, and the research group was interested in scientific advancements. Also, the legal issues became more complex regarding the separation of academic and industrial interest and regarding the construction of a company-financed laboratory on university grounds, which was unchartered territory for UFMG and introduced legal and administrative complications.

The construction of a laboratory that operates with explosive hydrogen was also a challenge and had to be resolved by engineers and architects together with the previously collected information of the research leaders. At that time, a building like this was never built before in Brazil and there was no legal nor architectural norm for such a construction. The planning and construction of the laboratory was a collective effort between the collected information of the research group, the expertise of CEMIG in the construction of hydrogen laboratories, and the previous work of the *Universidade de Campinas* related to the creation of norms for sensors in such spaces.

4.2 **The complexity of fuel cell technology**

Fuel cell systems are devices for power generation that convert energy from chemical reactions to electricity. Compared to other forms of energy generation, fuel cells provide renewable energy without or reduced waste, depending on the fuel used. They can be fabricated using different materials, which characterizes them into six types of cells. Among these types are the SOFCs, which constitute ceramic electrodes and electrolytes. The SOFCs operate at high temperatures, up to 900°C with an efficiency of 60%, the highest among the fuel cell types. Unlike other power sources used nowadays, SOFCs generate electricity from chemical reactions, instead of mechanical energy (such as hydropower and wind) or combustion (such as petrol, coal, and oil).

SOFC’s consist of three components: two electrodes, negative and positive, which are physically separated by an electrolyte. The stacking of multiple three-component cells, interconnected by ceramic or metal plates (interconnector), results in a modular power system, which intensity varies with the number of stacked cells. Although SOFC developers understood the operational principle of these cells, they still struggle with the fabrication process of the cell and with ways to obtain and store hydrogen. Besides the scale-up obstacle for commercialization, the main challenges of SOFC are expensive catalysis materials, high operational temperature, the durability of the cells, the complex and expensive balance of plant, and immature hydrogen infrastructure (Sharaf & Orhan, 2014).

Understanding the systems fabrication steps is essential to comprehend the innovation structure necessary for SOFC development. Figure 1 shows the simplified steps of the development of a SOFC system (Fernandes et al., 2020). The system requires six steps until it can generate energy that was separated here into three phases. The first one (1-4) is the fuel cell stack production, the second (5) is the completion of the system and the third (6) is the production or reforming and supply of the fuel.

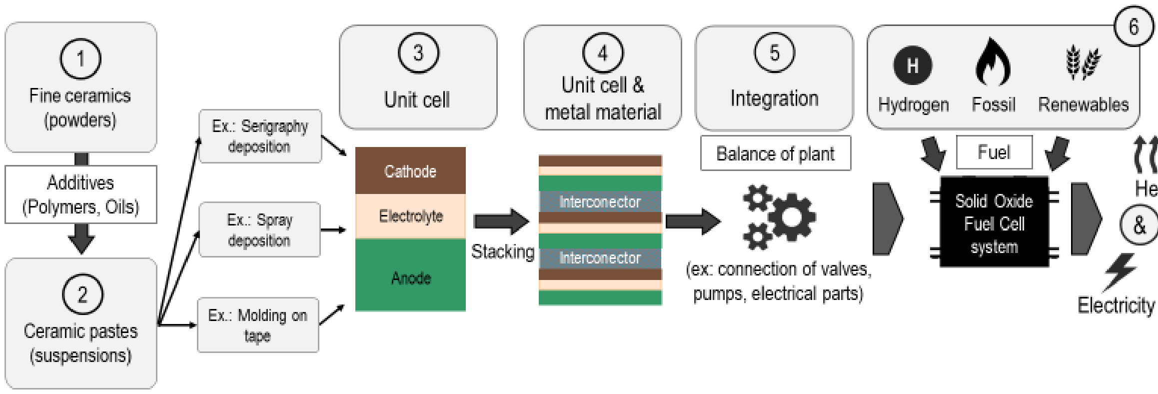

Figure 1 SOFC fabrication process (1-5) and power generation (6). Source: Fernandes et al., 2020

The first phase, stack fabrication starts with the preparation of ceramic powders which have specific properties such as high electrical conductivity and well-defined grain size among others. The powders are used to prepare three ceramic pastes with different properties: the paste of the anode, the cathode, and the electrolyte. The pastes are then shaped using diverse methods. For example, serigraphy printing, spraying, tape casting to produce cathodes, electrolytes, and anodes, respectively. Normally, extremely strict, and controlled steps of drying and sinterization are carried out throughout this process. Then, by uniting the three components of the cell and then stacking and integrating them into a system, the SOFC can operate with different kinds of fuels. At this step, the metallic or ceramic interconnectors are introduced to merge the individual cells into a system (Fernandes et al., 2020).

The challenges mentioned above are correlated with the fabrication and the power generation, represented in Figure 1. All the phases (1-6) require technological development to enable the commercialization of SOFC systems. Researches on material and cell fabrication have been the focus of SOFC scientists since they directly affect issues such as lowering the cell temperature and constraints on sealing and interconnector materials (Mahato et al., 2015).

From Figure 1 we can glimpse the main technological niches that must be developed in the manufacture and operation of a SOFC. Knowledge is needed in ceramic and steel to prepare the interconnectors, and reformers; in integration to put together all-ceramic and metallic parts and provide an automatized system of injection of fuel, water, and heat; and in catalysts to prepare the materials in the catalytic reform. Therefore, all those different areas of knowledge must be successfully combined to develop the separate components, assemble them into cells, stack them to a system and operate the complete generator.

4.3 The prototype projects

In mid-2004 the project entitled "Development of a 50W solid oxide fuel cell prototype" was signed by all parties involved: The research leaders, UFMG and CEMIG. Due to technological complexity, the project received an internal classification of high risk and low probability of market success by CEMIG. CEMIG financed the project with initially R$ 2.1 million, leaving RL1 and RL2 in charge of the project who hired RC as scientific support and responsible for the laboratory coordination. The project started with the two research leaders and the coordinator who assembled a core project group determined to reach the predefined project goals. This included the core group, contracted by CEMIG, which consisted of the research leaders, the coordinator, a technician, and interns (Intern1 I1 1033). To complement the core group, the research leaders included UFMG students with varying academic degrees and defined the individual project scope to complement the necessities of the project. Individual projects, like dissertations or theses, were usually defined and elaborated in collaboration with the student, however, the group needed to focus on all parts of the fuel cell system, therefore, the participant's research needed to be directed towards a specific area to develop specific parts of the cell. Those participants were associated with the department of chemistry via their studies as Ph.D., master, or bachelor.

Some of the participants needed to be hired after the project was initiated because the group realized their necessity when struggling in putting some of the theories they studied into practice. Those participants were not included in the initial project plan and were only hired during the project execution. Being exposed to the unforeseen accumulation of events, in form of various problem-solving attempts, along the trajectory of the development process, made the group realize the importance of an additional workforce. The group recognized their limitations and took the initiative to search and include an additional participant that would dedicate his work to that problem.

> "A gente pensava que ia ser mais tranquilo [the development of the interconector]. Era a única parte que a gente não tinha muito conhecimento. A gente conhecia a literatura de interconector e tal. Aí, a medida que o processo foi andando, [interruption of thought, too much information that RC wanted to talk about] Igual eu te falei, quando começou, a gente começou a ler muito mais sobre isto, porque era o que faltava. Aí a gente já percebeu que tava faltando gente aí. E aí nós já fizemos o deslocamento das vagas para ficar alguém antes do período que a gente começa a mexer com interconector, já trabalhando nisso. Pra poder viabilizar. Então a gente fez essa mudança de vaga. Algumas coisas você faz, né. A gente achou que o interconector ia dá para trabalhar mais. Mas de fato nós vimos que não. O interconector era complicadíssimo. A gente até pensou em comprar esses interconectores porque não era o foco. E aí a gente viu que não tinha comercial" (RC I2 010940).

The laboratory took another two years to be inaugurated, therefore, the research group advanced with their research in their old laboratories and started acquiring the necessary equipment to be installed in the laboratory after its completion. The delay of the project initiation, caused by the negotiations between UFMG and CEMIG, the prospection of the technology, and the construction of the laboratory had the consequence that several students that were trained and educated in fuel cell technologies already graduated by the time the laboratory was finally constructed. Through this, the trained workforce for the project diminished, and knowledge was lost.

In partnership with the university, CEMIG inaugurated the laboratory LaMPaC in October 2006 at the university campus with the most modern equipment needed for the research in different areas of knowledge. The main research focus of the first project was to investigate the influence of the chemical composition of materials on fuel cell performance. CEMIG managed the project by quarterly reports, which contained the technical progress and the future steps to reach the next milestone according to the chronogram stipulated at the project starting point. The research group had the autonomy to purchase the resources needed for the research, although a third-party institute managed the financials and logistics.

In June 2009, the successful partnership resulted in the first Brazilian SOFC prototype. The prototype represented an accumulated knowledge in material science, metallurgy, fuel catalysts, and engineering. After five years, the research group uncovered many technical bottlenecks not disclosed in the literature oftentimes because of its difficulty of being described. A differential of the project was that most of the team remained the same until the end. This facilitated the knowledge accumulation and the creation of research routines that prospered the technological development. Between projects I and II there was a two-year transition phase, which was caused by negotiations with CEMIG. The project-orientated SOFC development was put on hold but the research on technology-related issues continued

After the first prototype project and the two-year negotiation phase, CEMIG rejoined the project development and selected the same researchers to lead the second project. The second project had a similar scope, however, the target was to scale up and reach 1kW instead of a 50W cell system to obtain a higher power output. For the second project, the research leaders had to assemble and train new participants due to the fluctuation in the transition phase and formed a group around similar parameters as in the first project. Contrary to the first research group, most participants did not experience the SOFC prototype trajectory and needed to rely primarily on orientation from the research leaders, scientific articles, and the codified documents and manuals, produced in the first project. The new participants had not only to catch up with the advances from the first project but also to develop the necessary techniques to scale up the previous prototype.

End of 2014, the second project was concluded, resulting in a full functioning 1kW SOFC system prototype, four master dissertations, three Ph.D. theses, seven published journal articles, eight congress presentations, and one book chapter. After ten years of prototype development, the group successfully presented nine completed master dissertations, six completed Ph.D. thesis, 21 published articles and book chapters, 50 congress presentations (oral and poster), and two functioning SOFC systems of 50W and 1kW power. The two project phases were marked by a dynamic innovation process with many technical bottlenecks and unknown challenges that unfolded over time. The timeline of the case is visualized in Figure 2.

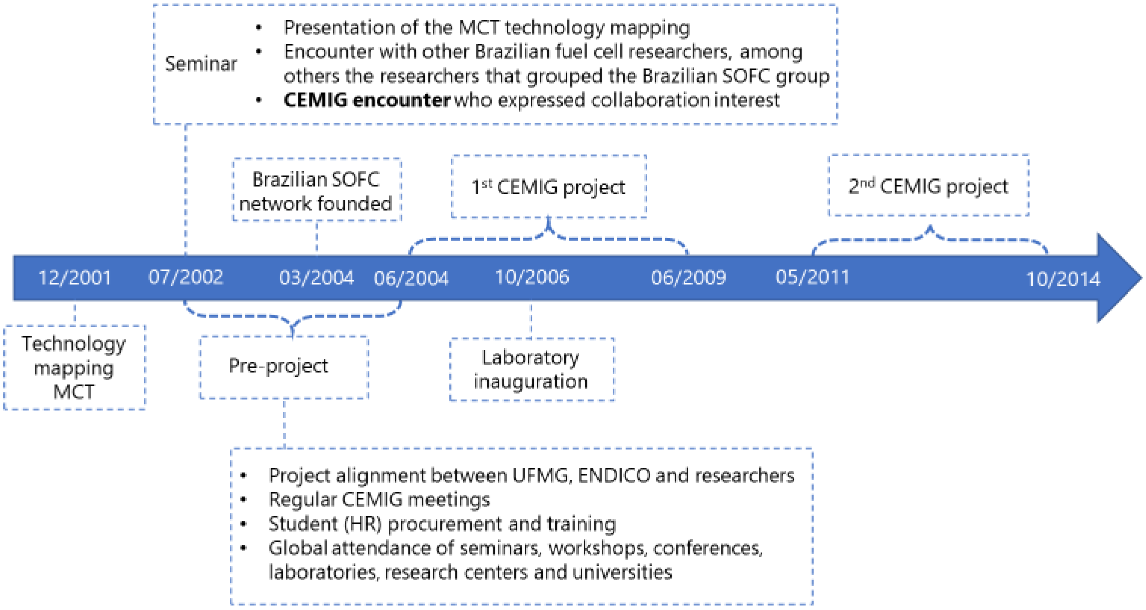

Figure 2 SOFC project events in chronological order. Own figure

The high uncertainty around the development impacted the projects significantly but did not prevent the projects to overdraw resources, budget, or time to the satisfaction of the energy company and the university.

The projects faced many challenges. The heart of fuel cells comprises three different ceramic parts, anode, cathode, and electrolyte, each of them composed of different materials and with a different function on the cell operation. Most of the scientific knowledge available on fuel cell production relates to a single part of the cell. University research is interest in researching on what are the materials with the best performance on each of these parts, not necessarily focused on the integration of them. There is scientific knowledge needed for cell integration as well, but the combination of these characteristics is normally the scope of enterprises, which are prototyping and testing. Such enterprises, however, have low or no interest in sharing their processes that are often protected. With this, the fabrication process of the cell relies on continuous testing and experimentation, as the codified knowledge available on papers is too fragmented for building complex prototypes.

After the conclusion of the project in 2014, the research coordination team continued the SOFC R&D using governmental support, but without being funded by CEMIG. None of the students that had participated in any of the SOFC projects continued researching at the laboratory or on fuel cells as no subsequent SOFC project was planned nor industrial opportunities were built. The low participation of the industry in fuel cell development in Brazil is one of the main differences in the SOFC technology path in other countries (Fernandes et al., 2020).

Even though the research group had a strong fluctuation of R&D personnel, the competences developed, and infrastructure built for the SOFC prototypes have enabled the laboratory to cooperate with companies from different sectors. More recently, the research leaders selected a new research group to participated in the project "Development and analysis of efficiency of architectures for APU with a multifunctional solid oxide fuel cell in regional aircraft" together with a national aircraft manufacturer (Fernandes et al., 2018).

4.4 ***Rede Pacos* – the Brazilian SOFC network**

Parallel to the first CEMIG project, the national SOFC network *Rede Cooperativa Pilha a Combustível de Óxido Sólido* (*Rede Pacos*) was founded in March 2004 that included initially five Brazilian researchers with expertise in SOFC and PEM technologies, including the research leaders from UFMG, who were involved in the network's managing activities. Together with researchers from *Universidade Federal de Rio de Janeiro*, *Universidade Estadual Paulista*, *Universidade Estadual do Norte Fluminense Darcy Ribeiro* and *Universidade Federal da Bahia Campus Ondina*, the UFMG researchers planned to do a similar technology prospection as the *Ministério da Ciência, Tecnologia* and the *Centro de Gestão e Estudos Estratégicos* initiated in 2001 on fuel cell technologies, but by focusing merely on SOFC's. Initially, the network's intention was merely to map the national competencies, but its activities expanded with time. The network organized annual meetings, initially at selected small hotels to exchange research activities, progress, ideas, and challenges. To diversify the research, the group including graduate, master, and Ph.D. students, whom they orientated, into their meetings. By participating in a governmental project that aimed at fuel cell research, development, and commercialization, the network started to grow and became more and more recognized for its R&D activities in SOFC technologies.

Initially, this network had only little impact on the CEMIG project preparation and was a parallel activity of the research leaders but the more it grew, especially through the first government project, the more SOFC researchers and students joined. Through the national SOFC network, which was supported and financed by the Brazilian Ministry of Science and Technology, the research group was able to get funds to participate in congresses and seminars around the globe to prospect the technology and create its own network for the CEMIG project. Learning from the international state-of-the-art of technology, all machines, and equipment used in the CEMIG project was acquired through contacts to companies that were made at conferences, seminars, and workshops.

By observing the newest advances, techniques, and equipment, and connecting it to the possibilities and limitations of the national resources, the research leaders and coordinator collected information on necessary resources for the Brazilian prototype. The UFMG group started exchanging advances, ideas, and challenges with other members of the network. Throughout all CEMIG projects, student interactions among the participating laboratories and research centers promoted the collaboration and training of the students and a thriving technology ecosystem increased the motivation of all participants immensely. The exchange of students, ideas, and experience supported the development of the CEMIG project proposal and later the development of the prototype, as I shall demonstrate in the next sections.

5 FINDINGS

In this section, I will present the findings and analysis of my research. This section is divided into five subsections that were designed to guide the reader through the chain of thoughts, one section building upon the previous. In the first subsection, I present the set-up within the project group including the internal processes of the group. The second subsection presents unforeseen events and uncertainties that were identified in the case through the methodology applied. The third subsection presents the practices, which were identified throughout the innovation process and analyzes how they were established and how they engaged with the unforeseen events that appeared in the case. In the fourth subsection, I took a more holistic approach to analyze the case and the findings. By exploring the organizational processes and the way, practices were implemented and ultimately interacted with uncertainty, I identified dualities within practice and analyzed how they were managed to deal with complexities within the innovation process. This revealed an interplay of organizational arrangements and ultimately lead to competence development, which is elaborated in the fifth subsection of the findings.

5.1 Set-up within the project group

After setting the stage for the project development, this subsection describes the internal project group context. It outlines the duties and deadlines and illustrates the dynamics within the group.

5.1.1 Time pressure and deadlines

The core group, including the project leaders, coordinator, technician, and students directly associated with CEMIG felt an enormous time pressure to meet all demands in time (RC I2 0420). This was mainly attributed to the complex, almost industry-like development, the regular feedbacks that CEMIG demanded, and the deadlines of the participants, affiliated with UFMG.

The group was confronted with many new equipment and processes. Upon project start, the group had to figuratively start from “zero” which was an expression used by many participants in the interviews. Very few participants had some prior experience in some areas of fuel cell research (Part2 I1 1145, RC I1 2640) but only partially related to the research on complete cells and systems (Part3 I2 0315; 4630). In the case of the cell integration, an engineering student was hired after the project already started as no one in the group had a notion of the interconnection of all the fuel cell parts. The engineering student was also inexperienced with fuel cells but dedicated his study to the project and specialized in fuel cell interconnectors. They all had to start from “zero”, but the students' previous background with experience in mathematics, engineering, and modeling, gave the project a solid starting ground for the integration (Intern1 I1 3045).

Deadline pressure

The project had to deal with two major sources of time pressure: (1) the quarterly reports of CEMIG that summarize the advancements of the SOFC project and were, therefore, linked to technological development; (2) the internal academic deadlines of the departments of UFMG (mainly chemistry department with some exceptions). Most participants, especially students, had to comply with the requirements of UFMG, however, most of them felt more time pressure from the CEMIG project, due to the more frequent deadlines in form of reports and the unfamiliarity with large projects and industrial project partners (Part1 I2 p2 0010; Part3 I2 0813). The results and data that had to be handed in for the report, however, were usually interrelated with respective internal UFMG works (e.g., thesis, dissertation, other projects). Although some tests, data, or results had to be rushed to meet the CEMIG deadlines, the work was always connected with the individual UFMG projects of students (Tech I1 4040).

Comparing the project and academic demands, the participants, officially associated with UFMG, had to prioritize academic deadlines even if their research was usually connected with the project. This enabled them to focus on their individual projects and the project leaders were challenged to connect them with the overall goals of the prototype project. The project leaders felt more the pressure of the project (Part2 I1 2950, I2 0310, Tech I1 4240), which can be explained by their responsibilities to CEMIG and UFMG concerning the development.

Working hours

The experimental use of materials and the R&D of electrodes, the electrolyte, cells, and systems can demand more time than initially expected. Some processes demanded several hours or days of constant observation and operation of equipment. It was, therefore, difficult to have a consistent and repetitive work process with fixed working hours as some development steps were required to constantly monitor the process. This usually led to longer working hours and more time spent in the laboratory setting. Most participants mentioned that they had to stay longer in the laboratory than expected to monitor the development of a process (e.g., Intern1 I1 5630). This, however, was difficult to align with the schedules of most participants that were associated with UFMG. Besides the project, they had other responsibilities like attending or giving classes and extracurricular activities.

The participants also needed to do overtime when certain results and data were requested for one of the quarterly reports of CEMIG (Part3 I2 0920). The participants sometimes had to stay at the laboratory through the night to accompany the process, which led to some stressful periods during the projects (Part2 I2 1350). Often the participants and primarily the technicians, helped each other to meet the demands and divided the working hours (Part3 I2 0920).

> "O laboratório não para às 6 horas. Às vezes, tinha aluno lá às 11 horas. **Eu também às vezes sai na madrugada** às 2 ou 3 da manhã esperando o forno" (Tech I1 3630, emphasis added).
>
> "**Na reta final, a gente ficava até mais tarde** porque era a fase de montagem do protótipo, de colocar a célula no forno. Isso era um projeto que exigia muito" (Part3 I2 0920, emphasis added).
>
> "**Passava madrugadas e madrugadas** [...]. Depois eu que eu saia, chegava em casa tinha as tarefas domésticas. E depois, de madrugada, voltava para minhas tarefas de doutorado. Então foram quatro anos de cabeça enfiada nos livros, nos artigos - foi bem puxado, foi bem estressante" (Part2 I2 1350, emphasis added).

Several participants stated that the group had to deal with work overloads, generally towards the end of project deadlines and that more participants would have been desired, especially ones completely dedicated to the project with only a few responsibilities towards UFMG (RC I1 0955, Part3 I2 3930)

5.1.2 Collaboration within the group

The participants were dependent on each other, primarily because each participant was focusing on a part of a larger system that needed to be interconnected. Secondary data show high communication and cooperative undertakings. Participants were assisting each other in diverse tasks like checking each other's progress, pointing out issues, finishing each other's tasks if necessary, and communicating results. The participants also engaged in joined activities, tests, or production and exchanged articles with each other. This collaboration was reinforced through the physical space, as the participants were working in proximity within the same laboratory (Part1 I1 1330). Some participants helped if able to, producing powders and pastes, reading equipment manuals, executing tasks, and interpreting results (Part4 I1 1735). A more integrated collaboration was among the Ph.D. students of the project (Part3 I2 0315). This can be explained by their long collaboration time (around four years for Ph.D. projects), the shared responsibilities that were attributed to them, and the technical interconnected activities.

The fuel cell needs three key cell components to work: Two electrodes: anode and cathode, and an electrolyte. To create a fuel cell system, many cells need to be stacked above each other, connected by an interconnector. The four system components consist of different materials and processes and need to be developed separately. However, they also rely on collaboration when they are stacked. Each participant was specialized in a different area (Part2 I1 2200, 4005) and was working separately from each other (Tech I1 3420, Intern1 I1 2105), but sometimes with a collaboration partner (master and/or bachelor), that specialized in the same development process (anode, cathode, electrolyte, and interconnector) until the components needed to be merged (Part1 I2 0410, Intern1 I2 5525).

When finally merging the developed electrolyte, cathode, and anode, the group's participants relied on each other to create a functioning cell as each component needed to be tested in reaction to another component that it is in contact with. This sometimes led to conflicts within the group when limited equipment was demanded by several participants simultaneously (Part1 I2 0410). The contracted technician supported the entire development and had a general overview of all the processes. She assisted with learning the equipment, teaching processes, producing powders, ordering, and repairing equipment, drafting reports, organizing the laboratory, and to a certain extent, assisting with writing articles (Tech I1 0200). The secondary data reveal the technician's thorough involvement in several types of meetings in various configurations, order processes, lab organization and maintenance, and in the creation and verification of Procedimentos Operacionais Padrão[7] (POP).

Although working separately, some participants had the experience of embarking on the project together as a group (Part3 I2 0315). Secondary data show that especially the three Ph.D. students, who each were dedicated to one cell component, and the technician were always sharing information and data, while students from the graduation and IC came and went (Part2 I1 3110). Everything was new to them and sharing the experience and their discoveries gave them structure as a team - sharing, collaborating, and working together (Part3 I2 4630).

[7] POP: Over the course of the project, successful process procedures and equipment operations were documented, revised, and organized in a physical folder that was accessible to everyone within the laboratory. How POPs were introduced to the project and how they were managed, will be elaborated on later in this thesis.

Each Ph.D. student was responsible for researching and developing one of the three cell components. They were constantly supported by master, graduation, or IC students. The 'support students' helped in many ways: They did research, read articles, studied the current state of the development, and contributed with ideas and new inputs; they helped with more repetitive practices like powder production or characterization or measurements; they assisted in publishing articles. The Ph.D. students usually asked them to do a specific task and after completion, the support students asked the Ph.D. students for more tasks (Part1 I2 0325-0600). Lower academic level students like graduation and IC students did more repetitive tasks and assisted the Ph.D. students wherever they could. Master students usually had their research agenda and were often paired with a Ph.D. student so they could complement each other's research (Part1 0820, RC I2 5720). The interviews and secondary data suggest that the collaboration among the participants was extremely high, and the participants observed each other's actions and commented if they could help with their experience to solve an issue (Part1 0820).

5.1.3 Distribution of responsibilities

The participants were given a lot of responsibility by the project leaders and were trusted with the usage of expensive equipment and materials (Part3 I2 1330). This had several purposes inter alia decentralizing tasks to distribute workload, encouraging group interaction, reducing equipment misusage, and accelerating their repair and maintenance if necessary.

Although being completely integrated into the project, the participants were sometimes reluctant to meet specific demands of the project and appealed to the fact that their primary preoccupation was their obligations to UFMG, not to the project (RC I1 3055, Tech I1 4545). Some participants had the impression that participants with strong ties to the UFMG programs sometimes made fewer incentives to deliver specific project demands in time (RC I1 3055, Tech I1 4545). Project leadership distributed project responsibilities to each participant within the project group but simultaneously recognized and reinforced the importance and priority of UFMG responsibilities for associated participants.

The participants were attributed with high autonomy in their research activities and they had the liberty to experiment and fail (Part1 I1 3330) while everything was negotiable (Intern1 I2 1030), as long as the deadlines of CEMIG (reports) and UFMG (e.g., thesis or dissertation defense and individual projects) were being met. They had the liberty to choose what and how to do their work but always had to give feedback to their project leaders (Part2 I1 4325, Tech I1 2155), either in individual or group meetings, as secondary data show.

> "A RL1 dava **muito independência** pra gente. Ela não queria a gente agarrado na mesma coisa o tempo inteiro. Ela **deu a liberdade pra gente errar** também. Pode experimentar e errar" (Part1 I1 3330, emphasis added).
>
> "A RL1 e a RC sempre deram **bastante liberdade e tudo era muito negociável**. Isso era ótimo. Nunca tive nenhum tipo de barreira nesse sentido" (Intern1 I2 1030, emphasis added).
>
> "Cada um **tinha a liberdade para escolher o que queria fazer**. Mas a gente sempre dava um retorno pra RL1 e RL2. Mas nunca falaram tem que fazer isso, isso e isso. Não. A gente era bem livre. **No final, contou o resultado, ne?** Mas a gente estava bem livre." (Part2 I1 4325, emphasis added).
>
> "Ela (RL1) dava bastante liberdade pra gente trabalhar, pra gente criar. **Ela esperava disso também"** (Tech I1 2155, emphasis added).

On the other hand, time and money were limited and there was, from an organizational point of view, not much room for errors (RC I1 1130). This created a tension between staying on schedule with the organizational overall objectives while giving participants the liberty to explore and research, which was inevitable due to the complexity and the novelty of the development process.

> "A outra parte que a gente teve que tomar muito cuidado foi a seguinte: Como o dinheiro era muito limitado, **a gente não podia errar.** A gente não podia especificar uma coisa errada. A gente não podia perder, de forma nenhuma, dinheiro. Então, essa parte de especificação de cada coisa, de cada produto, eu fazia pessoalmente pra que não fugisse ali algo que a gente precisasse" (RC I1 1130, emphasis added).

The long order process made them dismiss several potential tests and research to be performed only because the proverbial "Option A" was less likely to succeed than "Option B" (Intern1 I1 5810). The project leaders, therefore, had to find a balance between allowing the participants to test and experiment and staying on track with all the deadlines and financial limitations.

> "O que a gente passou a fazer foi pensar mais, tentar extrapolar as possíveis falhas que a ideia inicial poderia ocasionar. Quando a gente fazia esse exercício mental, assim: "ahh, isso aqui tem mais chances de dar errado que a opção B", por exemplo. Então, ao invés da gente tentar já *de cara* montar uma opção A, a gente pensou: "Não. Esquece a opção A porque pode dar errado. Nós não vamos tentar, vamos pensar num plano B". Teve mais exercício de [pause]... vou chamar de planejamento, mas é bem mais que planejamento. É mesmo fazer uma extrapolação de uma situação futura. **Como se fosse uma análise de risco, sabe?"** (Intern1 I1 5810, emphasis added).

5.1.4 Procurement and management of resources

Equipment orders were the responsibility of the project leaders and coordinator, due to complex specifications and high price tag. They were assisted by technicians and interns specifically hired for the project that would help in researching the equipment to order, in drafting the order, and in searching for the best fitting seller to buy from (Part1 I1 0855-1250, Intern1 I2 2315).

> "Se eu comprava com **minha taxa de bancada, eu mesmo fazia** o orçamento e comprava. Porque precisava uma nota fiscal. **Quando comprava via o dinheiro do CEMIG, pelo projeto, então era RC** [coordinator]" (Part1 I1 1250, emphasis added).
>
> "As pessoas que tinham **que lidar com os fornecedores eram mais eu, RC** [coordinator] **e a Tech** [project technician]. [...] era mais a função nossa fazer isso. Esse trabalho é um trabalho mais nós mesmos" (Intern1 I2 2315, emphasis added).

Notebook entries show that when the time came to buy more resources like powders or reagents, the research coordinator asked the group, via the technician, if they needed anything to add to the order. The materials and resources for the project were then ordered by the technician in cooperation with the project coordinator. Such an order process from demanding to receiving could take several months (Intern1 I1 4535). All participants were invited to give feedback and suggestions regarding the order, however, only the core project group was confronted with the difficulty of the order process (Part3 I2 1330). However, those orders were not very frequent, as most resources lasted months or even years (Part1 I1 0855 – 1250). Most equipment was imported, and it was very time demanding to order the equipment and have it delivered. After the order was sent the delivery time was rarely less than six months (Part1 I2 p2 0810; Part2 I1 1010).

Materials and resources that the Ph.D. students specifically needed for their research were sometimes ordered via the project budget but usually purchased with their '*taxa de bancada*'[8], designated by the department of chemistry and used with the authorization of the research leaders (Part1 I1 0855 – 1250). For smaller orders, the Ph.D. student was responsible for the process. She contacted the seller, ordered the resource, and should the situation arise, returned the material, or issued a refund. Larger resources that the student needed for their

[8] The 'taxa de bancada is provided by scholars of CNPq. "The 'taxa de bancada' is intended for the maintenance and improvement of activities necessary for the development of the academic programming, research and thesis project, and may be applied, with the supervisor's agreement, in cost and capital expenses, such as: acquisition of consumables and research inputs; as well as bibliographic material (books and periodicals); technical visits; participation in congresses and the like, among others." (CNPq, 2004, p. 1, Free translation)

research had to be issued over the project's budget after consulting with the research leaders (Part1 I2 p2 0535).

During the 10 years of prototype development, the range of the laboratory's equipment and resources grew constantly and needed to be administered. In addition, the processes that involved internal resources needed to be managed and systemized. The budget of the project in all its detail was defined together with CEMIG before the project was initiated. The project leaders and the coordinator estimated the necessary financial resources for each section of the total budget – called rubrics. However, due to the uncertainty within the development process, the financial needs of some rubrics extended the estimates and the group had to request a financial shift in some of the rubrics. This had to be administered constantly according to the demands of the project. The financial resource management also enabled the group to repair equipment from the project leaders that they acquired for other research, which gave them more budget for other expenses (RC I1 2330, Tech I2 1120).

The constant management of the laboratories resources was a demanding task and therefore decentralized. The participants were given high autonomy and responsibility in the usage of equipment and materials. Equipment notebooks were implemented, and participants were designated to oversee certain equipment with the responsibility to control the usage, transfer knowledge to other participants, and prevent their misusage. Some notebooks were implemented that would entail the location and number of smaller equipment within the laboratory, so nothing would get misplaced, and others that would keep track of the current materials, available at the laboratory, to be aware of any shortage of powders or solutions.

5.2 Identifying unforeseen uncertainty

The objective of this section is to present the occurrence of (1) "out of the blue" unforeseen events and (2) unforeseen uncertainty that was a result of the accumulation of events that, examined individually, might have been foreseen.

5.2.1 Integration of the German oven into the electrical grid

For the preparation of the cell components, a high-temperature oven needed to be imported from Germany. The group was aware beforehand that the installation of imported, complex equipment would come with some difficulties, however, they did not anticipate the complication of its integration into the power grid. Upon arrival, the group noticed that the plug was not compatible with the laboratory system and that the ordered adapter was not included in the shipment (Part1 I2 1335, Tech I2 1120, 1700, RC I2 2725).

> "Eu lembro que, tem um fornão lá no laboratório e ele veio da Alemanha. Aí quando o forno chegou, a tomada dele era um troço desse tamanho [draws a large circle in the air]. Ela tinha uns 8 pinos. **Não tinha tomada no Brasil pra poder encaixar aquilo**. Aí deve que importar foi mais 6 meses. 6 meses pra forno chegar e 6 meses pra vim a tomada dele pra cá**. Teve que trocar um quadro de energia do laboratório porque lá não comportava o forno daquele tamanho**. Nós demoramos quase um ano pra conseguir usar o tal do forno" (Part1 I2 p1 1335, emphasis added).

Although this was unexpected, the group could acquire an adapter rather quickly through national manufacturers. Most of the imported equipment from France, Germany, or Japan was built with different plugs that varied from country to country and the group was already aware of that problem as they previously bought equipment from those countries. The main complication with the equipment was attributed to the integration of the oven into the university grid and its immense power demands. The entire university grid had to be adjusted due to the high energy consumption of the oven. The unique electrical charge of the oven was difficult to integrate, and the thermal calculation had to be done by a technician of the university who then had to negotiate with the responsible sector at the university how the oven had to be integrated. Usually, such a process can take up to two years and, as the project had a tight schedule, it had to be accelerated by contracting an external technician, which was usually not university protocol.

> "Mas é porque tinha que fazer um sistema de carga elétrica especial só para aquele forno. **Não era só a tomada. Era muito mais que isso. Tinha que balancear uma carga só pra aquele equipamento.** Porque era um equipamento de alto consumo de energia. Então, como era um equipamento de alto consumo de energia as tomadas que vinham, **o sistema que vinha eram todos importados e demorou para chegar**. Só que quando ele chegou tinha a questão do departamento que tinha certas coisas que eram difíceis de lidar. Então assim, o [técnico do departamento de químico] tinha que ir lá e fazer o cálculo de térmica e negociar com o pessoal da universidade. Então eu lutei, **lutei e no final não era só a tomada. Mas no final teve que trocar a tomada também porque sistema da universidade era de tomadas diferentes**" (Tech I2 1120, emphasis added).
>
> "A instalação elétrica, a UFMG fornece para os laboratórios. **Mas nesse caso eles não quiseram fazer, porque eles falaram que era muito especial. Então, isso foi surpresa pra gente na hora**. A gente teve que contratar pessoal para fazer" (RC I2 2725, emphasis added).
>
> "**Não sabia da tomada**. Sabia da carga térmica e que foi feito um pedido no departamento para que o sistema fosse instalado. Só que pra esse sistema ser instalado na universidade às vezes demora 2 anos. Pra você conseguir alguém para resolver seu problema**. Pra instalar, a gente precisava rever a questão da carga térmica e também a gente teve que contratar um técnico de fora para poder ajudar**, mas com boa vontade do departamento" (Tech I2 1120, emphasis added).

The group was aware of the issues with the plug adapter and the integration; however, they did not expect the difficulties of getting the oven installed. An unexpected delay of approximately six months was the result. While the oven was being installed by an external service provider at the laboratory, the group relied on access to the ovens of collaborators and friends within the department.

5.2.2 Zirconium powder

The zirconium powder is the basis of the electrolyte and was needed by almost the entire research group (Part1 I1 2415) and its production is complex and time-demanding (Part1 I2 2555). An important point in the production was repetitiveness and, therefore, the project leaders stressed the importance of making powders on a larger scale so a batch would last for a longer period (Tech I2 3100). This eliminated the possibility of small changes in the powder's chemical compositions, which vary from batch to batch.

> "E a RL1 falava [to the Ph.D.]: "Não é para vocês fazerem sempre [the synthesis] e serem repetitivos" [continues the same sentence but not with what RL1 said] os processos **eu fazia** [the technician]**, eu preparava uma quantidade muito grande de pó para os meninos nas próximas etapas.** Porque, por exemplo, você pega a zircônia e você tinha algumas etapas e se transformava ela num pó. Micrométrico ou nanométrico, dependendo do processo que você usasse. Esse pó ele ia ser colocado numa lama que a gente chama que é uma mistura desse pó de zircônia com polímeros etc. e outros agentes quer iam formar o tape casting por exemplo. **Aí, para fazer isso eu preparava uma quantidade grande do pó e deixava disponível para os meninos continuarem os processos**" (Tech I2 3100, emphasis added).
>
> "**Então quando alguém chegava pra fazer, já fazia um tanto pra todo mundo usar.** Mas tinha vez que ficava assim, quatro dias só filtrando" (Part1 I2 2555, emphasis added).

At one point, the process of synthesizing the zirconium powder suddenly led to problems of filtering the powder. The participants responsible for the synthesizing at that time did not change the process in any way, however, the result differed in its characteristics from the powder they produced before. By assessing the entire process, the participants were not able to find the complication within the process until sharing their issues with members of *Rede Pacos* at a congress that was held at that time. Researchers from São Paulo suggested controlling the PH level during the entire process and not just at the beginning, which was the common practice of the responsible participants until then. Upon returning to the laboratory and reviewing the process, the participants noticed a deviation in the PH levels during the process when they did not measure it. According to the participants involved in the synthetization, measuring at several points within the process and adjusting the levels ultimately resolved the issue for the group. Measuring the PH levels throughout the process and not just in the beginning and the end was not described in the literature. Only by their involvement with their network, and going beyond explicit knowledge, the group was able to overcome this unforeseen event.

> "Nessa época, a gente tinha um congresso da *Rede Pacos*. Quando a gente tinha esse problema [pause]... **a gente conversou com pessoal de São Paulo** e eles deram uma dica pra gente controlar o PH o tempo inteiro, e a gente estava medindo o PH só no início. **Quando a gente fez isso, a gente não teve mais o problema na síntese**" (Part1 I1 2415, emphasis added).
>
> "Esse pessoal é especialista em síntese tipo da zircônia. Então nosso primeiro procedimento pra começar resolver um problema, **era procurar algum livro ou artigo que falava sobre o assunto.** Se a gente não conseguia resolver internamente, a gente buscava ajudar de alguma forma que fez esse processo (Part1 I1 2620, emphasis added).
>
> **Não [estava descrito na literatura].** Porque você lava o tempo inteiro. Então quando você lava, lava, lava, o PH muda o tempo inteiro" (Part1 I2 2555, emphasis added).
>
> "Primeiro conversei com a RL1. Mas ela conferiu que estávamos fazendo tudo correto. **Mas nesse problema faltava a informação de medir o PH o tempo inteiro que estava faltando**" (Part1 I1 2700, emphasis added).

Upon revealing the solution to the entire group, the project leaders noted they were already aware of the importance of controlling the PH levels during the entire process but assumed that the other participants were informed about that procedure. The participants responsible for the process at that time coincidently produced the zirconium powder successfully for some time until environmental changes in temperature and the washing process influenced the PH levels in a way that active intervention in the process was needed to achieve the same results.

5.2.3 Interconnector steel

The prototype development at the laboratory faced many technical challenges that initially were not considered to be the main concern of the technological challenge. One of them regards the difficulty of producing and acquiring peripheral components and parts of the fuel cell stack, not considered to be the main scope of the project as they did not directly relate to the cell itself such as interconnectors. To generate energy, fuel cells need to be stacked and separated by an interconnector that controls the hydrogen and oxygen flow. Those interconnectors are usually metal plates, requiring specific steel with properties such as a high melting point (as the cell operates until 900°C) and strong oxidation resistance.

For the metal interconnector, a part of the group had to identify, buy, and test suitable steel that would resist the high temperatures and permit a continuous oxygen flow. A mechanical engineering student was specifically hired for this purpose after the project leaders realized that the project of developing an interconnector was more complicated than initially calculated. Together with the project coordinator, herself an electrical engineer, the student was responsible for the interconnector development and the cell integration (RC I1 4900, I2 4135). As the field of fuel cell interconnectors was new to both group members, they were confronted with several challenges that needed to be approached by combining their existing knowledge with the new experiences they gained throughout the process and within practice (Intern1 I1 5023).

> "**Ninguém estava pensando em isso**. Então elas me colocaram nessa parte" (Intern1 I1 1720, emphasis added).

> "Então, o primeiro é um estudo de uma seleção. O segundo é começar a comprar esse material e fazer testes no laboratório" (Intern1 I2 3325).

Identifying

To identify the correct steel that would resist the high temperature and the oxidation of the oxygen flow, the group did extensive literature research on fuel cell materials, interconnectors, design, modeling, metallurgy, and prototypes (Intern1 I1 4243). After selecting a couple of possibilities, the plates with different steel types were bought for testing (Intern1 I2 3325).

Buying

Buying raw and highly specialized steel in small quantities turned out to be a huge challenge, as steel mills only sell large metal sheets, which would have been too large and too expensive for the project's predefined budget. As the group initially did not calculate with a complex development of the interconnectors, they also did not allocate enough funds, to execute the process in the best way possible.

> "Então, por exemplo, a parte do interconector, que nós previamos no projeto, não dava para comprar o material da maneira que tinha que ser feito. Comprar um lote do material, testar, fazer, e não sei o que... Nós não fizemos certo. Nós não colocamos o valor que a gente precisava ter colocado. Então, nós compramos retalhos. Mas isso não é a melhor prática. Eu acho que no segundo projeto a gente aumentou. Eu acho que a gente aumentar a verba para isso aí, porque a gente viu que a gente subestimou" (RC I2 3906).

The group spent a lot of time contacting potential sellers as it was difficult to find someone that would attend them and offer smaller cutouts (Intern1 I1 3555). As soon as a suitable distributor that would sell the desired steel was located, he would then cut the ordered amount and send it to the laboratory. The group was not able to see the stock upon ordering and could not choose in person, therefore, the distributor had to be entrusted with that part of the process (Intern1 I2 4340).

Many types of steel were bought and tested in parallel as they could not test one steel after another to analyze the results due to time pressure (RC I2 4135). Sometimes the group received different steel that they had ordered, which was shipped by untrustworthy sellers. As, at that time, they did not know about the existence of a device that could measure the chemical composition of materials, they took many detours in learning the (in-)compatibility of a certain steel type (Intern1 I2 3325). Due to missing equipment, they were not able to test if the delivered material was in fact with the same specifications as the one, they ordered (Intern1 I2 4800).

> "**Às vezes a gente comprava o material e recebia outra coisa**. Comprava gato por lebre. Então algumas vezes isso aconteceu" (Intern1 I2 3325, emphasis added).

Testing

When trying to apply the theoretical knowledge into practice, it often did not work as described by the literature (Intern1 I2 4243). Even after following the theory, enclosed in books and articles, certain materials did not deliver reliable results when testing them. They oxidated, descaled, broke, or burnt and the group realized that the literature was not sufficient to replicate the process (Intern1 I2 3911)

> "E a terceira parte é o seguinte. OK - Eu estudei, selecionei, comprei - OK. Deu tudo certo. Agora vou fazer o teste. **Alguns materiais a gente descobriu que não funcionava tão bem igual a gente tinha imaginado lá na leitura no estudo**. Não dava um bom resultado" (Intern1 I2 3911, emphasis added).
>
> "**Só a literatura não foi suficiente**" (Intern1 I2 3911, emphasis added).
>
> "Algumas coisas [a gente consegui tirar da literatura]. O inox 316 não funcionou. A gente trocou o material pra um mais caro: Inox 310. **A gente tentou variou coisas. Muitas vezes o que você tirava da literatura, quando você ia pra prática, não funcionava**" (Intern1 I1 4243, emphasis added).

Repeat

The process of identifying, buying, and testing had to be repeated various times to finally achieve the desired results with the obtained steel (Intern1 I1 5023). Each purchase changed the context and the relational constellation of the development step as new material and sometimes new manufacturers or sellers were introduced. This new context also gave more insights into previous steps, enhancing the group's temporal experience of the interconnected social and material conditions.

> "**Não. Foi uma compra só.** Cada uma delas era um desafio. **Não tinha uma regra final** – Não tinha esse e esse passo e tudo vai dar certo. Então a gente fazia várias montagens e vários protótipos" (Intern1 I1 5023, emphasis added).

> "Muitas vezes eu ir lá no fornecedor, comprar pessoalmente. Eu era aluno então não tinha carro nem nada. Mesmo assim, eu pegava meu dinheiro e ia lá na empresa ou de ônibus ou pegava um carro emprestado do meu pai – algo assim. **Fui lá, cobrar, pedir, negociar – Muita dedicação.** Muito além do que se espera de alguém do projeto. **Eu aprendi fazendo"** (Intern1 I1 5230, emphasis added).

> "**A gente percebeu que não dava pra esperar as coisas chegarem**. De alguma forma a gente tentou otimizar o tempo. As compras não eram uma compra única. **A gente fazia as coisas em paralelo**" (Intern1 I1 5248, emphasis added).

Solution

When finally finding the right type of steel for the interconnector, the group ordered a larger amount from the same seller to finish the prototype. However, doubts were raised if the second steel order came with the exact same steel as the one, they tested before, as it oxidized more than expected. Due to the deadline approaching, the tests to confirm the steel type could not be done before the end of the project (RC I2 4135), but as the performance of the prototype fell within the desired range, it did not delimit the initial goal of the project.

By dealing with such unforeseen events, the group collected experience and improved their communication within the group and with collaborators and manufacturers. The group collected more information from their internal and external network, studied the order requests in more detail, and improved communication on the specifications of the order so the funding agent had less room for making mistakes (Intern1 I2 2015).

> "**Eu acho que, ao longo dos anos, nós passamos a ser mais experientes e termos mais cuidado na comunicação um com o outro. De se proteger mais**. **De buscar mais a informação do outro. E de priorizar aqueles fornecedores**... porque é tudo edital. [...] De qualquer forma, eu acho que a experiência que a gente foi tendo que fez com que a gente tivesse mais cuidado na hora de se comunicar com o fornecedor. **De buscar mais evidência, de especificar com mais detalhe**, de não deixar muito na mão do *funding agent*" (Intern1 I2 2015, emphasis added).

5.2.4 Unpredictability of results

The previous events are single cases that stood out as unforeseen events. The next two subsections group several unforeseen events as they presented similarities. Replication of the process was essential to assure conformity in the results and controlled continuous development. A slight deviation of the process might lead to different results or faulty material.

This happened when using the same chemical composition of material but from a different manufacturer or when moving from a self-made material to a commercial one, or vice versa.

In an example, this occurred when the group decided to buy Nickel-(II)-oxide (NiO) after discovering that the commercial material was more cost- and time-beneficial than making it themselves. NiO is a chemical component of the anode and influences the porosity of the electrode. Being the same material with the same chemical composition, the group expected no change in the processes and a smooth transition from the self-made NiO to the commercial one. Unexpectedly, upon testing the anode with the commercial NiO, the anode performed inferior, and measurements revealed a lower porosity of the electrode. The result deviation can be explained by a different grain size or a different fabrication process that influences the final product and its characteristics. Those results implied that if the group would continue with the commercial NiO, the entire process would have had to be adapted to the new powder. Changing the production process of the anode, however, would be more labor and research-intensive than returning to the self-made NiO and, therefore, the group returned in fabricating their own.

Another example of the unpredictability of results was the shift from commercial testing cells to self-made cells. The group utilized commercial cells as reference material and to enable a parallel development process and to not merely rely on their own cells when developing the system. After all cell components passed their individual tests, deposited on the commercial components, the group started to build a cell that consisted only out of self-made components. This led to a new adaptation process in which all components needed to be modified to deliver the same results as with the commercial components.

5.2.5 Order process

For many participants, the order process of equipment or other resources was a completely new experience that they had to learn while being confronted with new challenges and immersed in practice (Part2 I1 0850). The upkeep of smaller resources like reagents was monitored by the technician of the project and secondary data show that it was her responsibility of contacting the group's participants via email and asking about desired reagents. After receiving feedback, she would organize the order list and pass it on to the project coordinator who would then place the order with the manufacturer. The order process of equipment, however, was more complex and not a common practice for students but as being part of this prototype project, they all were confronted with it to some degree.

The processes started with extensive research on the specificities of the resource or the equipment setup. Next to academic papers and books, the group had to visit congresses, lectures, and institutions to learn about those product specificities (RC I1 1130, Tech I1 1020, RL1 I1). For expensive, highly technical, and imported products, the research leaders accompanied the entire order process personally (RC I1 1305), however many other equipment and resources fell in the responsibility of the research coordinator and the technicians.

The intense research to draft the highly detailed product inquiry was also necessary due to the rigid financial structure. The project's financial resources were separated into rubrics, each with a determined value for certain spending, e.g., equipment, equipment repair, human resources, materials, travels, etc. If the group needed to allocate funds from one rubric to another, they needed to request this shift with the funding agent, which was a highly bureaucratic and time-consuming activity (Tech I1 1330, 2505).

After specifying the resource, the manufacturers and sellers needed to be identified and contacted to gather information and cost estimates from them. Usually, the resources needed to be purchased from large manufacturers that commonly provide industries and large companies with their products. As the laboratory demanded smaller quantities for the prototype development, the sellers often did not respond to their requests or stopped communication and the group needed to seek out another manufacturer or seller (Part2 I2 0710, Intern1 I1 3825). An example is a purchase and communication with a company providing a current measurement system.

> "**Você determinava qual equipamento, qual a especificação**; corre atrás de qual empresas que tinha esse equipamento. Aí você entrava contato com eles e pedia orçamento. Aí era só esperar eles mandaram. **E nossa, tinha muitos que não mandavam"** (Part2 I2 0930, emphasis added).
>
> "**Empresas brasileiras não querem lidar com projetos de pesquisa.** Não tem interesse" (Intern1 I1 3825, emphasis added).

<u>Current measurement system:</u>

The group bought many flow meters to measure the weight of the gases used in the processes. The initial communication and order process was dragging but ultimately, they were delivered within the expected timeframe. Upon installation, the laboratory group noticed that due to a miscommunication the manufacturer sent flow meters with an unsuitable connection piece that was required to connect the tube to the instrument. Upon several e-mails and phone requests, the manufacturer refused to exchange the flow meters, so the group needed to adapt the connection piece with a workaround (Intern1 I2 1200).

> "Nós compramos de uma empresa, aqui no Brasil, esses medidores. Eles mandaram pra nós. Aí a conexão do tubo com o instrumento veio errado. O tubo não encaixava na conexão. **Teve um erro de comunicação** de entendimento entre eu e eles. **E aí eles não queriam... [reformulating the sentence], a gente não conseguiu fazer uma negociação que atendesse os dois lados** pra resolver o problema. Eles não queriam trocar e a gente tentou resolver isso de uma forma que ficasse bom para os dois lados, mas eles não quiseram. **Então eu tive que bolar uma gambiarra para adaptar o tubo**" (Intern1 I2 1200, emphasis added).

The equipment was bought with a redefined calibration that was suitable at the time of the purchase. After some time, the group needed to extend the working range of the equipment and had to adapt the calibration. This is usually performed by the manufacturer, so the group sent them back for recalibration, however, the manufacturer lost the equipment (Intern1 I1 3840) (More: Intern1 I2 1200). Trying to contact to company repeatedly did not solve the issue as they could not explain the whereabouts of the flow meters and did not agree to replace the instruments.

> "**Compramos vários medidores de vazão e a empresa fez a calibração errada.** A gente mandou os equipamentos de voltar pra eles refazerem a calibração, **mas a gente nunca mais recebeu os equipamentos de volta**" (Intern1 I1 3840, emphasis added).

> "**Eles extraviaram os instrumentos**. Eles ficaram enrolando a gente e depois falaram que perderam o negócio. A gente **nunca recebeu de volta**" (Intern1 I2 1200, emphasis added).

Those events set back the project on their deadlines and the group did not have the necessary resources to deal with this issue. They did not have the budget to fly to São Paulo and confront the company and did not have the resources nor the time to get into legal disputes (Intern1 I2 1200). The group was forced to acquire the current measurement system from another manufacturer, ultimately losing time and money.

After any product research, the participant in charge of the order drafted an order request with several options and delivered it to the funding agent, which in turn continued with the purchasing process (Intern1 I1 3045) This was common practice as the funding agent needed to have options in buying a product when exceeding a certain value.

> "**Eu acho que, ao longo dos anos, nós passamos a ser mais experientes e termos mais cuidado na comunicação com o outro.** De se proteger mais. De buscar mais informação do outro. E de priorizar aqueles fornecedores" (Intern1 I2 2015, emphasis added).

Each order process was pervaded with uncertainty and came with many difficulties and often with events that were impossible to anticipate. The extensive process which included research, defining the desired specifications that would serve all users in the group, identifying manufacturers or sellers, and communicating with the funding agent, oftentimes resulted in delays and sometimes inexpedient resources. Receiving unsuitable resources could be traced back to wrong or incomplete specifications, miscommunication with the manufacturer or the funding agent, faulty orders from the funding agent, or faulty delivery from the manufacturer.

5.3 How practices cope with unforeseen events

The unforeseen events, identified in the previous subsection, interfered with the innovation process. They delayed the development and jeopardized deadlines, complicated the order process, introduced unforeseen costs, and challenged internal and external collaboration and knowledge development. This subsection presents several sets of practices that provide insight into how the group reacted to those unforeseen events and embraced uncertainty to develop the organization further and meet the overall objectives of the project.

5.3.1 Dealing with time pressure and deadlines

5.3.1.1 Adapting the working process due to accumulated delays

Because of the strict UFMG and CEMIG deadlines, the group had to continuously adapt the development process to the project rhythm by simplifying goals or launching subsequent project steps simultaneously as a response to accumulated events that delayed the process. This meant that they had to set goals that were realistically manageable in the given time, accounting for all the probable difficulties and bureaucracies. This accumulation of events had the consequence that some ideas were abandoned or simplified because they would not be viable to execute in the given time (Intern1 I2 0120). Their routinized interaction with the working process (in practice), made them establish the practice (*Praktik*) to simplify plans and ideas.

> "O que eu consigo fazer aqui e que é realmente viável dentro desse prazo que eu tenho? **Não adianta ter uma ideia linda, maravilhosa, mas que não cabe no meu contexto de execução**. Então eu tinha que pensar as atividades numa forma que cabia dentro do meu contexto. [...] Às vezes acaba tendo que ser um pouco simplista. **Reduzir um pouco.** Porque você sabe que não adianta pensar muito grande por causa da burocracia e as dificuldades" (Intern1 I2 0120, emphasis added).

Besides excluding options and ideas due to the lower probability of success, the group started to launch development steps simultaneously. Initially, the group planned in sequence and executed their plan milestone after milestone. Upon finishing one project step, the group dedicated their research to the next, which was at first a successful strategy and was aligned with the group's goals as they could dedicate more time to basic and applied research. The accumulation of delays attributed to unexpectedly long equipment order process, repair process, and testing cycles affected the project in a way that they could no longer research one project step at a time. The project milestones set to fit a predefined schedule had to be readjusted constantly and to be communicated with the project partners. To ensure that the delays would not harm the project development, the team had to start project steps before finishing preceding ones and work on them in parallel, abandoning synoptic development steps (Intern1 I1 5248, RC I2 3720, 3906). This increased the workload but implementing practices (that will be discussed later in the thesis) like bulk production and passing on processes prevented an overload of activities.

> "A gente percebeu que não dava pra esperar as coisas chegarem. De alguma forma a gente tentou otimizar o tempo. As compras não eram uma compra única. **A gente fez as coisas em paralelo"** (Intern1 I1 5248).
>
> "Foi o seguinte, **no início a gente tinha plano A, B, C. Se plano o A não deu, fazia o B. Se não deu, fazia o C. No final, com a pressão do tempo, cada um tocava um [plano]. Ou então a gente tocava os 3 ao mesmo tempo"** (RC I2 3906).
>
> "As abordagens foram várias. Uma delas foi fazer os primeiros ensaios para todas as opções e continuar o processo apenas com o mais promissor, mesmo que, os demais merecessem continuidade. Sempre procuramos distribuir bem o trabalho. Os materiais que estavam padronizados eram fabricados em maior quantidade pela técnica para uso de todos, assim, os demais ficavam apenas no cerne da questão examinada. [...] **A carga de trabalho aumentou, mas nada que fosse impeditivo**" (RC, whatsapp).

The interconnector case is a suitable example of the group's adaption to the delayed process. The group was testing each steel type one at a time to define the appropriate specification of the material, however, it turned out that identifying the ideal steel was more complex than initially expected and each testing cycle demanded time. To accelerate the process, the group acquired several potential sheets of steel and tested them in parallel, even though it was not the optimal scientific approach to the development as a larger set of tests was not able to be executed.

5.3.1.2 Introducing bulk production

Another response to the time pressure of the deadlines was practices related to bulk production. The basis of all three cell components is a mixture of powders. All powders must be prepared, synthesized, and characterized before using them. The initial idea was to produce the amount of powder to last for the entire process (Part1 I2 3507). Before the equipment arrived, the group needed much fewer powders, but when using new and larger equipment, they also needed a larger quantity of powders and therefore had frequently repeat the production process.

> "A ideia era fazer pó pro seu trabalho todo. Só que nunca dava, você sempre tinha que fazer mais pó**. E a gente perdeu muito tempo fazendo pó**. Porque além de fazer, você também tem que caracterizar o pó tem que fazer radiação de Raio X, você tem que ter certeza de que aquilo realmente é o que você fala que é. **Quando a gente viu que estávamos perdendo muito tempo fazendo** pó, e fazer só um pouquinho não adiantava, o que a gente começou fazer? **A gente começou dedicar, por exemplo, uma semana só fazendo pó**. E [o pó] durava 4-5 meses" (Part1 I2 3507, emphasis added).

> "Na verdade, **a partir do momento que a gente teve reagente suficiente** [a gente começou com essa prática]. Porque na verdade o projeto foi implantado e a gente tinha que dar resultado, mas os reagentes ainda não tinham sido comprados" (Tech I2 3255, emphasis added).

Through discourse, within conversations among the group participants in informal settings and meetings, the group started introducing a practice in which they would routinely attribute time to the production of powders instead of individually producing small batches. The implementation of this practice was attributed to the interaction of the group and being immersed in the powder-making process. The efficiency of the practice of producing small batches of powders was questioned by the participants and communicated among them. Individual powder production was considered the best way for the given moment, but with the higher demand of material, they decided to adapt and scale up the process.

> Então, em vez de cada hora a gente sintetizar um pouquinho e caracterizar aquele pouquinho... aí vinha um outro aluno. Ele também precisava material. E aí ele sintetizava aquele material mesmo que a outra já tinha feito. **A gente colocou uma regra**, o técnico sintetizava, sei lá, 10 kg. **Porque era muito mais fácil a gente caracterizar uma vez só e a gente tinha um lote**. A gente tinha todas as especificações aquele material (RL1 I2, 1300, emphasis added).

When noticing that the group was losing a lot of time preparing these powders, they started dedicating slots to scale up the production and prepare the powders in bulk. The participants rotated and alternately spend a week preparing powders which in turn lasted for 4-5 months and the group could focus on other things without being interrupted by that process (Part1 I2 3507, Part3 I2 3500). The technicians and IC students were mainly allocated to the powder production (Part1 I2 3715).

A second impulse that contributed to the decision to produce larger quantities of powders came from the testing process of cell components and their vulnerability towards breakage when throughout the heating process. Due to the time-demanding process, a larger quantity of powder would enable the group to not constantly start from the beginning of the process, but already improve the cell component with characterized powders.

> "**O que a gente fazia era bastante pó. Porque se a coisa saia quebrada a gente tinha mais pó pra começar de novo**" (Part1 I1 4600, emphasis added).

A third unforeseen event occurred when the group noticed that replicating the process was much more complicated than initially expected. A slight variation of the procedures would lead to a different product, which in turn would not be valid for comparing results or assuring replicable materials. To resolve this issue, the research leaders purchased a large amount of material to produce a volume of powders that would last for the entire project. This practice was successful as it economized time by grouping the repetition of smaller processes into larger bulk production and was, therefore, carried out for the entire project.

> Tudo pra andar mais rápido, porque tinha prazo (RL1 I2 1625).

5.3.1.3 Introducing commercial cell components to save time

The bulk production of the powders accelerated the development of the cell components, however, each component depended on subsequent components, which complicated a parallel development process. To enable parallel development of each cell component the group started using commercial cell components. The commercial cells were established as reference material to compare the group's research to already established scientific advances and as a technological base for each cell component.

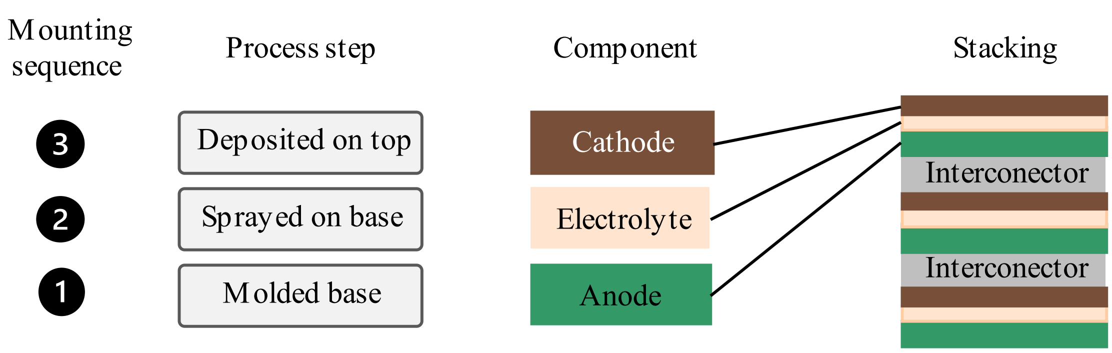

Figure 3 Mounting sequence of fuel cells. Own figure

An objective of the project was to develop an exclusively nationally developed prototype, including all development steps of the fuel cell system. This comprised the synthesizing, characterizing, and production of all materials as well as the complete development of the electrodes and the interconnector. Two electrodes, anode and cathode, and an electrolyte are necessary to build a fuel cell. They need to be deposited above each other to form a cell, illustrated in Figure 3.

In the first development stages, each component needs to be developed individually, but as one cell component is supported by another and reacts differently depending on the material and surface it is deposited on, they rely on the preceding component to be fully developed. This implies that the electrolyte development could only be completed as soon as it is applied to a fully functioning anode, and the cathode could only be completed when testing it on top of the fully developed electrolyte and anode.

> "**A gente não podia esperar fazer pra testar o anodo e catodo só depois que nós fizéssemos um eletrólito. Então a gente tinha que começar a testar o catodo e anodo sobre o eletrólito que vieram da França que a gente sabe que sinteriza bem** [...] E a outra coisa é a comparação ente o nosso pó e o pó comercial. Isso é importante tanto pra gente ver no que que o nosso iria dar quanto para os trabalhos acadêmicos, para você compara o nosso pó com os dos artigos" (RC I2 1:06:20, emphasis added).

> "A ideia era o seguinte**: como você sempre tinha que testar meia célula, você pegava um material bom e o seu que você estava testando**" (Tech I2 5745, emphasis added).

> "**Tem a questão do prazo, mas eu acho que, principalmente, pra gente conseguir e estudar separadamente esses materiais**" (Part3 I2 5750, emphasis added).

As the process steps on merging the cell components were more complex than initially calculated, the group acquired commercially available components to research the cell integration of all components in parallel. To develop each cell component, they were separately researched with the help of commercial cells. This usage of commercial cells made a parallel development possible without each self-made LaMpaC cell component being completely developed first. Commercially available cell components in fuel cell research are commonly used as a reference material to compare own results and to calibrate new equipment, however, using cells to test and develop their own materials was a practice implemented due to time restrictions and, therefore, each component research was at first not dependent on the completion of the subsequent cell component.

> "Eu desenvolvi o eletrólito. Mas ele funciona em cima do outro material que era anodo. **Então pegava uma pastilha dum anodo comercial e fazia o meu por cima.** Aí se dava problema sabia que era o meu" (Part3 I1 3720, emphasis added).

> “Então em vez de esperar a Part3 fazer o anodo, a Part1 fazer o eletrólito, para depois a Part5 testar o catodo, que era o último componente a ser colocado, a gente já comprava anodo e eletrólito prontos e entregava para Part5. “Você vai testar em cima dessa célula que já está pronta, e você vai testar o seu catodo.” Porque a medida de impedância permite você discriminar cada uma dessas partes. Então você sabe qual é a resistência relativa ao anodo, ao eletrólito e ao catodo. Então mesmo se você pegar um material comercial, você sabe se o seu material tá bom ou não (RL1 I2 010120).

When reaching satisfying results with the LaMPaC cell components, deposited on the commercial components, the group started depositing all LaMPaC cell components upon each other to form a complete self-made cell, however, as the self-made components differed from the commercial ones, they needed to be adjusted once again to perform similarly. Therefore, for example, the porosity and suspension of the electrodes needed to be adjusted as the commercial electrolyte were much denser than the self-made one. The parallel development process and final merge of the LaMPaC cell components to create a cell and then a stacked system is visualized in Figure 4.

In addition to using commercial cell components to complete them with their own materials, the group wanted to acquired commercial interconnectors as a contingency in case the project

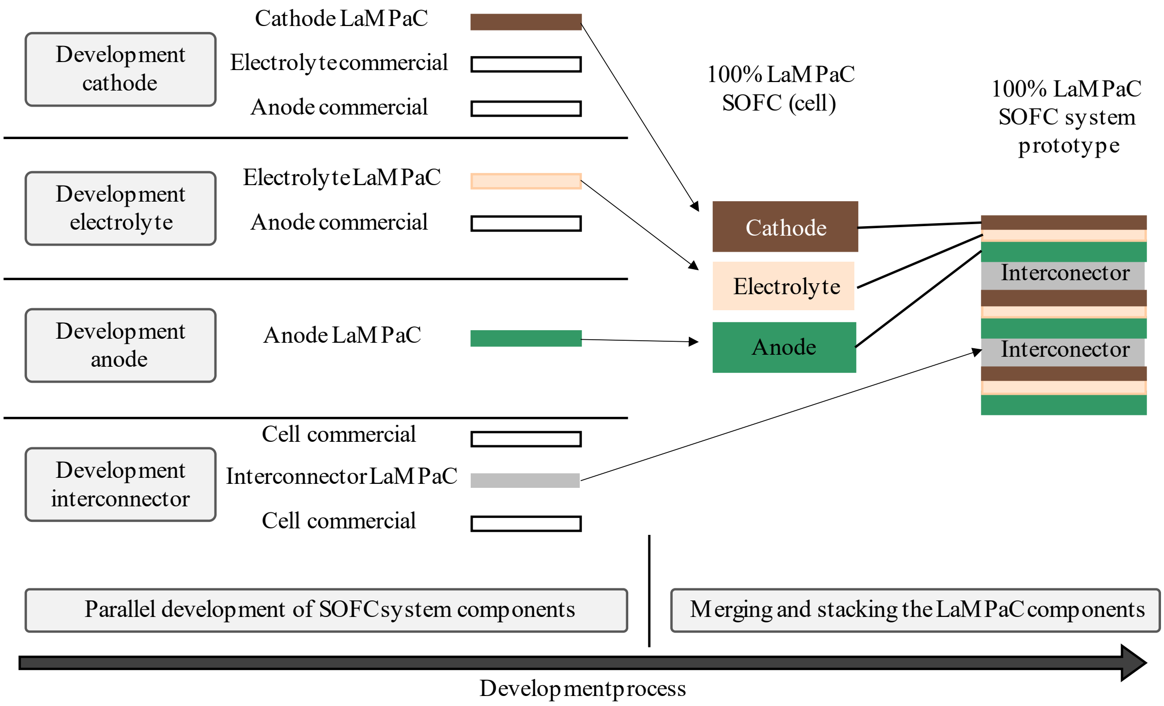

Figure 4 Parallel development process of LaMPaC cell components. Own graphic

would not be able to develop their own in time. The idea for a backup emerged when realizing that the prototype development was more time-intensive than imagined. However, at that time and with their available resources, there was no interconnector for their use commercially available, which increased the importance of developing their own.

Implementing the practice of introducing commercial cell components to save time, was a successful practice to overcome the unknown event when realizing the impossibility of developing the cell system in sequence, as the cell components could be developed simultaneously while having a research reference.

5.3.2 Decentralizing tasks and responsibility

Another set of practices that was implemented to deal with uncertainty and facilitated the execution of the project relates to the decentralization of tasks and responsibilities. The research leaders established practices that would distribute the exposure to uncertainty among the entire group. Assigning participants to be responsible for certain equipment, implementing control notebooks, shielding participants from certain tasks, and distributing processes and tasks among the group accelerated the distributing of knowledge, reduced wrong usage and malfunctioning of equipment, and ensured that participants would stay focus on important tasks.

5.3.2.1 Assigning equipment responsibility

When the project started, the usage and management of equipment was the responsibility of the project leaders. As the project leaders had administrative responsibilities and duties as professors, however, the equipment was usually operated by other participants, also for teaching purposes. Due to the high complexity of the equipment the participants' usage sometimes led to malfunction and resulted in technical issues that needed to be fixed, however, no participant felt personally responsible (Tech I2 4515, RL1 I2 3700). When new equipment arrived, it was the responsibility of the research coordinator or the technician to oversee the installation and resolve any emerging issues. Usually, the installation was executed without major incidences, however, in the case of the German oven, the research coordinator and the technician had to resolve the complications with the missing plug and the energy grid integration. Being responsible for the new oven and its integration, facilitated the process as they could act quickly, order a new adapter and get in contact with the UFMG technician to investigate the energy grid integration.

> "Porque na hora que começou um problema, ninguém que se responsabilizava. Na hora que quebrava, na hora que tinha um problema, não tinha nenhum ponto que a gente pudesse detectar onde ocorreu o problema. **Então o que que a gente fazia?** O técnico ou responsável por aquele equipamento **tinha que controlar essa ordem de utilização**. Quem vai usar? E quando? A partir de que momento o equipamento começou a dar problema? Porque se a gente sabe o que que foi que acarretou o problema a gente consegue resolver o problema rápido" (RL1 I2 3700, emphasis added).

After installation of the equipment, the project leaders distributed the responsibilities to some selected participants that were already using the equipment intensively for their research and spend a lot of time in the laboratory - primarily the technicians and Ph.D. students (Part1 I1 2120, I2 1840). The implementation of these practices was to address the uncontrolled usage, which resulted in many cases in time-consuming recalibration of maintenance. As the responsibilities were assigned according to which equipment the participant was using the most, for some participants the diffusion felt like a very organic distribution of tasks (Part2 I1 2200).

> "Isso foi implementado, **primeiro, pra garantir que os POPs estavam sendo produzidos**, para as medidas. A outra causa: **Algumas coisas sumiam no laboratório**, perdiam ou quebravam. Então, era importante ter uma pessoa responsável, olhando e garantindo o bom funcionamento. Se alguém fosse usar a pessoa **dava uma orientação**. **Acompanhava primeiro a pessoa, até a pessoa ganhar uma expertise"** (RC I2 5445, emphasis added).

> "Na verdade, a RL1 colocou a gente. Uma responsável pra isso, outra pra forno, outra pro potencial zeta[9]. **Tinham muitas pessoas usando os equipamentos. Aí de repente tinha alguma coisa quebrada e foi ninguém.** Então essas coisas aconteciam" (Part1 I2 1840, emphasis added).

> "Quando chegaram os equipamentos novos, a RL1 colocava cada um responsável por um. [...] **Porque aí, a gente começou atender quem estava chegando**. Então, tinha aluno do mestrado, iniciação científica, até doutorado quem chegou **depois a gente, aí a gente ajudava eles usarem o equipamento também. Então ajudamos ensinar e manter o inteiro"** (Part1 I1 2120, emphasis added).

> "Por que **começavam a estragar os equipamentos?** Porque às vezes era uma pessoa que não tinha conhecimento ou não tinha participado do curso. Íamos ao equipamento e as vezes tinha uma burrada dele. Isso acontecia às vezes. Aí estragava o equipamento. [...] Aí tinha que conversar com ela (RL1) e ela falou "**então vamos fazer assim: cada um vai ser responsável pelo equipamento".** Aí, nessa época, começou tentar implementar isso. Nunca funcionou direito. Começava funcionando. [...] A pessoa responsável às vezes não ficava tempo suficiente pra controlar. Por exemplo, a pessoa ficava lá até 4 ou 6 horas por dia. E as outras horas? Quem usava? Aí às vezes a pessoa não usava direito e outra pessoa ia lá e usava" (Tech I2 4515, emphasis added).

The decentralization and diffusion of responsibility had several purposes: They included maintaining and taking care of the equipment and in the case of malfunction, taking responsibility and action in repairing the equipment (RC I2 5445, Intern1 I2 2955). The participant responsible taught participants that were new to the project group (from now on 'novice') and other participants how to operate the equipment and monitor its usage (Part1 I1 2120, Intern1 I2 2720). It also included giving internal seminars about that equipment or the usage method, being the reference within the laboratory for that equipment (Part3 I2 5235, Part2 I2 3150, Intern1 I2 2955), and ensuring the creating of POPs (RC I2 5445).

> "Se a pessoa tivesse lá dentro ainda - no grupo - **eu ia lá e pediu ajuda pra ela"** (Intern1 I2 2720, emphasis added).

> **"É você que cuida da integridade dele, se tá funcionando** ou se não está. Se ele estraga. Como nós vamos arrumar? **Operar ele corretamente**, porque eram muitos" (Intern1 I2 2955, emphasis added).

> "Essas coisas todas era eu que também pensava. **Onde comprar. Como montar**. E quanto também queria fazer um teste que não funcionava eu também que tinha que dar um jeito de achar uma solução" (Intern1 I2 1200, emphasis added).

This practice continued throughout the entire project (Part1 I2 4410), as all participants could not learn all equipment, which also was not necessary, as everyone did not need to use all the equipment available (Part2 I2 3150).

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[9] Equipment to analyze Potential Zeta. Potential Zeta is an important measurement for material characterization.

Implementing the practice of making participants responsible for certain equipment helped in many ways. The project leaders could transfer some job responsibilities to the participants, gaining more time for administrating the project and UFMG duties. The responsible was specialized in the equipment and the reference person for that equipment within the group. That person educated others in the methods and usage, was responsible for systemically organizing and creating POPs, maintained the equipment, organized its usage, and taking care of the repair process if needed (RC I2 5445).

The practice was constantly re-made by extending responsibilities or refining them. The routinized activity in being responsibly for specific equipment was implemented after the accumulation of unforeseen events in form of equipment breaking, malfunction, and wrong usage. Responsible participants acted and assumed responsibility in incorporating equipment teaching, repairing, and creating POPs in their daily work practice. The implementation of this practice came with many perks but also had its problems. The responsible participant was not constantly present to observe or liberate the usage of the equipment, due to other obligations like classes or personal life. As the equipment was used intensely, the responsible person was often not present what resulted in faulty usage and even equipment damage. The project also liberated the usage of some equipment to external researchers within the university, which sometimes led to faulty usage even though the person had to be taught and authorized before being liberated for the equipment operation (Tech I2 4515).

5.3.2.2 Introducing an equipment notebook to control usage

To give more control over how and by whom the equipment was used and to reduce the usage of equipment by unqualified personnel, internal or external, the research leaders started to introduce equipment notebooks. Each piece of equipment had a notebook physically located next to it. It contained the documentation of each participant who was responsible for using the equipment and for what. The notebook was accompanied by a calendar in which a participant could reserve the equipment for using it at a certain time (Part1 I2 3715) and entailed the calibration of the previous user (Part2 I2 4430). The notebook was also implemented to track the usage of equipment and other materials as they sometimes disappeared. For some time, the group was working in three laboratories in parallel and shared resources among them. It was, therefore, not unusual that a participant would take a resource from one lab to another, which in turn would lead to a distorted stock of materials. A notebook was implemented to track the materials and ensure they would be returned (RC I2 010200).

> "**Sumia coisas demais**. Até nas ferramentas no laboratório a gente implementou um quadro lá que tinha que escrever quem foi o último [...] **pra garantir que as coisas retornassem**. Pra ficar fácil de achar" (RC I2 010200, emphasis added).

This practice was functioning without issues for a period, but after a while, some participants neglected the use, either because the student did not want to be identified in the case, they used the equipment incorrectly or they simply forgot to make notes or thought it was unimportant. The technician and project leaders did not have time to control the notebook and it was therefore left incomplete (Tech I1 3630). Secondary data show, however, constant and recurring entries by participants and external users, demonstrating a successful adaption overall. More data indicates that due to its importance of monitoring and organizing the equipment usage, the practice was continued throughout both projects and adopted by the participants in the group.

5.3.2.3 Shielding participants from certain tasks

To ensure that each participant could focus on their individual research with academic deadlines within the larger prototype project, the project leader shielded certain participants from certain tasks. The purpose of this practice was to relieve participants from time-consuming tasks that would not directly contribute to their thesis or dissertation research agenda that was defined by the department of chemistry. Secondary data suggests that technicians often acted as support for other participants. To shield participants, their duties covered drafting, controlling, and improving POPs, distributing tasks among group members, the synthesis, filtration, and production of powders, and executing tests for other participants. Furthermore, technicians, scholars, and IC students were designated to keep the laboratory organized and clean equipment, which relieved other participants from those tasks. Personal notebooks document a monthly organization of the laboratory and the reagents, usually performed by the technician with the help of interns or CEMIG scholars. Instructions from secondary data show cleaning schedules and dedicated timeslots to be filled out by previously defined participants including a detailed explanation of how to clean each piece of equipment. This relieved other participants from such duty, which gave them more time for their research.

Each participant that had resources to fund their research in form of a *taxa de bancada* had to procure the materials needed on their own, however, acquiring the equipment and materials for project purposes was the responsibility of the project coordinator with the help of the project technician. The equipment and materials were accessible to all participants to use for their research. The participants were included in defining the specification of the resource (as they needed to suit all research purposes within the group) but did not have to participate in its order process.

Assigning equipment responsibility was not merely to control the usage of the equipment but also to allow the participant to focus on only the equipment that they needed the most for their research. But the participants relied on other equipment besides the one they specialized in, so either the responsible for that equipment or the lab technicians performed the measurements and tests for other participants. The participants, therefore, helped each other out and used the equipment they were specialized in not only for their own research but also for others.

> Aluno de mestrado e doutorado iam lá para aprender. Não estavam lá para ficar mecanicamente repetindo 1 kg de síntese. Você tinha que ficar lá 3 dias 4 dias para fazer uma etapa, mais outra etapa. **Eles tinham que avançar em termos de novidades** (RL1 I2 1450, emphasis added).

The development of each component of a fuel cell consists of many processes. For their research, Ph.D. and master participants needed to develop several processes that were not essential for their academic contribution but were necessary for cell development and often needed to be executed repeatedly. To liberate those participants from such tasks, the project leaders asked them to pass on such processes to other participants such as technicians or students from IC or graduation that would benefit from learning and executing such processes.

> "Nossa, eu ganhava tempo demais. **Nosso maior ganho era ganhar mais tempo pra estudar**" (Part1 I2 3920, emphasis added).

Depending on the task and the student, some processes only needed to be replicated but others needed to be scaled up. Scaling up and modifying the process was a time-demanding process and was usually done by the technician to relieve other participants from those tasks. She needed to adapt the calcination and the synthetization as the processes changed slightly when producing in higher quantities. The technician's job was to take the newly developed process, scale it up, and modify it if needed. This gave the Ph.D. students more time to focus on other developments (Part2 I2 3550; RC I1 3055), however, they were never completely liberated of the process as some things had to be exclusively monitored by the Ph.D. student.

> "Às vezes eu passava parte de um processo, mas um processo inteiro eu **nunca passei e fiquei livre dele**" (Part3 I2 3955, emphasis added).

5.3.2.4 Passing on processes

Passing on processes to other participants within the group had two motives: First, it distributed the workload, and Ph.D. students could focus on further developing parts and processes of the fuel cell as elaborated in the preceding subsection, and second, it served to pass on knowledge and educate novices to learn the theory and methods of fuel cell development. Such processes were usually related to technological and scientific methods or equipment usage, however, also more basic and simpler tasks were distributed among the participants. The secondary data provides several examples, in which the technician teaches interns and IC students how to organize the laboratory and clean equipment.

When elaborating on passing on processes, however, it usually refers to more complex fuel cell technologies procedures. The participant, involved with the development of a new method or process, had to research, and develop continuously until she arrived at an optimal condition. Upon the development of a new process, more repetitive, manual, and mechanic tasks were passed on to technicians and IC students so they could replicate but also specify and develop the process further (Part2 I1 4255).

> Muitas vezes tem que repetir os processos que davam errado. Então, até chegar numa condição ótima aquela pessoa ela ia fazendo, fazendo, fazendo, repetindo, votando pra análise, até chegar em uma condição do material que vou trabalhar. **Mas quando chegava nesse material, e era esse material que a gente iria usar para a pilha, para as medidas elétricas de depois o projeto, aí a gente passava essa receita, esse procedimento para mão do técnico.**
>
> "Depois a gente ia passando pra técnica. Depois que a gente entendeu o processo. E ela às vezes **especificava o processo**" (Part2 I1 4255, emphasis added).

To start, the participant teaching (from now on called 'instructor') sat down with the participant learning (from now on called 'apprentice'[10]) and explained the theoretical implications of the process (Part3 I2 3955). The instructor implied that the apprentice would have already gathered some information on the process through POPs and the literature. For a couple of days or weeks, the instructor continued doing the process with the apprentice observing and studying the process (Part3 I2 3955). When the instructor felt comfortable with leaving the process to the apprentice, they let them take lead on the process while observing them as a bystander. When the apprentice did the process flawlessly, they were left alone, and

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[10] It is to be noted that an apprentice is not necessarily a participant that just entered the project, or novice. Participants that were already integrated into the project group and wanted or needed to learn how to use equipment are also referred to as 'apprentice' in this context.

the instructor dedicated the newly acquired time slot to other tasks like research or studying (Part1 I2 3920; Part3 I2 3955).

> "Sempre que entrava alguém novo laboratório, **eu sempre passava algo"** (Part3 I2 3955, emphasis added).
>
> "Normalmente essa parte, que é trabalho mais manual, tipo fazer pastilha, uma coisa assim mais mecânica, ficava tudo pros alunos da IC" (Part1 I2 3920).
>
> "Sempre assim, vamos supor: Era técnica que ia trabalhar com a síntese do pó. Então, toda vez, eu **sempre sentava e explicava teoricamente o que eu fazia**. O processo em si que consistia e **essa pessoa me acompanhava durante alguns dias** naquela síntese e naquele preparo do filme. Então, a pessoa **acompanhava a parte experimental do início ao fim** até onde ela ia trabalhar. Então, ela ficava ali vários dias comigo participando das atividades ali" (Part3 I2 3955, emphasis added).
>
> "**A gente ensinava algumas semanas e depois eles conseguiam fazer sozinhos**. **A gente fazia e eles faziam ao lado da gente.** Depois eles faziam e a gente ficava olhando eles fazendo. **Quando a gente confiava que eles conseguiam fazer direitinho aí eles podiam fazer tudo sozinho**" (Part1 I2 3920, emphasis added).

Throughout the project, the interaction among the novices or other apprentices, the instructors, and the material artifacts like POPs, scientific literature, and the process to be passed on, intensified and created a web of practices. All those practices were interconnected, with the common goal to transfer knowledge of a production process or equipment usage from one participant to another, highlighting the larger structure that appears when all practices come together. The practice of "teaching other participants", is enacted when the instructor interacts with the apprentice and the element to be taught (equipment, process). By teaching in practice (*Praxis*) and passing on POPs and literature, this practice (*Praktik*) acknowledges the importance of tacit knowledge which is not transferable through language.

Decentralizing tasks and responsibilities, however, had the issue that knowledge was dispersed among the participants and was either passed on inefficiently and incomplete or was at risk of being lost. The systematization of knowledge management and transfer entailed a set of practices that would ensure a more controlled approach of spreading knowledge throughout the organization and help participants to continuously use the organizational knowledge, build upon and contribute to it.

5.3.3 Systemizing knowledge management and transfer

Several practices were implemented that systemized the learning of equipment and processes and assured that novices were integrated and brought up to the state of the art as fast and efficient as possible without slowing down the development process. Other practices approached issues by documenting and categorizing knowledge or focused on the continuous learning of the group related to order processes.

5.3.3.1 Including new participants into the project

The group was constantly restructuring and the fact that many participants joined the group for only a short period between a couple of weeks and one year, stressed the importance of establishing a systemic way to transfer knowledge effectively. The prototype project with its high financial capabilities and valuable equipment attracted many students that wanted to adapt their individual projects to match the prototype development or create it around its objectives. Students from many academic levels with varying project timeframes were included in the project to benefit the development but also to share the laboratory including all its resources to promote educational purposes. The varying timeframes of the projects challenged the group and the fluctuation had to be managed to assure a smooth integration and to benefit the group and the novices without delaying the milestones of the prototype development.

Upon entry, the novices were introduced to the group in a short meeting. From the start, they were completely integrated into the process of the project, were provided with literature, and had to accompany an established participant, who had most in common with their work project (Part2 I2 4040, RL1 I2 0050). The novices were integrated into the new context of the project by an interconnected mesh of social and material interactions. Relational complexities arose through the interrelations between the novice's project, the larger context of the prototype, and all the connected projects of other participants. The intertwinement between those smaller and larger projects and goals complexified with each participant joining and leaving the group.

To tame those complexities, practices surrounding the introduction of new participants were established. Being usually coordinated by one of the project leaders and supported by established participants (from now on 'veterans' in the context of experienced participants). One of the project leaders was usually responsible for the coordination of novices' projects. Additionally, several participants within the project group would assist the novices by providing study material and introductions and courses to the extensive inventory of equipment, materials, and documentation of the project.

> **Os alunos de iniciação científica normalmente faziam um projeto que estava relacionados com os alunos de mestrado ou de doutorado**. E os alunos de mestrado às vezes a gente tentava também colocar mais vinculados aos alunos de doutorado porque é mais fácil você ter um grupo mais coeso quando você tem 2 ou 3 pessoas que trabalham no mesmo assunto. Até para discutir (RL1 I2, 0050, emphasis added).

Depending on their academic level, the novice had its project defined or co-developed with the project leaders. Upon entry, the veterans presented themselves briefly, provided relevant articles and books, and explained those if necessary (Part2 I1 4005, Tech I1 2155, Intern1 I1 1720, I2 5350). Besides theoretical knowledge via literature recommendations, the novices mainly studied the processes by learning from the experiences of others (Intern1 I2 5525, Part3 I2 3955). They quickly got integrated into a continuous workflow, in which they followed the veterans doing their activities (Part1 I1 2220, Part2 I1 4005) and would have to enter the rhythm of the laboratory as the veterans could not afford to spend much time outside their work schedules (Part2 I2 4300).

> "Teve uma apresentação rápida da equipe. [...] Aos poucos a RC e RL1 pediam para ler alguns artigos. Passavam alguns livros e outros materiais sobre a parte de modelagem de pilhas" (Intern1 I1 1720).

> "A primeira coisa que eles faziam eram as matérias, depois eles pegaram alguns artigos e a RL1 fazia um pré-projeto pra eles" (Tech I1 2155).

> "Mas toda vez que entrava alguém a gente colocou: "**Leia isso aqui, leia o artigo aqui"**. **A gente sabia os artigos que eram interessantes** porque a gente tinha como referência. Então na hora que entrava alguém a gente falava: "leia essa aqui que já vai ajudar". **A pessoa sempre te acompanhava**. Então assim, se você fazia alguma síntese, a pessoa ia aprendendo junto. Se eu fazia uma medida elétrica pessoa ia junto e você explicando o que você estava fazendo. Então durante um tempo a pessoa te acompanhava" (Part2 I2 4040, emphasis added).

The veterans showed and taught the novices the diverse processes so they could observe and learn. After demonstrations, the novices operated the processes and the veterans accompanied and supervised to be sure that everything was working correctly (Part1 I1 2220). Novices had 6to research and study articles, which in turn, also supplied the veterans with new ideas and impulses.

> "**Na marra mesmo. Você entra no ritmo, você vai junto**. Cada um, por exemplo, o novato vai trabalhar com o cátodo, então você fica com a Part2 porque ela vai te ensinar um processo. Então assim, ele me acompanhava desde o início, e eu ensinava a síntese, ensinava fazer as medidas elétricas. **Então ele era meu ajudante durante um tempo. Ele apreendeu ser meu ajudante**" (Part2 I2 4300, emphasis added).

> "No meu caso a RC, RL1 e o RL2 **passaram alguns materiais iniciais porque quando eu entrei eu não tinha noção do que era esse assunto**. Então eles me passaram vários materiais que eles já tinham e a partir daí eu ia procurava mais" (Intern1 I2 5350, emphasis added).

> "Então, a gente ensinava para eles. **A gente estava fazendo o nosso, e levávamos eles pra eles irem acompanhando e aprendendo a fazer**. Depois eles faziam o deles e a gente acompanhava pra ver se está tudo certinho" (Part1 I1 2220, emphasis added).

> "Por exemplo na época a gente colocou um engenheiro eletricista para ajudar a gente em alguns problemas. **Aí eu trabalhava com ele e eu passava a minha experiência para ele** pra ele poder entender como as coisas funcionavam. [...] **Era importante**

> **pra eu ajudar ele porque se ele não fizesse as coisas funcionar, eu também ficava prejudicado**" (Intern1 I2 5525, emphasis added).

> "**Sempre** que entrava alguém novo laboratório, eu **sempre** passava algo. Eu lembro sim de ter tido alunos de mestrado depois de mim que eu ajudei inicialmente, passei coisas. [...] Então, toda vez, eu **sempre** sentava explicava teoricamente o que eu fazia. O processo em si que consistia e essa pessoa me acompanhava durante alguns dias naquela síntese e naquele preparo do filme**. Então a pessoa acompanhava a parte experimental do início ao fim até onde ela ia trabalhar.** Então ela ficava ali vários dias comigo participando das atividades ali" (Part3 I2 3955, emphasis added).

In some cases, a participant leaving the project accompanied another participant that would take over their tasks. In such a transition period, the participant leaving the project introduced the participant theoretical and practical to the processes and methods in detail (Tech I2 4200).

Along the process, practices were formed, and veterans included novices by routinized activities that would support their integration. As each novice entered with different experiences and previously acquired knowledge, the practices were less or more extensive, which depended on the contextual situation that the novice, the veteran, and the entire organization were exposed to at the time of the introduction. The practice of actively including novices into the group, was, on the one hand, time-consuming for the veterans, but on the other hand, beneficial as they contributed in the long term to their research. Either in supporting their research agenda and contributing with new articles or ideas or in keeping the laboratory organized and providing them with a suitable research setting.

> Eles usavam esses meninos para fazer as coisas deles. Como diz a Tech, aluno de iniciação científica lava proveta, arruma laboratório, eles ajudam etiquetar, ajudam a colocar as coisas em ordem no laboratório. **Então, eles tinham um trabalho deles, eles tinham alguém que normalmente orientava. Mas por outro lado também, eles contribuíam com esse outro alguém para o andamento do trabalho dessa pessoa. Era uma troca** (RL1 I2 1450, emphasis added).

The emergence and establishment of practices that introduced novices to the organization was part of the holistic development of the entire organization. Those practices facilitated the inclusion of knowledge and new ideas which in turn contributed to an acceleration of the development process. If no practices would exist to implement novices, they would likely either not be able to contribute effectively to the project (if no effort would be made to include them) or would slow down the development process (if uncontrolled actions would be taken to include them).

Participants entering the project were asked by the project leaders to familiarize themselves with the documents the group had already complied with and to study the literature relevant to the area of research of the novice. This included POPs, equipment notebooks, and personal diaries[11], and selected literature. The systemized creation of POPs was an important source of information for participants that sought learning processes, methods, and equipment usage that was already developed by the group (Tech I2 3445). This included not only novices but any other participant that needed to appropriate the information, gathered in this physical database.

> "**Começou a fazer os chamados "procedimentos operacionais padrões", os POPs**, de todas as coisas que davam certo. E outra coisa que a gente tinha eram os **cadernos de laboratório**" (Tech I2 3445, emphasis added).

Each participant had to keep notes in a personal diary on their development process which included to-dos, results, successes, and issues. The practice was initiated by the project leader to track the process and facilitate the replication of certain processes. The notebooks were forwarded to novices, so they had an advanced point of entry and did not have to start from 'zero' (Part1 I2 2415; Part3 I2 4630).

> "A RL1 fazia a gente escrever tipo um diário. **Todo mundo tinha esse caderno de laboratório. Quando chegava outro aluno, pra ele não começar de zero, ele pegava,** lia o que a pessoa que foi embora deixava, pra começar a partir desse ponto aí" (Part1 I2 2415, emphasis added)

> "**A gente sempre tinha um caderno que a gente anotava todas as sínteses e a gente sempre conseguiu passar pra quem estava entrando.** A RL1 sempre pedia pra que a gente tivesse uma organização pra isso - pensando que quem viesse depois tivesse um material que a gente conseguisse passar" (Part3 I2 4630, emphasis added).

Along the project process, the group created a small library of research papers, books, and other literature which grew constantly. It was a collection of documents that addressed the specific development of solid oxide fuel cells and was a source of knowledge for all participants who used and constantly expanded its range.

Those documents did not give the participant the complete understanding of what she needed to learn, due to the missing practical experience, but it was an important steppingstone. It also relieved the other participants in explaining all the processes and methods that were needed for the participants' research.

[11] Personal diaries are notebooks that contained the individual development process of each participant. They will be elaborated on later in the thesis.

5.3.3.2 Establishing reference participants

Due to several equipment misuses and uncoordinated usage, the research leaders decided to assign equipment responsibilities to some participants as elaborated in the subchapter on decentralization. One purpose of assigning responsibility to certain participants was to establish reference persons for certain equipment. The research leaders assigned participants, usually Ph.D. students and technicians, to certain equipment, to become experts in its usage and the reference within the group for that equipment. Besides being responsible for the equipment's maintenance, the participant was teaching and training participants that wanted to use the equipment and was liberating its use to them as soon as they would have sufficient knowledge on the equipment – theoretically and practically. Through this practice, the group was able to systemize the knowledge on equipment by having equipment experts that could be consulted when needed. When a participant needed assistance with equipment or other processes, she would approach the reference person and ask her to be taught the fundamentals and methods that were required to understand the equipment operations.

> Muitas vezes, as pessoas, principalmente os novatos, quando chegavam, o pessoal ia falar e o novato ficava bem perdido. E aí ele falava, "oh, pelo menos eu sei para quem perguntar – fulano está trabalhando com isso ou fulano já fez isso" [...] E como os assuntos eram bem separados, **as pessoas sabiam com quem tinha que conversar**. Tinha equipe de anodo, equipe de catodo e equipe de eletrólito. **Então pessoal sabia se tiver problema com quem conversar**. (RL1 I2, 1110, emphasis added).

5.3.3.3 Systemizing the utilization of POPs

The constant changes in the group's constellation also emphasized the need to document and systemize the knowledge that the group accumulated. Due to their prior experience in university research and projects, the project leaders and the coordinator were aware of the loss of knowledge that naturally happens when participants leave the research, usually because they completed their individual projects or studies. To assure constant results and replicability of each process, all materials and equipment settings had to be documented in detail as a slight change in the adjustment might lead to complications and result deviations.

Throughout the project, successful process procedures and equipment operations were documented, revised, and organized in a physical folder that was accessible to everyone within the laboratory. Those internal documents were termed *Procedimentos Operacionais Padrao* (POP). Secondary data suggests that the project's technician was primarily responsible for drafting, collecting, and organizing the procedures, retesting the methods, and keeping the processes updated. Notebook entries show that the procedures were drafted and revised by more than one person and only printed and filed when the process was flawless, however, due to the complexity of the processes, most POPs had to be revised and updated even after printing one or two times during the project. It was a fundamental practice of the group to register knowledge and pass it on to other participants, but only in combination with passing on tacit knowledge by practically showing the process (RC I2 4620).

> "Olha, não [The POP alone was not sufficient to do the process]. O POP é suficiente porque ele é feito e a pessoa geralmente passa para outra antes de sair, né? Então geralmente por exemplo**, além do POP, a pessoa que ia fazer era acompanhando de alguém que já tinha feito**" (RC I2 4620, emphasis added).

When a new process was developed, or equipment set up, the person who arrived at the optimal testing point, material, or calibration, either drafted the POP or described in detail the process of passing the process on to the technician who would then prepare the POP. When another participant wanted to use equipment or a process, they could use the POP to have an initial starting point and then even add modifications if necessary (Part3 I2 4940). The goal of the POP was to register the process so it could be repeated but also, so novices did not have to start from 'zero' (RC I1 4340).

> "É uma prática comum de produção. De qualidade. Na minha formação, eu tive aula de qualidade. Eu acho que desde o início a gente propõe isso pra não ter esse problema na rotação das pessoas pra não se perderam. Não sei se outros laboratórios faziam isso. **Mas a gente fazia**. Porque é um projeto diferente. **Não pode começar do zero com cada um**" (RC I1 4340, emphasis added).

The project leaders and coordinators, however, requested the participant, who either created or already learned the POP and put it into practice, to accompany the person learning the process, method or equipment as they thought that the POP alone is not enough (RC I2 5445). When accompanying, the apprentice sometimes had questions that were not covered in the POP, so the instructor modified the POP accordingly. The POPs, therefore, were constantly changed and revised every time someone would start learning a procedure (RC I2 4620) but also were rechecked by the technician before finally printing and filing the POP.

> "**Quem chegasse ao pronto ótimo do ensaio ou de um material escrevia o POP. E passava pra outra pessoa.** Se o outro tivesse dúvida ele **acrescentava lá no POP**. Isso foi fundamental. [...] Muitas vezes alguma coisinha fica né. Um pouco fica. Por isso que esses **POPs têm que ser revisados constantemente**" (RC I2 4620, emphasis added).

5.3.3.4 Diversifying meetings to intensify knowledge transfer

Meetings were an especially important practice and frequently associated by participants as a tool to solve problems and share knowledge and information. During the meeting, articles were indicated or presented and measurements, results, updates, or problems were shared with the rest of the group (Part3 I1 4210, Part2 I1 3110, Tech I1 4823, Intern1 I2 5130). Several types of meetings were established through the project process. One type was the one-on-one meetings between participants, coordinators, or project leaders which were constantly scheduled autonomously among the participants, depending on their needs (several times a week according to notes from secondary data). Notes suggest that usually those meetings were scheduled to approach smaller technical issues, give orientation, provide updates, engage in organizational planning, or joined work processes like revising POPs, help each other, pass on processes, or monitor tests and experiments. Another type of meeting was cell component meetings, in which a participant – often a research leader – scheduled a meeting with all participants who were working on a specific component like anode or cathode. In those meetings, the component status was discussed, and tasks were distributed among the participants.

Besides such smaller meetings, complete group meetings were held regularly in which all participants shared their experience, updated everyone about the course of their work, and defined new objectives (Part3 I1 4210, Part2 I1 3110, RC I1 3725, Tech I1 4545) (Part1 I1 3700: Part1 I2 4230). Those meetings were held usually weekly but depending on the demand only every 14 days and were communicated via email with the request to be confirmed by all participants (source: secondary data). They were the cornerstone of spreading newly acquired knowledge quickly within the group. A primary objective was to resolve pending issues concerning what was missing for each participant (e.g. material, infrastructure, knowledge) to prevent a standstill of the development (Tech I2 5300). The group meetings were scheduled by the project leader (Part1 I2 4230), however, as secondary data suggests, the participants had several autonomous meetings a week among each other to update each other on current processes or plan future research steps.

> "**Uma pessoa ou duas apresentavam** o que ela tinha feito desde a última reunião o que ela apresentou" (RC I2 5225, emphasis added).
>
> "**A gente fazia reuniões semanais.** Toda sexta feira. Como está o **andamento das coisas**? quem tem **dificuldade**? quais eram as dificuldades? (Part3 I1 4210, emphasis added)
>
> **Artigo que tinha lido, ou medida ou resultado ou problem**a. Eram nessas reuniões em que a **equipe inteira** ficava mais a par do trabalho de cada um" (Part1 I2 4230, emphasis added).
>
> "Aí renuíam todo mundo do laboratório e **tinha reunião em anodo, eletrólito e catodo.** E aí, cada um falava **o que estava acontecendo** e o andamento da pesquisa.

> Não, na reunião **ficava tudo mundo junto**, mas assuntos separados e cada um falando sobre o seu tema" (Part1 I1 3700, emphasis added).

> "E aí a gente fazia uma roda, juntava todo mundo no laboratório. **Aí chegava com que tinha feito, os artigos que tinha lido, o que achou de novo na literatura, em relação àquela literatura, o que você pretende fazer**? E como você pensava em fazer? Então cada um levava os **artigos que tinha lido** e visto o que você estava fazendo e o que poderia ser feito. Era assim. **E mostrava o que a gente tinha feito** o que deu certo que deu errado. O que a gente viu, o que a gente poderia mudar..." (Part2 I2 4545, emphasis added).

Urgent matters that would stop the progress of a participant had priority and were discussed in the meetings (RC I2 5225). Additionally, one or two previously defined participants had the chance to present the status of their work or their developments since the last time they presented in front of the group, which included problems, successes, and upcoming developments. The entire laboratory group was involved in those meetings and contributed with feedback and ideas (RC I1 3725, I2 4830, 5225, Tech I2 5300). Depending on the current development status of the project, the meetings had different topics, and sometimes smaller meetings were scheduled in which a specific cell component was discussed (source: secondary data). Generally, all participants were encouraged to give input on the current situation and their current development – successes, failures, newly acquired knowledge, or other relevant information (Part2 I2 3853).

> "E nesta reunião todo mundo falava das suas dificuldades. Então, eram várias experiências junto. **Porque a gente estava no projeto há mais tempo ou menos tempo, mas cada um tem uma história de vida e experiência passada** [...] então quer dizer a gente tinha uma vivência anterior das coisas relacionada àquilo. E cada um. Quando a gente falava sobre aqueles problemas na equipe, era tipo um brainstorming sobre a dificuldade de cada um e todos se envolviam**. Porque tinha um objetivo em comum que era sair essa pilha**. Então todos se envolveram todos tentaram dar uma **colaboração para resolução daquele problema**. Então se alguém tinha dificuldade em alguma coisa que não ficou bem descrita, um outro que já fez ela ensinava" (RC I2 4830, emphasis added).

> "Cada semana, tentava se discutir algum projeto de algum aluno com maior profundidade. **Mas sempre tinham as questões gerais**. O que tá faltando de reagente para tal aluno para ele poder trabalhar? O que tá precisando pra resolver o problema do aluno? A RL1, O RL2 e a RC sempre conversavam nesse grupo de alunos nessa hora que tudo mundo estava junto, **pra tentar dar estrutura para esses alunos**. Quais as coisas que eles precisavam para continuar o projeto deles? [...] Mas em relação das reuniões, sempre tinha esse objetivo: **Resolver as pendências em relação ao que estava faltando pra cada um**" (Tech I2 5300, emphasis added).

Although all meetings had an agenda, previously defined by the project leaders and coordinator, the discussions and presentations felt very organic to many participants (Intern1 I2 5130). If a participant did not have the chance to talk, or needed to talk separately, the project leaders scheduled a separate meeting to get updates or provide assistance (RC I1 4200, 5500).

> "Mas se alguém tivesse com problema e estava parado com o processo, a pessoa ia falar ou essa pessoa também falava. **E assim a pessoa nunca ficou parada**. Se está com uma dificuldade a pessoa sempre vinha atrás de mim, atrás do RL2 ou da RL1. **Colaboração era muito presente**" (RC I2 5225, emphasis added).

Participants that acquired new knowledge on equipment use, measurements, tests, analysis, or other methods, were asked by the project leaders and coordinator to give seminars. This type of meeting was introduced to pass theoretical and practical methods to other participants that had an interest in such knowledge and needed it for their work (Part2 I2 3735, Tech I2 5300, RC I2 4830).

> "A RL1 também implementou um período, **um período que cada um falava um pouco sobre a teoria as técnicas**. Então é o que acontece: A gente dava **tipo um seminário,** falando sobre cada técnica. O que ela oferece" (Tech I2 5300, emphasis added).

> "Tipo assim: "Nessa semana você apresenta sobre o Zeta." Aí eu dava um seminário sobre o Zeta. "Na semana que vem o fulano fala sobre reologia." Aí falava sobre reologia. **Cada semana era um falando sobre um tema**. Em torno de 20 a 30 minutos fazendo depois os outros poderiam fazer perguntas" (Tech I2 5300, emphasis added).

> "**Então, todas as etapas a gente acabava expondo para grupo**. Mas, por exemplo, quando eu aprendi fazer essas simulações na França, quando eu voltei, quem foi fazendo as simulações com pessoal fui eu. **Peguei todo mundo que foi fazer medida elétrica e que tinha os resultados [and helped them to learn the simulations]**. [...] Eu juntei, não todo mundo, mas quem quis fazer essa parte de medidas elétricas, **quem realmente queria trabalhar com isso.** Por exemplo a Part3 fez medida elétrica, mas ela só queria a análise então ajudei fazer a simulação, mas não ensinei tudo para ela porque na verdade não era o foco dela. Mas Part5 precisava." (Part2 I2 3735).

Notebook entries from secondary data show that the distribution of tasks among the participants was common practice within the group meetings. In some cases, the entire group was mobilized to make a collective effort to do literature research to solve a specific problem. In other cases, the research leaders asked to organize the calendar so the entire group can learn the usage of specific equipment, for example, the electrical measurement instrument.

Along the project process, the purpose of the meetings diversified and served several objectives: To find solutions to current, urgent issues (RC I1 3725, I2 4830, Tech I2 5300); to discuss articles and methods (Tech I1 4823); to keep everyone informed about the specialty areas of all participants and their responsibilities in the project, including equipment expertise (Tech I2 5300); to integrate novices in the group and keep participants informed about new participants; to keep everyone up to date on the development status (Tech I2 5300); to distribute tasks (source: secondary data). And as the group was working closely together in the same laboratory, many informal meetings emerged in form of lunch and coffee breaks that lead to further exchange of information (RC I1 5500).

Additionally, the meetings served to control and monitor the completion of tasks by all participants (RC I1 3725, Tech I1 4925). Not only as a control mechanism but also to align the advances of the individuals with the overall objectives of the project. The research leaders and the coordinator used the meetings to balance the autonomy that the participants had to pursue their research goals with what was realistically possible to reach the industrial objectives of the CEMIG project.

> A gente tinha que fazer essas reuniões. Porque muita autonomia ... Se você abre demais o leque depois não consegue fechar resultado. **Então você tinha que deixar abrir um pouco mas tinha uma hora que você falava: "Olha, agora chega. Vamos trabalhar com isso assim".** Em cada reunião a pessoa comentava: "Olha, o catodo hoje deu uma potência de tanto. Ele estava dando só isso? O que você acha? "Muda, muda. Vamos fazer de outro jeito. Vamos fazer do jeito que tá dando o melhor resultado" (RL1 I2 3035, emphasis added).

Cases like the one with the zirconium powder synthesis, which revealed an unknown event when the PH was not measured during the entire process, revealed the importance of intensifying knowledge transfer. On the one hand, the participants of the group said that they did not encounter the solution within the literature, and on the other hand, the research leaders were convinced that it was a common issue and that it was described in diverse scientific contributions. Motivated by cases like this one, the meetings served as a tool to align the state of the art of knowledge within the group and level some of the contradictions. Within those meetings, issues were raised, experiences were exchanged, and literature indicated to resolve issues.

> **Não [estava descrito na literatura].** Porque você lava o tempo inteiro. Então quando você lava, lava, lava, o PH muda o tempo inteiro" (Part1 I2 2555, emphasis added).

> A gente fazia reuniões com ele e falava: "Se tem alguma coisa que vocês estão fazendo que não está dando certo, vocês leram isso?". A gente passava capítulo de livro, alguns artigos para eles lerem pra gente discutir. Acho que toda semana tinha uma reunião. E eles às vezes não colocaram os problemas. Porque o zircônio é umas das primeiras sínteses que foi feita no laboratório. Então eu achava assim: "impossível que os alunos não soubessem fazer esse negócio**". Estava escrito na minha tese, estava descrito nos artigos, estava escrito em tudo** (RL1 I2, 0900, emphasis added).

By diversifying and intensifying the meetings, uncertainties were confronted and dealt with in a systematic matter. The recurring, formal meetings gave the group a stable platform for knowledge exchange. They enabled a constant flow of information to keep the entire group up to date on the current project steps and facilitated to confront and deal with challenges as a group.

5.3.3.5 Systemizing equipment learning

Most equipment used by the project group was complex and difficult to learn (Part3 I2 1555) as they were new to the group - some even to the project leaders (Tech I2 1700). Only a few participants had prior experience in some parts of the equipment operation (Part3 I1 2125) so learning how to operate the laboratories equipment, was essential for developing a full functioning fuel cell system.

According to the project coordinator, being able to learn new equipment and deal with difficulties is part of every new project. Ordering, importing, installing, and learning new equipment can be time-consuming and uncertain but should be in the capabilities of a research group. Integrating new equipment to benefit the project relied on the initiative, maturity, and experience of the participants and how they reacted in certain situations (Tech I2 2911). During the project, four major sources of knowledge were established that facilitated the learning of equipment: courses given by manufacturers and specialists, engaging with literature research and experimental testing, and learning through POPs and veterans.

With manufacturer and specialists

Together with new equipment, a specialist was usually sent from the manufacturer to give a course on the fundamentals and operation of the equipment (Part1 I1 1755; Part1 I2 2025; Part3 I1 2125; Part2 I1 1600, Tech I2 1700). The courses varied between a few hours and a few days depending on the complexity of the machinery. For some participants, the courses were of limited success as the equipment was usable for a vast variety of applications and the area of SOFC research was extremely specific. The main application of most of the equipment was not related to fuel cell development at all but to other industries including apparel (print screen for shirts) and food (tape casting for *pasteis*). The specialist could therefore not introduce the group to the specific equipment applications and settings for the group's work with SOFCs (Part4 I1 2253, RC I1 2640).

> "**Todos os equipamentos não eram feitos pra desenvolver pilhas a combustível**" (RC I1 2640, emphasis added).
>
> "Então quando um equipamento vinha, as pessoas que tinham conhecimento dele, eles sabiam fazer funcionar pra um uso específico. Por exemplo, tem esse equipamento do tape. **O representante que vinha ele sabia muito bom como fazer screen print pra camisa. Pra ele nosso uso era novíssimo. Então ele podia ajudar a gente em esse sentido**" (Part4 I1 2253, emphasis added).

Not all participants had the possibility to participate in the manufacturer's seminar, so after the specialist left, the project's technician, who usually attended all the courses, passed on the knowledge by replicating the training she received from the specialist (Tech I1 3630, I2 1700).

> "Fiz os treinamentos [cursos] dos equipamentos. **E as vezes o aluno não podia participar no curso e aí eu fiz o treinamento com eles**" (Tech I1 3630, emphasis added).

To understand the entire coursework a complete dedication was necessary. The technical part was taught by the specialist, but the theory was up to each participant to understand, which was inevitable to adapt the equipment to SOFC R&D. As not all participants had the time or endurance, some profited more from the course than others (Tech I2 1700). After the course, most participants went back to other activities and, therefore, had difficulties recalling all the knowledge that the specialist or the technician transmitted.

Some equipment was acquired without an accompanying course, so the group relied on other knowledge sources or their own network. Through the *Rede Pacos* a specialist was invited to come to the laboratory to help with the installation of a press compressor. Another example that exhibited the usage of the group`s network to acquire knowledge on equipment operation was the spraying system. This equipment was not new to the group per se, however, its application area (Part3 I2 1555). The spraying and coating techniques of cathodes are very similar to the study of works of art, which researches how the paint reacts when applying it on top of other layers (RL1 I2 2645). To learn the scope of the application possibilities, one of the project leaders put a participant in contact with a professor from the school of arts who was familiar with the equipment. The professor explained the usage and demonstrated how to vary thickness and distance to receive more homogeneous results. Even though some things had to be explored without the help of this contact (e.g. a very thin and even more homogenous spraying technique), it helped the participant to get a deeper understanding of the equipment (Part3 I2 2410, Whatsapp).

The courses and help from specialists were an initial starting point and an important part of the equipment learning process. They provided the participant with a solid base to then adapt and explore the equipment to their research.

With literature research

Before testing and working with the equipment, an extensive literature review was needed which included articles with practical and theoretical focus (Part4 I1 4220, Part2 I2 2715, RC I1 3450. Tech I2 1700). The group had to research how to use the equipment for their specific application to fully understand what was passed on by the specialist (Tech I2 2207, Part1 I1 2020). This included the study of articles and the search for experts that were familiar with a similar process or equipment and could contribute with their knowledge (Part3 I2 2253; Part4 I1 3230), however, often there was no one to share the experience with due to the equipment and application complexity (Part4 I1 2955). The literature research was essential for understanding the theoretical implications of the equipment which in turn usually helped in operating the equipment to serve the group's specific application area.

> “**[Os cursos] resolveram as 20%.** Porque é muito específico, sabe? [...] **Então, a gente estudava muito, lia muito sobre o assunto**” (Part1 I1 2020, emphasis added).
>
> “**Então, não tinha com quem trocar muita experiência. E a responsabilidade era muito grande**. Porque eram equipamentos grandes e se estragasse uma pecinha que tivesse que importar e chegar de novo, atrasava todo o processo do todo mundo” (Part3 I1 2955, emphasis added).

With tests and experimentation

The project coordination only liberated the usage of equipment when the participant had a basic theoretical and practical knowledge of the equipment (Tech I1 3630). The group had to test and experiment by orientating themselves on the literature and adjusting the settings on the equipment accordingly (Part2 I2 2715). This stage was essential to understand the equipment usage and its application (Intern1 I2 2425). By applying the theory from articles and books to the equipment and changing variables one at a time, the group adjusted the new equipment to their research. Upon positive results, the participant who needed to use the equipment first standardized the settings and recorded the results in the equipment notebook or drafted POPs. As the equipment needed to be calibrated and set to different settings depending on the cell component, this process resulted in several different standardizations (Part1 I2 2025).

Commercial cells were not only acquired to test their own materials and cell components but also to understand the equipment's functionality and application and to calibrate and set them. To confirm an equipment setting, the group used commercial fuel cells. After successfully finding the correct setup, the group applied the equipment configuration to the LaMPaC cell components to continue development (Part3 I1 3720).

> "Então, **a gente usou as células** comerciais que a gente sabia que funcionavam bem. A gente colocava lá no forno pra aprender como usar o forno" (Part3 I1 3720, emphasis added).

POPs, equipment diaries, and veterans

When the equipment was already integrated into the group and successfully operated, its usage was either described in a POP, equipment diaries or incorporated into the knowledge and experience of one or more group participants. Upon learning new equipment, the apprentice was directed by other participants (usually the project leaders) to all the established sources of knowledge. This included studying POPs, equipment diaries, selected articles, and most importantly, accompanying and observing a veteran, equipment responsible, or technician who would teach the apprentice the essentials of the equipment.

All those practices contributed to a more systemized learning of equipment usage and were intensified along with the project by including external equipment specialists in the group's network, categorizing essential literature that introduces the mechanics of certain equipment, constantly improving POPs, updating equipment diaries, and training participants.

5.3.4 Strengthening and refining network interactions

This section presents the collaboration activities, the group established outside the project-dedicated working group. This comprises personnel, technicians, professors, and specialists from UFMG as well as national and international scientists, research groups, and institutions.

5.3.4.1 Exploring and diversifying networks

UFMG

The chemistry department established itself as the first contact when seeking support outside the project group due to its accessibility, proximity, and collaboration availability. The department assisted with repair, equipment sharing, and teaching (Tech I2 0640). UFMG colleagues, for example, shared equipment or traded them (RC I1 2330) for laboratory access, and other professors of the department were available for giving seminars in relevant areas. Additionally, a UFMG technician was often consulted on equipment malfunctioning or integration and installation. Another example for accessing the UFMG network provides a notebook entry from a technician, documenting the use of silicon oil, that was previously borrowed from another researcher at another laboratory at UFMG, which reenforces the high interaction with this network link.

> "Às vezes eu pedi ajuda de algum professor. **Por exemplo, eu queria usar microscopia eu ia lá no centro da microscopia**, que era na física, conversava com o [professor do centro]. **A RL1 falou: "procura o [professor do centro]**, conversa com ele". E ele explicava pra mim" (Tech I2 0640, emphasis added).
>
> "Outros equipamentos, tipo balança era mais fácil, **eu consegui emprestar para os professores**" (Tech I1 2800, emphasis added).
>
> "Mas nós chegamos também a **fazer troca,** eu acho, com algum laboratório **pra fazer ajuste num equipamento. A na troca a gente colaborou de alguma forma**" (RC I1 2330, emphasis added).

If a research topic was interconnected with other specialization areas, like engineering, some participants searched directly in other departments for assistance (Intern1 I1 010310). Within the case of the interconnector, for cutting and forming the steel for the interconnector, the participant responsible identified a workshop at the UFMG physics department that offered to collaborate with the group. The constant collaboration with that workshop facilitated and enabled the fabrication of the interconnectors (Intern1 I2 1905)

> "Então eu **procurei muitos professores na engenharia mecânica, na elétrica**, para tirar dúvidas" (Intern1 I1 010310, emphasis added).
>
> "Várias peças mais simples eu fazia no departamento de física da UFMG. La tem uma oficina. Tinha um senhor lá, um senhor bem velhinho. Era muito, muito camarada, muito legal. E competente também. Então com ele tudo fluía bem. **Eu podia ver as coisas sendo fabricadas, eu ajudava ele fazer.** Eu estava ali do lado dele e ele tinha o interesse de ajudar. Teve uma peça do stack que a gente fez toda com ele. Era todo de inox, ele fez tudo para nós. Funcionava super bem" (Intern1 I2 1905, emphasis added).

France & Germany

In 1988, one of the research leaders completed her Ph.D. in France at the *Institut National Polytechique de Grenoble*. Those contacts were useful for the CEMIG project as they enabled student exchanges between the institute and the research group. Some Ph.D. students were able to execute parts of their research at the French Institute for a couple of months and acquired knowledge on research methods, result interpretations, measurements (e.g. impedance), characterization and equipment usage that they then passed on to the entire group (Part2 I1 2500, I2 1815). Researchers from France visited the laboratory repeatedly to help with the project development (Part2 I2 1815, Part5 I1 5510) and German researchers spend some time at the laboratory to give insights into their own processes (Part2 I2 2845) and provided the group with full-functioning fuel cells for testing and reference purposes.

Rede Pacos

The *Rede Pacos* supported the project in several ways. Through the national network, the group had access to different equipment and could perform measurements and tests. The network interaction actively encouraged information exchange, research visits, courses, and internships by organizing congresses and meetings to stimulate knowledge exchange (Part3 I1 3230, Part2 I1 1420, 3605, I2 2845, Intern1 I2 0810). As an example, the group invited a researcher within the network to give a speech at UFMG and in combination with that visit, help install a press compressor and introduce the group to the technology (RC I2 2110).

> "A gente tinha uma prensa que fazia pressão de todos dos lados. Era uma prensa à óleo. Mas faltou um compressor. O que a gente fez? No projeto da CEMIG foi uma das primeiras coisas que a gente colocou foi a compra desse compressor. **Esse profissional que a gente conheceu na Rede Pacos,** ele foi para o departamento de química para dar uma palestra porque todo professor tem o direto pra indicar uma pessoa pra dar uma palestra. **Então ele deu uma palestra, em impressão 3D, mas também ajudou a gente no laboratório com a prensa. Ele instalou para gente** porque ele já tinha essa prensa do laboratório dele. **Então a gente instalou sem risco nenhum porque ele era expert no assunto.** Foi muito bom porque a gente tinha um ambiente discussão dos problemas era importantíssimo" (RC I2 2110, emphasis added).

The network also acquired equipment that could be used by the project team (Part3 I2 1330, RC I2 1620). With the help of *Rede Pacos*, the group could, for example, purchase an infrared machine and installed it in a partner laboratory at UFMG, which already had experience with such machines. This gave them immediate access to the equipment without having to study a completely new research area as the partner laboratory would carry out the tests for them (RC I2 1840)

> "Acho que era o infravermelho... O aparelho era de um pessoal dum outro laboratório da UFMG, a gente entrava numa fila de espera junto com todo mundo da UFMG. Então, a gente tava na fila e o projeto parado. Então, o que a gente fez foi **adquirir pela Rede Pacos um equipamento** para essa caracterização. E aí que foi a coisa mais interessante que eu acho que eu te falei numa coisa que teve muito nesse projeto que ajudou era criatividade e colaboração além de coragem. Por que a gente fez? **A gente entregou esse equipamento para essas pessoas desse laboratório e eu que já tinha expertise.** Entregou para uso. **Disponibilizou também para eles no laboratório deles que já estava preparado para receber. E aí a gente passou pro primeiro lugar na fila**. A gente tinha prioridade" (RC I2 1840, emphasis added).

Through the network, parallel projects were launched that provided access to other equipment of external institutions (RC I1 1550). The network turned out to be so fundamental for the project development that some participants commented that if it were not for the network, the project would have been impracticable (Part4 I1 4320).

5.3.4.2 Accessing different networks to repair equipment

It occurred that equipment needed to be repaired, either due to manufacturer error or because of faulty usage (Tech I1 2155). The project had a special rubric designated to finance equipment repair, however, it was not always available, and funds needed to be allocated to the said rubric (Tech I1 2505). Before tapping into the project funds, the group tried to resolve the issue within the department. The infrastructure of the department of chemistry gave access to people with the expertise to assist when the equipment was not working properly or needed repair (Tech I1 2800).

> A primeira coisa a gente fazia era tentar identificar se o problema era um problema que o [técnico do departamento de química] conseguia resolver (Tech I1 2800).

When equipment unexpectedly malfunctioned, the group used the university resources and connections to repair and borrow equipment if available (Part2 I1 3605, I2 2155, Tech I1 2800) which resolved most of the issues. A technician from the chemistry department was often consulted on equipment, electrical, and installation problems (Part2 I2 2155, Tech I1 2800). If the UFMG technician could not help or a piece needed to be replaced, the project technician searched for manufacturers that would sell the required piece, however, often the piece was not produced anymore or needed to be imported, and therefore, an adaptation was necessary. This process always included several order estimates and sometimes lasted months to resolve (Tech I1 2800).

> "Caso tenha acontecido [equipment broken], **a gente procurou dentro do departamento se tinha um equipamento pra usar**" (Part2 I1 3605, emphasis added).
>
> "Quando a gente precisava das peças ou uma pecinha [interruption to give na exemple] por exemplo, eu tinha que fazer um depósito no filme do print screen. Falei para ele [chemistry department technician] o que eu queria **e ele foi e fez a pecinha para encaixar a partilha**. Nossa ficou ótimo, sabe?" (Part2 I2 2155, emphasis added).
>
> "Algumas vezes nós tivemos problemas com o forno ou a mufla. Mas lá no departamento de química tem as pessoas que consertam. **Tem da mecânica, da elétrica, então quando acontecia isso, o próprio pessoal do departamento, na maioria das vezes, conseguia resolver.** [...] Quando tem um equipamento mais sofisticado, [...] aí tinha um técnico de São Paulo que acertou" (Part1 I2 1055, emphasis added).

Due to the complexity of the equipment, sometimes specialists from outside the university had to be consulted (Part1 I2 1055). Those unknown events disturbed the time management of the deadlines (Part1 I2 1055). During the time of repair, the participants that needed to use the equipment, spent the time researching or doing other measurements as there were always parallel developments to pursue (Part1 I2 1840, Tech I1 3255). Usually, the person who initiated the repair process was the one who understood the most about the equipment (Part3 I2 5330), but everybody tried to solve their own issues if possible (Part2 I2 2425).

5.3.4.3 Refining the elaboration of order processes

The laboratory often received products, that did not respond to their demand, either because the order specification was not detailed enough (which was a reason for to constantly growing preoccupation with the description of the inquiry), because of miscommunication with the manufacturers, or the funding agent, because the funding agent did not order exactly the demanded product (RC I1 1415, 1550, Intern1 I2 5035), or because the seller delivered the wrong product (Intern1 I2 3911). The group ordered material and expected that material to be delivered in time and with the specified characteristics. However, during some order processes, either the funding agent or the seller changed the material to something incompatible, which did not serve the needs of the laboratory. As this situation was recurrent it led to an accumulation of unforeseen events.

> "**Eles insistiam em mandar um produto que não nos atendia com preços muito maiores que a gente achava pra comprar.** [...] Foi um problema o tempo todo. Então **a gente mesmo teve que se responsabilizava por isso**" (RC I1 1415, emphasis added).
>
> "**Cada coisa comprada era especificada bem tecnicamente para não ter a menor possibilidade da pessoa trazer alguma coisa diferente**. Nada podia faltar. Isso tomava muito tempo, mas sem isso não saia nada não" (RC I1 1550, emphasis added).
>
> "**Comprava uma coisa e vinha outra**" (Intern1 I2 3911, emphasis added).

This recurrent issue was approached by the group taking responsibility in the order processes as much as bureaucracy would allow it. The practice developed further with each order process and the group refined the specifications of the resource needed. The order processes were a complex intertwinement of social and material elements. The responsible of the order needed to specify the order and confirm with all participants in the group that the resource would serve everyone, which constantly changed due to technical advances. The funding partner needed to be integrated into the practice as their role was to control, check and finally place the order with the seller. This continuously changing arrangement and relational complexity often led to difficulties that had to be approached by the actors involved as soon as the unforeseen event appeared. By improving research and the specification of the order, the group was able to reduce relational complexities and the confrontation and engagement with those events contributed to the group's competence development.

Along with the project and several unexpected events, the group learned that every order process took time and could rarely be rushed. The funding agent was responsible for the final step of the order process and did the selection and purchase of the resource. The institution had its own criteria for selecting one of the options that the group provided when drafting an order. The group usually had a preference of the resource they ordered and sometimes only an extremely specific one would serve the project needs. As the funding agent always requested options to select, the group began to make the order so specific, that the funding agent had to choose the group's preferred option to reduce the risk of receiving unsuitable resources.

To delimit uncertainty, the group intensified the research on the specification of the resource, the communication with the manufacturer, and the description of the order. The importance of detailed and dedicated specification during the order process was also emphasized when wrong products got delivered that were specified by participants without the inclusion of the project leaders. This resulted in the project leaders and the coordinator being more personally involved in the order process and oversee more complex orders more carefully as they had the experience and knew how to specify and place the order to receive a product as expected (RC I1 2140).

> "O que chegou errado não tinha muito jeito não. Teve uma estufa que, por exemplo, não foi nenhum de nós três que especificou. Aí a gente já viu que isso não ai dar certo. A gente sempre sabe o que tem que ser especificado. Mas a gente tinha que fazer pessoalmente. **Tinha essa vivência - saber como pedir pra chegar certo**" (RC I1 2140, emphasis added)

This practice was also ought to prevent issues like the ones that emerged from the order of the German oven. The missing plug, nor the complication with the power grid was foreseeable for the group at that time, however, a more systemized and controlled order specification and process reduced the probability of missing components or unexpected consequences.

To improve the order process, another practice was established which involved the selection of the most probable option to fit the project needs. To avoid receiving materials or resources that would not fit for the purpose, the participant in charge of the order needed to evaluate all options and, in some cases, abandon the option, less likely to succeed. Therefore, the group needed to assess the possible outcomes as detailed as possible to then determine which material or resource will have to highest probability of serving the needs of the project (Intern1 I1 4535, 5810).

> “**Quando eu entrei no projeto não tinha noção de isso** [the difficulty of the order process]. Mas alongo do projeto a gente falou assim: “tá bom, pra tudo que a gente for fazer, todas as compras vão demorar”. **Eu percebi que agora tenho que tomar muito cuidado antes de sair e fazer proposta** de teste, porque cada tentativa demorava meses. Eu e a RC passamos dias pensando em o que tem mais chance de sucesso**. Como minimizar essas dificuldades de comprar as coisas**” (Intern1 I1 4535, emphasis added).

> “O que a gente passou a fazer foi pensar mais, tentar extrapolar as possíveis falhas que a ideia inicial poderia ocasionar. Quando a gente fazia esse exercício mental, assim: “ahh, isso aqui tem mais chances de dar errado que a opção B”, por exemplo. **Então, ao invés da gente tentar já *de cara* montar uma opção A, a gente pensou: “Não. Esquece a opção A porque pode dar errado. Nós não vamos tentar, vamos pensar num plano B”**. Teve mais exercício de [pause]... vou chamar de planejamento, mas é bem mais que planejamento. É mesmo fazer uma extrapolação de uma situação futura. **Como se fosse uma análise de risco, sabe?”** (Intern1 I1 5810, emphasis added).

Within the constantly changing contextual process, the order practice was constantly reformed and with time, the group began to see the practice as risk analysis, by allocating higher probabilities of success according to their research on the resources to order. Due to events like the flow meter incident, the group started to preference certain manufacturers, however, as the funding agent made the final decision on purchases and the group needed to provide several options, it was often out of their hands to decide from which manufacturer they would buy the resource.

5.3.4.4 Solving problems through networks

The continuously growing network of the research group led to opportunities that provided the use of missing resources or helped in acquiring them, assisted with the installation and repair of equipment, and supported the exchange of knowledge. This can be exemplified in the German oven event, in which the group calculated with the immediate use of the oven, however, when noticing the missing adapter and complications with the power grid, the participants had accessed their network to (1) enable the usage of similar ovens within the department of chemistry while waiting for the installation of the oven, and (2) contracted an external service provider to assist with the grid integration and acquisition of the plug adapter.

When any equipment failed working and the group could not solve the issue, they could often rely on the UFMG technicians, especially from the chemistry department. Other laboratories within the department would often share their equipment if needed or would accept trades of sorts. For the development of some materials, the participant of developing the interconnector was able to seek assistance in a workshop within the department of physics.

The national fuel cell network was constantly consulted and provided access to knowledge via congresses, student exchanges, meetings, research visits, and collaborative research projects. Because of their previous studies abroad, the research leaders could organize student exchanges that would assist in specializing the participants in their area of research such as measurements and data interpretation. The attendance of global congresses and seminars provided the group with new contacts that would help them with their research and supplied the group with e.g., test cells and interconnectors. Furthermore, professors from the local School of Arts provided teaching and training to group participants to learn the techniques of applying liquids as a spray.

5.4 **Managing duality within practice**

The intention of this subsection is to abstract the learnings from analyzing the emerged and established practices through confrontation with uncertainty. Intensifying the analysis on the established practices, I identified them as key factors in dealing with relational and temporal complexities and in creating synergy between opposing elements. Throughout the analysis, I identified that the management of dualities was crucial to deal with the relational and temporal complexities within the development process. This subsection presents how dualities and tensions are interacting as coexisting elements with synergetic character as they define and develop one another. Due to the context-dependent nature of the innovation process and its complexities, the practices that were implemented and emerged during the project continuously unfolded within practice and created a balanced tension among beneficial oppositions.

5.4.1 Tacit and explicit knowledge

The high technological and social complexity of the project and the lack of knowledge prior to the project launch immersed the group into a highly uncertain environment. Hence, the organization was constantly confronted with developing tacit and explicit knowledge and transforming it to cope with the project complexities. Explicit knowledge was extracted from scientific literature, conference proceedings, and manuals, which was the foundation and steppingstone of the development process and often provided the necessary data or information to solve development issues. As prototype developments are usually not executed within education institutions but in the industrial sector, the entire manufacturing process was not disclosed in the literature. The explicit knowledge alone would only be useful to a certain point in the development. This point was usually reached when approaching the integration of the cell components as several areas of research are combined and the scale-up of material production as scientific research does not bother with a larger production.

Due to constantly appearing unforeseen events, the group found itself constantly switching between developing and applying knowledge from explicit and tacit sources. Those dynamics reinforced the performative development of the project as the knowledge of the organization was constructed within practice and, therefore, the organization was constantly becoming something else. Through this ever-changing learning process within practice, the project group continuously experienced the process differently, making their development possible.

Tacit and explicit knowledge was essential for equipment learning, and the complexity of this process lies within the intertwinement of those two types of knowledge. Those relational complexities appeared when the many sources of explicit knowledge needed to be interconnected with tacit knowledge and can be demonstrated in the difficulties of learning to operate new equipment.

To learn new equipment, a participant needed to develop explicit knowledge by studying documents, articles, reports, manuals, and tacit knowledge by actively being emerged in the process of operating the equipment. Both types of knowledge could be developed independently, however, only with great efforts as the development was dependent on one another. The theoretical knowledge helped to understand the practical knowledge and vice versa.

To ensure fast integration of participants the organization approached the relational complexity by establishing a practice of passing on processes to other participants, which was routinely enacted. To support the intertwinement of tacit and explicit knowledge, a veteran provided explicit knowledge like research articles, documents, and POPs and complemented it with tacit knowledge by demonstrating and exemplifying the processes for the apprentice. By integrating an experienced participant and, with that, adding another social element to the process of equipment learning, the organization embraced the relational complexities that emerged through the dynamic of and dependence on tacit and explicit knowledge.

Knowledge management within the project is another example of balancing tacit and explicit knowledge to deal with complexity. Throughout the project, the group gathered scientific articles, books, manuals, and conference proceedings, that were essential for the prototype development. To facilitate the connection between this stack of explicit knowledge with the tacit knowledge from equipment usage and production processes, the organization drafted documentation and POPs and introduced reference participants. Those practices intertwined the two types of knowledge and dealt with the relational complexities.

This bundle of explicit knowledge was essential to facilitate the inclusion of new participants and to enable the consultation of methods and techniques, that were already developed and archived within the project. The project leaders asked for personal diaries of each participant which entailed the individual development processes, tests, and methods of each participant and was passed on to novices that needed to continue the development when someone left the project. This explicit knowledge, however, was always accompanied by practical demonstrations. A participant that wanted to learn a new process, approached other participants or references persons which already were involved with that process to receive a practical demonstration. This knowledge management enabled the documentation of knowledge and its transfer.

Along the process, the group extended their knowledge base, documenting their advances and passing them on along with practical demonstrations. The contextual experience of each participant, by routinely gathering knowledge from their current research and passing it on, contributed to a continuous transformation of the entire organization. Novices added new insights to the processes either in form of documentation or by including them into their practical execution and refining POPs. Those constant modifications and continuous development of practices highlight the 'constantly becoming' of the performative process and the dual development of explicit and tacit knowledge and its dependence on one another.

The practice of systemizing equipment learning also reinforces the successful balance of tacit and explicit knowledge. To tackle the increasingly intricate entanglements of social and material elements, the group implemented several ways of systemizing the methods and processes of the machinery. The intertwinement of theoretical and practical knowledge needed to be developed to successfully operate the equipment with the application of fuel cell prototyping. If no orientation or practice would have been implemented, there might have been an uncontrolled learning process and a higher risk of equipment being operated falsely, ultimately leading to a longer development process and higher expenses. The established practices indicated a systemized and predefined learning path which started with taking practical and theoretical courses with specialists, continued with an in-depth theoretical study on the production of fuel cell components and equipment, and led to practical and controlled testing and experimentation phase. The group relied on explicit knowledge like literature and manuals and tacit knowledge like courses and experimentation to operate the equipment successfully. The relational complexity within the process was reinforced by the increasingly intricate entanglements of social and material elements, which were necessary for the development.

To further systemize this learning path, the group established practices by recording their steps and created explicit knowledge by organizing equipment manuals, collecting information on the theoretical operation, and creating POPs. New participants, that were not present at the initial learning process of the equipment needed to study those materials before being guided through the practical implications of the equipment procedures, resulting in the transfer of tacit knowledge.

5.4.2 Autonomy and control

The innovation process is prevailed by uncertainty and contextual decision making that depends on the technological and social configurations at each moment in time, which adds temporal complexities to the process. At a certain point in time, we cannot predict the effect and implications of our actions and, therefore, we cannot completely define job tasks until the configurations that define and shape those task requirements are in place. Within the process of innovation, those tasks may shift and rely on competent actors to recognize those shifts and act accordingly. A suitable task today might not be suitable in the context of tomorrow. However, to not lose track of the initial objectives and to coordinate the involved actors the organization needs to define and allocate roles that need to be filled, even when knowing that they change with time. Within the analyzed case, a balance between the duality of controlling deadlines and resources and giving the participants a certain degree of autonomy to pursue their research was identified.

The duality was beneficial to push the development of the project but also kept the focus on reaching the overall objectives with the available resources. Besides the coordination and orientation of the project's participants, project leaders were faced with many different responsibilities within the project, like administrative tasks, research, networking, teaching classes, student orientation, and research connected to other areas besides fuel cells. The project coordinator was hired to manage the project process but monitoring all participants of the project would have exceeded the coordinator's capacities. To facilitate relational dynamics, to ensure productivity, and to promote a successful development process with the resources at hand, the project leaders implemented several practices along the project process.

Defining the individual projects of all participants beforehand, either as a proposition or developed together with the participant, resulted in a more systemic embrace of the present complexities as it secured control over the research activities and aligned them. This ensured that all areas of the development were covered and pursued simultaneously. Recurring feedbacks were requested but the participants were encouraged to explore options and possibilities to solve problems, mainly because most of the development of methods, processes, and catching up with the state of the art was new to the research leaders themselves and they relied on the innovation competences of the participants.

At the beginning of the project, several problems with equipment usage emerged. Faulty or unauthorized usage complicated the organization of the equipment and sometimes led to equipment failure. The equipment was used by many participants that operated them with different settings for different applications. As soon as one participant finished their tests, the next one had to recalibrate the equipment for her needs. Sometimes participants with insufficient knowledge of the equipment applied wrong methods or processes which occasionally led to malfunction. Through those interdependencies among equipment settings, equipment knowledge, user experience, and knowledge, relational complexities emerged.

To deal with those complexities, project leaders designated responsibilities to selected participants, which ultimately gave them more autonomy in executing their tasks. To diminish equipment malfunction that could result in a complicated, time demanding, and costly repair process some participants were entrusted with the usage and administration of predefined equipment and resources. Linked with the assigned responsibilities, several practices emerged over time. To control not only a more responsible handling of the equipment but also an efficient and thorough transmission of knowledge, the project leaders took advantage of the fact that some participants became experts in operating certain equipment or using specific methods, which was a beneficial consequence of assigning responsibilities. The project leaders asked those participants to give seminars on methods and the fundamentals and operation of equipment; to monitor the usage and ensuring that only authorized participants, that received enough training, would operate it; to initiate repair requests and follow up on the process; to create and evaluating POPs.

From a participant's viewpoint, it is to note that accepting those responsibilities demanded them to be autonomous in their execution. To successfully step up to the responsibilities of teaching, administrative tasks, equipment failure, or POP creation they needed autonomy to execute those tasks. This highlights the entanglement of autonomy and responsibility.

Besides assigning responsibilities and defining project objectives, the participants were granted the autonomy to follow up on theories and ideas, which was also in the best interest of the research leaders as they could not oversee every step of each participant. The participants had the liberty to experiment and fail, but only within certain parameters, as the project's goals needed to be accomplished and time and money were limited. When facing challenges, the project leaders usually did not define the next steps for the participant but contributed with ideas, orientation, and possible development paths. Participants with higher academic degrees were usually given more autonomy in their actions, however, also more responsibilities. The research leaders were, therefore, confronted with the constant tension of giving the participant autonomy in their research while controlling the deadlines and overall objectives. The project leaders had to balance this duality routinely to produce scientific and technological results for the university and CEMIG, respectively, within the specified deadlines.

This tension reinforces the existence of relational complexities within the innovation process as control and autonomy are dependent on social and material intertwinement. The practice of assigning equipment responsibility was routinely enacted by all participants and constantly re-made when new equipment, processes, participants, and situations arose. Control and autonomy are constantly evolving through their tension, either by reducing or extending them, which in turn creates new contexts and situations. By implementing these practices, the organization created a web of actions that became a fundamental part of the organization. Whenever a participant was looking for equipment support, she was referred to the responsible participant to provide her with literature and documents or to introduce her to the equipment through demonstration. Participants that assumed responsibilities of equipment assisted participants that needed support. This made the equipment usage and knowledge transfer more controlled and systemic, which facilitated meeting deadlines and reduced uncertainty throughout the project process. Therefore, the search for assistance and providing it went both ways and became routinely enacted whenever the need emerged. This constant exchange of knowledge through participants with responsibilities became part of the organizational practices and the constant interaction resulted in a fluid process that changed the organization continuously.

The relational complexities emerge constantly due to the social and material interconnectedness of equipment, participants, and the project's objectives but temporal complexities can be observed when responsible and autonomous actions intensify at certain points in time. When, for example, new equipment or participants entered the project or the demand for knowledge transfer emerged, the participants, responsible for a certain resource needed to engage more with those practices than in other stages of the project. The temporal complexity of autonomous practices can be observed when participants needed to develop new solutions, decide on possible paths, and follow up on them.

The duality of autonomy and control demonstrated to be beneficial to the organization also regarding risks. Limiting the extensiveness of the project by simplifying technological objectives, created a safer environment for the group and controlled risk factors like stretching deadlines or exceeding available financial resources. For example, the risk was reduced when inviting external experts through the group's network to give seminars at UFMG and, during the same visit, install equipment for the laboratory. This gave the group more control over the installation of the equipment and reduced the risk of spending time and resources on the issue.

5.4.3 Shielding and integration

The organization had to constantly balance the demands of each participant's individual project and the overall prototype development goals. The project group was bound together by the overall objectives of developing the SOFC prototype, but each participant had their own project and academic deadlines. The individual goals were aligned with the project goals as the participant's individual projects were coordinated to match the prototype project, however, due to the academic demands of the university, participants needed to orientate themselves primarily on the deadlines and demands of UFMG.

Keeping participants on track to meet the academic demands, was extremely important, but they also needed to be integrated into the development process of the project and contribute with their experiences to meet all industrial goals. The individual projects needed to be integrated into the overall project and be connected among each other which generated relational complexities. Each development project was independent of the overall project as the cell system consists of several detachable cell components and, therefore, relies on distinct areas of knowledge and demands individual research procedures and schedules. Anode, cathode, electrolyte, interconnector, other smaller components, and methods and processes were developed by different participants which created relational complexities when merging the individual developments to mount the fuel cell system prototype. An example of this complexity was the project step of abandoning the commercial cell components which served as a guide for the development of each component. When merging the LaMPaC electrodes and electrolyte, the group was confronted with several technical difficulties that did not reveal when working separately with the commercial cell components. The LaMPaC cell components were different and when merging them, they had to readjust several variables.

Within those relational complexities, which emerged from the intertwinement of all technological elements with the participant's development and experiences, also temporal complexities started to appear. Certain individual advances that were achieved through shielded activities could only be merged at certain points within the timeline. If one component did not reach a certain development status, it could not be integrated with others, which led to context but also time-dependency. Creating integrated practices that would contribute to intertwining the shielded advances among the participants and the fields of study was inevitable but balancing individual and group efforts successfully are not self-evident. It was, therefore, important to balance the group interactions and collaboration with individual work activities.

The diverse deadlines and the interconnected development created tension between clock time, or *chronos*, which included all the individual and group deadlines from CEMIG and UFMG and event-based time, or *kairos*, which referred to the development process entailing unforeseen events and learning events of all participants involved (Dougherty et al., 2013; Garud et al., 2011). A clock time event has a clearly defined beginning and end like a deadline for a scientific or financial report, or the calendar date of an academic document to hand in (e.g. thesis or dissertation). Event-based time, on the other hand, depends on activities, like the development of a new method of fuel cell component, which entails unforeseen events and, therefore, its end cannot be predicted (Dougherty et al., 2013). This tension between *kairos* and *chronos* created temporal complexities as all clock time deadlines and objectives needed to be coordinated with the event-based research and development activities.

To deal with the relational complexities, which emerged from the interconnected technology development and the temporal complexities that were attributed to the diverse timelines and the appearance of unforeseen events, the research leaders started to shield participants from certain activities, so they could focus on their individual project deadlines and development but simultaneously integrated them into others, so the individual developments could be aligned among each other.

An example of the duality of shielding and integration while being confronted with the *kairos* and *chronos* deadline pressure are the practices like “passing on processes” or “diversifying meetings”. Such practices ensured a redistribution of tasks among the research group while interconnecting the individual research strings through meetings. Those practices shielded participants from work overload and supported the completion of research tasks within time. But they also integrated the individual developments by giving the participants a space for collaboration and collective learning. This exemplifies how practices can be complementary with each other to deal with dualities and benefit from them as they help in reaching milestones in a given time.

Generally, participants were completely integrated into the organizational procedures and the laboratory environment. This included their participation in meetings and seminars, taking on responsibilities, and actively exchanging tacit and explicit knowledge among each other. Participants were actively integrated into the group’s network by introducing them into the UFMG infrastructure, enabling them to participate in conferences and seminars, and facilitating national and international student exchanges, which in turn, expanded the reach of the group constantly. Integrating participants into the organization’s ecosystem resulted in accelerated information exchange as, for example, the entire group participated in meetings and could support each other with individual experiences and knowledge. Integration also facilitated participants to locate reference participants when trying to gain access to equipment or discussing their research and creating an environment in which participants were stimulated to be aware of each other’s projects and developments. This increased productivity as participants were constantly up to date on each other’s progress and did not need to spend time on finding out the experience and knowledge of other participants when engaging in collaboration of equipment teaching activities. Integration practices were also related to equipment orders in which, to some extent, all participants were involved to mainly give feedback to meet all the participants’ demands.

The university and CEMIG deadlines, however, demanded a fast-paced, result-orientated development. Each participant had a designated project to deliver at the end of their stay at the project group, which ranged in complexity from an IC report to a Ph.D. thesis.

Autonomous and individual work was, therefore, essential. The project leadership started to actively shield participants from certain tasks so they did either gain time to meet academic demands or would not have to face responsibilities that would not match their experience. Ph.D. students were instructed to pass on repetitive and administrative tasks so they could focus on the development of their research. The project group relied on the development of new methods and techniques from all participants, but Ph.D. students were often shielded from those activities and as soon as they developed a new process or material, they passed it on to participants that would either benefit from repetitive production (for example IC or bachelor students that could benefit from practicing and extending their knowledge with assuming such tasks) or were hired for that purpose. This took the project pressure off those participants, that needed to focus on their academic advances and on the active prototype development.

An important aspect of shielding and integration of participants was the equipment and resource procurement, which was constantly refined to reduce the possibility of receiving unwanted equipment. Most participants were involved in the specification of the equipment or resource before ordering them but only a few executed the very time-demanding order process. Most equipment was defined before the project started as they were identified as essential for the prototype development by the research leaders, but some needed to be acquired along the project process and depended on what was needed at the given time, which introduced relational and temporal complexities. The performative development of the project revealed new necessities of equipment or resources, which could not have been identified beforehand.

With new participants entering the project group continuously, the project leaders established integration practices that would enable a smooth introduction to the project. Established participants routinely introduced new participants to their research by providing access to theories, scientific articles, internal documentation, and by showing them certain processes in practice, depending on the novice's qualification level. The practice of integrating new participants was simultaneously a practice of shielding as the research leaders would not assign tasks to novices that would exceed their academic qualifications.

On the one hand, only encouraging individual, shielded work activities would hinder a synchronized development and constrain the synergetic potential of knowledge exchange, but on the other hand, putting all emphasis on a cooperative and collaborative development would risk the successful completion of individual deadlines. To create a collaborative environment and equilibrate individual efforts, several practices contributed to an integrated development throughout the project group. Regular meetings, seminars, or knowledge transfer practices facilitated information exchange and gave room for conversations and discussions. The individual work efforts were balanced out and tested when the entire project group met to discuss the progress of individuals but also the project. The present relational complexity arrangements that were present due to the confrontation of individual and collaborative work efforts was confronted when creating practices that would facilitate the integration of both types of works. Meetings, for example, gave the group a platform in which shielded work efforts like isolated research and development could flow together with the collective knowledge and experience of the entire group. Participants presented their advances and received feedback, which was reflected, processed, and incorporated into further R&D.

5.4.4 Industrial development and academic results

The prototype development was a highly complex process that relied on the acquisition and application of scientific and technological knowledge. The development of a fuel cell stack comprised the combination of various areas of research and was, therefore, an uncommon university project. Brazilian universities are commonly dedicated to basic and applied research to produce scientific results and advances in very specialized areas, whereas industrial development focuses on the integration and development of interactive knowledge areas and the scale-up of such technologies (Albuquerque et al., 2005). Those diverse objectives created tension and complexities within the project. The project group and each participant were aiming at research and the advancement of knowledge; the university at the education of the workforce and producing academic results and intellectual property; and the funding agent aimed at industrial development and the creation of a first national SOFC prototype.

The prototype development demanded, therefore, on the one hand, research that would lead to academic results, and on the other hand, industrial results that ensure repetition, consistency, and scalability. This paradox put the group and its participants at risk of spending their time on academic research and neglecting the industrial prototype development and vice versa. To achieve the objectives of the project by simultaneously meeting the demands of the project group, the university, and CEMIG, the group needed to balance these oppositions. This often led to the decision of prioritizing one or the other and balancing the development to satisfy all parties. This tension among industrial results, academic research, deadlines, and objectives led to relational complexities.

With the paradox between industrial development and academic research, the tension between *kairos* and *chronos* was intensified. The deadlines of CEMIG and UFMG collided with the rhythm the researchers were used to. Instead of research on a research-based *kairos* rhythm, they now had an increased number of *chronos* deadlines and obligations. We can observe the shift from a *kairos*-orientated development to a process that is predominantly defined by *chronos* when the group had to simplify their research objectives. The group acknowledged that the optimal research path would not fit into the strict deadlines of CEMIG and had to, therefore, limit the academic research and increase industrial development.

To ensure continuous funding from CEMIG, the group often reduced the pursuit of basic research and shifted their efforts to industrial development. This can be evidenced by the parallel development. Within certain testing steps, the project group planned to pursue each test successively to register the outcomes and exclude failures systemically. Towards the end of the industrial deadlines, the group had no time to do all tests in sequence, so they started to execute them in parallel. By reducing the extensiveness of recording academic data, although without compromising research objectives the group was able to interconnect their results with the industrial demands. The parallel development, therefore, dealt with the relational complexities, but sometimes reduced the potential of academic research like in the interconnector case. The research on the steel types could not be intensified as originally planned, but the practice could speed up the process to meet the industrial goals. From a research perspective, the group identified an ideal path for the interconnector development but had to simplify their methods to reach the industrial demands in time.

Another example of the paradox of academic and industrial objectives and the reduction of relational complexities was the use of commercial cell components. The group was not able to develop each cell component completely from scratch and consulted literature, scientific contributions, and their network. One of the main supports they received for the prototype development was commercially available cells that were used to accelerate the development process. By using these commercial cells, the group could test their own cells instead of developing each component in a sequence that would exceed the industrial schedule. When noticing the complexity of the interconnector, the group also search for commercially available ones to have backups in the case their own development would fail but could not find any that were available for purchase. This practice also dealt with temporal and adaptive complexities that emerged due to the difficulty of connecting the isolated development processes as they would only be concluded at different points in time (temporal) and dependent on the finished preceding component (adaptive). In other words, only when the anode was finished, the electrolyte could be finished as it needed to be adapted to the specificities of the anode. And only after those two components were merged, the cathode and subsequentially the interconnector could be added. Using commercial cells not only as a scientific reference but also as a tool for bridge the gaps between the components was a practice that successfully dealt with those complexities and ensured the production of a finished prototype in time.

Table 6 summarizes the identified practices and matches them with the duality pair. All practices interact, somehow, with all duality pairs, however, this figure visualizes only interconnections with the duality pairs that they are mostly associated with.

Table 6 Duality pairs and associated practices.

practices \ duality pairs	Industrial development and academic results	Shielding and integration	Autonomy and control	Tacit and explicit knowledge
Dealing with time pressure and deadlines				
Adapting the working process due to accumulated delays	X			
Introducing bulk production	X			
Introducing commercial cell components to save time	X	X		
Decentralizing tasks and responsibility				
Assigning equipment responsibility		X	X	
Introducing an equipment notebook to control usage			X	
Shielding participants from certain tasks	X	X		
Passing on processes	X	X		X
Systemizing knowledge management and transfer				
Including new participants into the project		X		X
Establishing reference participants			X	X
Systemizing the utilization of POPs			X	X
Diversifying meetings to intensify knowledge transfer		X		
Systemizing equipment learning			X	X
Strengthening and refining network interactions				
Exploring and diversifying networks			X	
Accessing different networks to repair equipment		X	X	
Refining the elaboration of order processes		X		X
Solving problems through networks			X	

5.5 Competence development as practice

This subsection is dedicated to shedding light on competence development as practice and will complete the analysis on how practices emerged out of uncertainty and create opportunities for competence development by outlining evidence from the case. At first, I will present which competences can be identified throughout the studied case and how practices influence the innovation process. Subsequentially, I will highlight how the organizational environment cultivated the development of competences and then finish by elaborating which competences the participants developed and how they match with the established practices. In this thesis, I recognize the interwoven socio-material relationship that constitutes practice and acknowledges that competence emerges out of routinized activities within a work context. The unforeseen events analyzed, and practices identified in this thesis reveal competences as practice that the group applied - as individuals and as a collective.

5.5.1 Generic competences as practice

An essential competence that was demonstrated and continuously developed through practices (*Praktiken*) was the ability to **take initiative and assume responsibility**. By allocating equipment responsibilities, implementing POPs, and equipment and personal notebooks, the group management set up opportunities for the participants to develop their competences. A closer investigation on the implications of the practices showed that equipment failure was less frequent, integration of participants, and knowledge transfer became more efficient while research participants gained more time for the completion of their objectives. The success of the practices, evidence that the autonomy given to the participants resulted in them taking initiative and assuming responsibility. As an example, when identifying problems with the zirconium powder production, the involved participants, with the given autonomy, took initiative and, therefore, assumed responsibility for their tasks and resolved the issue with new information from their network to adjust the PH levels during the entire synthesis process.

If we take a step back and consider the entire project group as one entity, we can observe competence as practice on a collective scale. The group was given high autonomy from the university and CEMIG to manage, execute, and reach the project milestones with the resources at hand. Although most participants, including the project leaders, had to ‘start from zero’ with little understanding and knowledge on the entire fuel cell system and the interplay of all its components, the group, even though its participants varied across the years, took initiative, and assumed responsibility of the 10-year project. By implementing practices from the beginning and implementing new ones when unforeseen events occurred contributed to the successful completion of the fuel cell prototypes and show competence development as practice.

By entering a related, however, new area of knowledge surrounding fuel cell system technologies, the group was confronted with an interplay of several areas of knowledge including, inter alia, electrical and mechanical engineering, and physical and material chemistry. Connecting several different areas of knowledge and advancing each of those areas individually challenged the group and all the participants to **develop a practical understanding of situations with the help of previously acquired knowledge and transforming the knowledge to the extent that it increases the diversification of situations**. To exemplify, the participants acquired tacit and explicit knowledge through scientific contribution, technical documents, practical tests, and experiments. Those learnings needed to be transposed into other scenarios, for example, into knowledge transfer or - teaching. Competence as practice can be observed when developed methods, processes, and equipment knowledge were passed on to other participants in practical demonstrations, seminars, meetings, informal conversations, and POPs. Additionally, when studying related but different applications, methods, or equipment usage and adapting the extracted knowledge on the specificity of their prototype development, competence was developed when transposing the knowledge and applying it to a new situation.

Developing practical understanding can be well observed within practice of refining the elaboration of order processes. The group was faced frequently with situations that were new to them and had to constantly improve the order process to ultimately receive the resource that they previously identified as necessary for the project development. Only when confronted with the uncertainties within the context of the order process, for example in the case of the German oven, the participants realized the importance of that practice and developed their practical understanding further by confronting the situation. Integration, and more specifically the practice of recurrent meetings, act as a support for processing knowledge and for transforming that knowledge to diversify situations. Those meetings provide a platform for feedback that was being utilized by participants to develop their competences further and guide their individual development processes.

Furthermore, competences as **mobilization of networks** were constantly demanded and developed during the project preparation and throughout the entire prototype development. Due to the previous experience of the research leaders, the project started with several network ties but intensified and expanded with each development step and confrontation with difficulties and unforeseen events. But merely having built a network does not necessarily imply that it is being activated and accessed. To fully benefit from the network, the implication of the needed help must be shared, and the network needs to assume co-responsibility. The practice of mobilizing networks was observed in several parts of the project.

The group amplified and mobilized their extensive network to assist with little and larger challenges. UFMG and their researchers provided assistance when equipment was needed (using equipment of colleagues during German oven installation), helped with tests and measurements (infrared machine), integrated equipment (German oven), and assisted in the fabrication of parts of the cell (interconnector). Intensifying the communication with the funding agent during the order processes ensured a higher probability of receiving the correct resource. The network outside the university assisted with student exchange (France), scientist exchanges (France, Germany, *Rede Pacos*), equipment orders (infrared machine), and equipment usage (press compressor, school of arts spraying technique). All those ties gave access to knowledge, experience, conferences, congresses, and meetings (for example, to solve the issue of zirconium and the PH adjustment).

Those networks contributed to overcoming difficulties that emerged during the prototype development. Some of those networks were previously built and accessed when needed, like contacts that enabled student exchanges or assisted with lending equipment. Others had to be created or extended to overcome problems that emerged due to the confrontation with unforeseen events, like the service provider that installed the German oven or the professor at the school of arts that gave insights on spraying techniques.

5.5.2 Competence and work organization

After identifying competence and competence development within the project group, I will elaborate on the work organization within the project and how it fostered an environment for competence development. This includes cultivating complementary knowledge, creating spaces to enable communication and collaboration, and developing internal and external networks since the beginning of the projects.

The creation of the group was fluid and its constellation changed continuously. Participants usually approached the research leaders and asked to be integrated into the project. The research leaders suggested an individual research project to the participant that would complement the research of the group and, if expectations were met, the participant was integrated into the group. In other cases, the research leaders actively searched for participants with specific knowledge like research coordinators, chemists, engineers, or technical staff. The research leaders included participants with varying academic degrees and varying levels of complexity of individual projects from small and short IC projects to complex four-year Ph.D. theses. This diversity contributed to a synergetic complementarity of competences within the group. Participants with different academic specializations, tasks, and experiences assisted in different technical and administrative challenges, and with their varying academic degrees they took on different tasks to support the prototype development: The research leaders coordinated the scientific development and participants within the project, the research coordinator coordinated the group's participants and oversaw financial and administrative tasks. Participants with a chemistry background developed the cell components, engineering students assisted with the development of interconnectors and the system integration, and technicians supported the entire group by producing powders, organizing the laboratory, using, and teaching equipment, and creating equipment and resource orders. Ph.D. and master students pushed the scientific frontier with their individual projects, and interns, bachelor, and IC students were assigned to support them while working on their own individual projects. A rich and diverse environment emerged with each participant assuming a complementary role within the project group, which was facilitated by a professional bureaucracy in which projects and objectives were predefined while recognizing the complexity of the work and attributing the participants with high autonomy in the execution of their projects.

The project management actively contributed to the development of competences by supporting cooperation and communication within the group. The research leaders deliberately created spaces to enable the collaboration of the participants. The laboratory LaMPaC provided a physical space for interaction as all participants spend most of their research time there. From the beginning of the projects, the research leaders implemented recurrent meetings with the entire research group to discuss the advances on the project and individual meetings within the duties of a university student supervisor, which was dedicated to the separate research of each participant. During the project process, the meetings evolved and diversified: Core component development group meetings were implemented that addressed each component, seminars with educational character promoted knowledge transfer and communication; constantly recurring smaller meetings among the participants were organized to encourage cooperation. The implementation of equipment reference persons, equipment notebooks, individual diaries, and

POPs created figuratively technical spaces as they established constant direct and indirect collaboration. POPs and diaries codified knowledge that was revisited, reviewed, and elaborated by other participants and reference persons established a bridge between an apprentice and an unknown process or equipment.

Developing the organizational network was another source of competence development that was explored. The previously established network was utilized and extended, which included local, regional, national, and international ties that provided a basis for technological competence development. The participants had access to the university infrastructure and the research leaders indicated contacts within the department of the university, usually to access equipment or borrow resources. The extended network outside the university provided the group with knowledge, like in the case of the spraying technique from the school of arts, with equipment, like the infrared machine via *Rede Pacos*, and services, like the installation of a press compressor and the integration of the German oven into the energy grid. Additionally, exchanging students, hosting and visiting conferences, and organizing additional, separate projects and meetings with other groups contributed to extensive knowledge transfer. Participants also extended their own networks like in the interconnector case, in which a participant created a partnership with a UFMG workshop to manufacture the interconnector. By utilizing their network, the participants continuously contributed with new experiences and extended the network themselves.

Finally, the project arrangement promoted competence development by valuing the opportunity of unforeseen events. The research leaders relied on the development process of each participant and their responsible use of the given autonomy. Upon new challenges and uncertainty, the research leaders, the research coordinator, and more academically advanced students within the group were consulted to receive feedback and orientation. Often, such unforeseen events were not known to anyone in the group and, therefore, had to be resolved upon the emergence of such an unk-unk. This is exemplified in the German oven case, in which the equipment was delivered with a missing plug adapter and turned out to be too energy-intensive for the energy grid. This unforeseen event contributed to accessing old networks (UFMG technicians to analyze the energy grid and UFMG colleagues to give access to equipment while the oven was being integrated) and establishing new ones (external service providers to integrate the oven). It also encouraged the group’s technician to take initiative and assume responsibility to handle the challenge and promoted a more systemized order process with increased supervision of the research leaders and the research coordinator.

5.5.3 Identified competences within practices

Another finding of this thesis was the competence development within practices of the participants. Within the interviews, each participant was asked about her personal competence development, without providing them with a definition of ‘competence’. This had the purpose of leaving the participant free in their concept of what ‘competence’ is for them. Repeatedly mentioned competences that participants developed were multidisciplinarity, research, equipment usage, organization, time management, problem-solving and showing initiative. This section provides insight into those developed competences and their interconnection with the practices established during the project process.

When being asked about their own competence development, certain responses were repeated across the interviewees. Multidisciplinarity was frequently mentioned and referenced the development of collective working by interconnecting groups and individual objectives. Cooperation within the group was highlighted which included dealing with different people with different characters. Certain practices contributed to the development of multidisciplinary, for example, the ‘diversification of meetings’ in which participants frequently met to discuss trending topics, ‘passing on processes’, with which the knowledge transfer and, therefore, interaction among participants was encouraged, and ‘solving problems through networks’ which contributed by giving participants the possibility to access all types of networks to overcome issues.

Organization and time management were also often cited by participants when referring to developed competences. This included the administration of the entire group but also the management of resources. Other participants mentioned that they developed how to better divide their time to meet certain deadlines. Many practices actively, or passively promoted the competence development of administrative skills. Recurrent meetings and established deadlines introduced pressure into the project development and each participant had to learn how to manage their time to deliver results. Assigning equipment responsibility and equipment notebooks gave tools to participants to increase their organizational competences.

The practice of shielding participants from certain tasks and bulk production had a strong impact on the time management of each participant. Tasks that do not contribute to gaining more knowledge on methods or techniques were distributed among the participants and production processes that would take up a lot of time when executed in smaller quantities started to be produced in bulk. Participants, who were determined to develop the fuel cell components, gained more time for research and pursuing their studies. This resulted in the competence development of searching and finding new solutions, interpreting results, and more general: academic reading and writing.

Participants had to manage certain equipment and control their usage, which enabled their organizational competences and gave grounds to learning how to operate the equipment. Participants claimed that they acquired the competence of learning different techniques and methods and using different types of equipment while being responsible for their usage. Decentralizing tasks, giving autonomy, and shielding participants proved to be successful as they assumed responsibility for tasks and equipment which resulted in acquiring knowledge in diverse areas of their practice.

The organizational structure of the project group fostered an environment of problem-solving. This was essential as the prototype development was new grounds for the entire research group. The participants involved in this innovation process claimed to have developed the competences of being able to deal with problems and unknowns and to learn how to handle diverse situations. The knowledge-intensive research project impacted participants in wanting to know why something fails and why it had success. This notion of wanting to solve problems implied the competence of showing initiative and being able to extract knowledge from one situation and transposing it onto another situation.

> "Aprendemos de tudo. Éramos responsáveis pelos equipamentos. A gente aprendeu usar. Lia muito. **A gente pegou do zero. Competência foi tudo. Cooperação. Trabalhar em grupo. Correr atrás. Não tem problema não saber, mas você vai aprender em etapas. Buscar. Vai aprendendo."** (Part2, I1, 4610, emphasis added).

> "**O melhor jeito de resolver esses problemas era trabalhando**. Era ter **iniciativa**, era testando, era realmente mão na massa. **É a iniciativa que é a característica mais importante**." (Part5, I1, 010805, emphasis added).

5.6 Practicing the unknown

This subsection aims at summarizing and visualizing the dynamics among uncertainty, dualities, complexities, practices, and competence development within the context of a complex innovation process. Due to missing knowledge, any innovation process is confronted with uncertainty and unforeseen events. Theoretical contributions demonstrate how this process reveals adaptive, relational, and temporal complexities (Garud & Turunen, 2020; Tsoukas, 2017; Usher, 1954) and duality (Andriopoulos & Lewis, 2009; Hargrave & Van de Ven, 2017;

Papachroni & Heracleous, 2020) within a performative world view (Garud, Gehman, & Tharchen, 2018; Garud & Gehman, 2019), which is visualized in Figure 5. The existence and emergence of uncertainty, dualities and complexities are intrinsic to the context of a complex innovation process, if we consider performativity as an open-ended, ongoing journey.

With evidence from this work, this constellation can be exemplified by the unforeseen events within the order processes of the analyzed case. Whether orders arrived delayed, incomplete, or not suitable for the project group, unforeseen events repeatedly emerged within the order processes. The constantly changing elements, such as manufacturers and sellers, resources, specifications, or involved participants, within this process, revealed relational complexities. The uncertainties that emerged through the order processes also created tensions and duality between shielding participants and integrating them. On the one hand, the group realized that it was important to integrate participants to specify the orders, as the resources needed to suit the demands of all participants in the group. On the other hand, the order

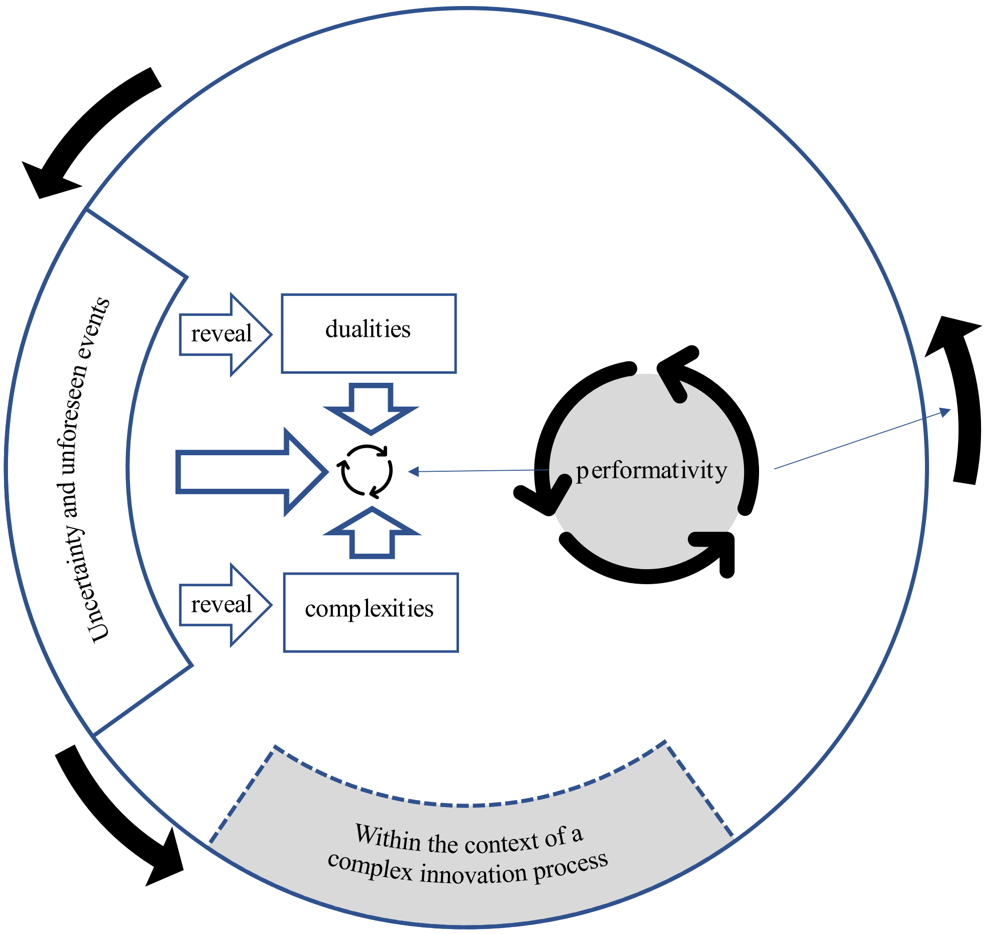

Figure 5 The dynamics of practicing the unknown. Part 1. Own figure

processes were complex and extensive which reduced the time, participants had for research and development.

Furthermore, this thesis identified practices that emerged and developed by being confronted with uncertainty throughout the innovation process and analyzed how they synergize dualities, deal with complexities, and cope with uncertainty, which is visualized in Figure 6. Several practices within the analyzed case had an impact on coping with unforeseen events. Let us exemplify this on the established practice of 'passing on developed processes to other participants'. Implementing and continuously executing this practice had synergetic effects on several dualities that were present in this context, like shielding and integration. When passing on developed processes, the group was able to integrate new participants as they acquired new knowledge and learned about the technological processes and the dynamics of the group itself. Simultaneously this practice had the effect that processes were distributed, and

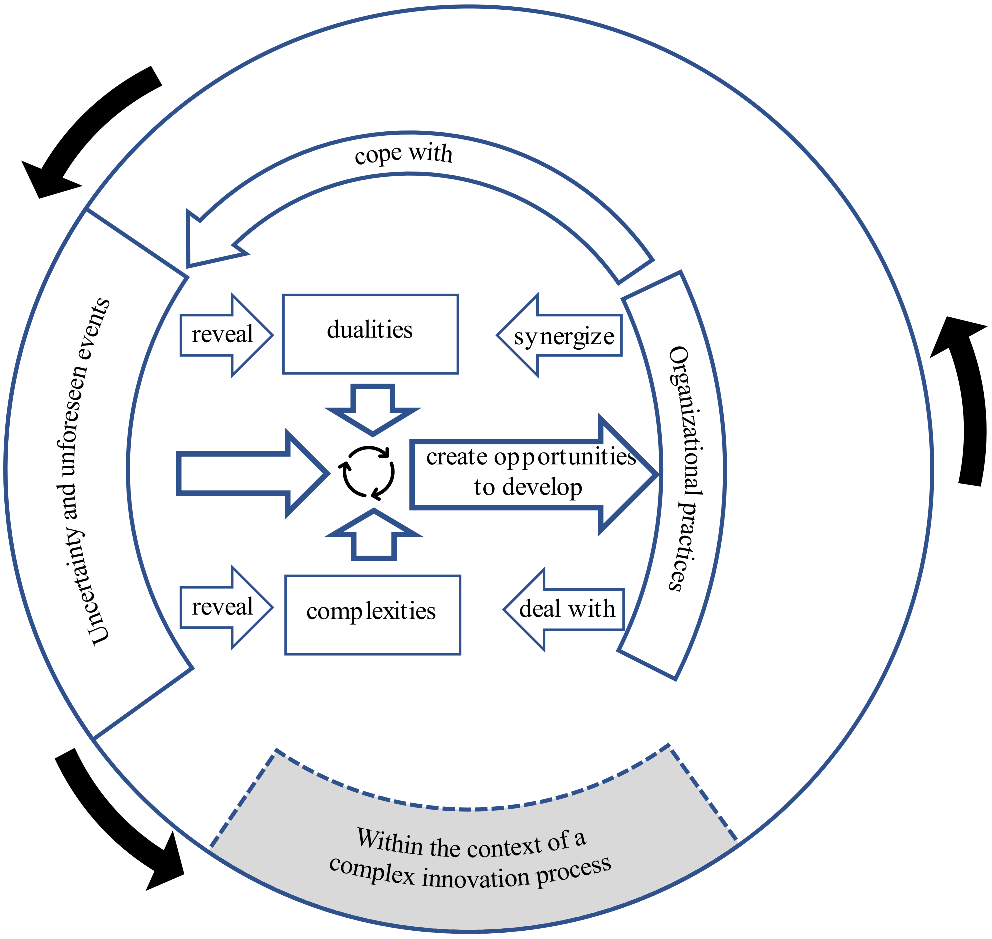

Figure 6 The dynamics of practicing the unknown. Part 2. Own figure

certain participants had more time to devote themselves to research, ultimately shielding them from repetitive tasks.

The practice also balanced the contradiction of industrial development and academic results. After passing on a process to someone else, the participant was able to focus on producing academic results and scientific advances without the need to continuously replicate already developed processes. However, those processes were essential for the prototype development and were, due to the implementation of this practice, executed by participants that learned the new processes, which ultimately contributed to the industrial development.

Those practices, therefore, confronted such organizational tensions and dealt with the present complexities. For example, when the deadlines of CEMIG reports and university demands (*chronos*) clashed with the research pace of the group (*kairos*), the temporal complexity emerged through that tension of *chronos* and *kairos*. Dualities such as autonomy and control, shielding and integration, and industrial development and academic results enabled participants to advance their individual agendas while assuring the group's objective in reaching predefined project milestones. This created opportunities to developed practices like 'shielding participants from certain tasks' and 'diversify meetings' that obtained synergetic effects from dualities like 'shielding and integration' and confronted the temporal complexities that emerged from a time-shifted development of each cell component. This performative intertwinement among dualities, complexities, uncertainties, and infinite other arrangements and elements within the context of a complex innovation process created opportunities to develop new and refine established practices.

This thesis demonstrates that practices emerge and develop by being confronted with unforeseen events, deal with adaptive, relational, and temporal complexities, and utilize the synergetic dynamics of the tension among dualities. The intertwinement among those elements is part of a continuously unfolding context (performativity) that can create opportunities to develop practices that in turn can cope with emerging unforeseen events.

As the last element of practicing the unknown, I introduced competence and competence development as practice. By analyzing the practices, their emergence, and development throughout the innovation process, I identified competences and their development, which approached uncertainty and contributed to deal with unforeseen events, which is visualized in Figure 7. By implementing practices that allocated equipment responsibilities, implementing

POPs, equipment notebooks, and personal diaries, the organization stimulated the development of competences, like taking initiative and assuming responsibility. Unforeseen events, like the German oven integration, led the group to develop practices like refining the elaboration of order processes, which developed their competences of developing practical understanding using previously acquired knowledge from those experiences and confrontations to transform knowledge to the extent that it increases the diversification of situations and can be accessed to other unforeseen events, as soon as they emerge.

Another example of this process is the unforeseen event of the interconnector, which provided us with insight on how continuously exploring and diversifying networks can develop competences of mobilizing networks, sharing the implications of the situations, and making them assume co-responsibility. When the interconnector steel turned out to be more complicated than expected (unforeseen event), the participant identified and utilized a contact at a physics workshop within the university (practice: exploring and diversifying networks) to

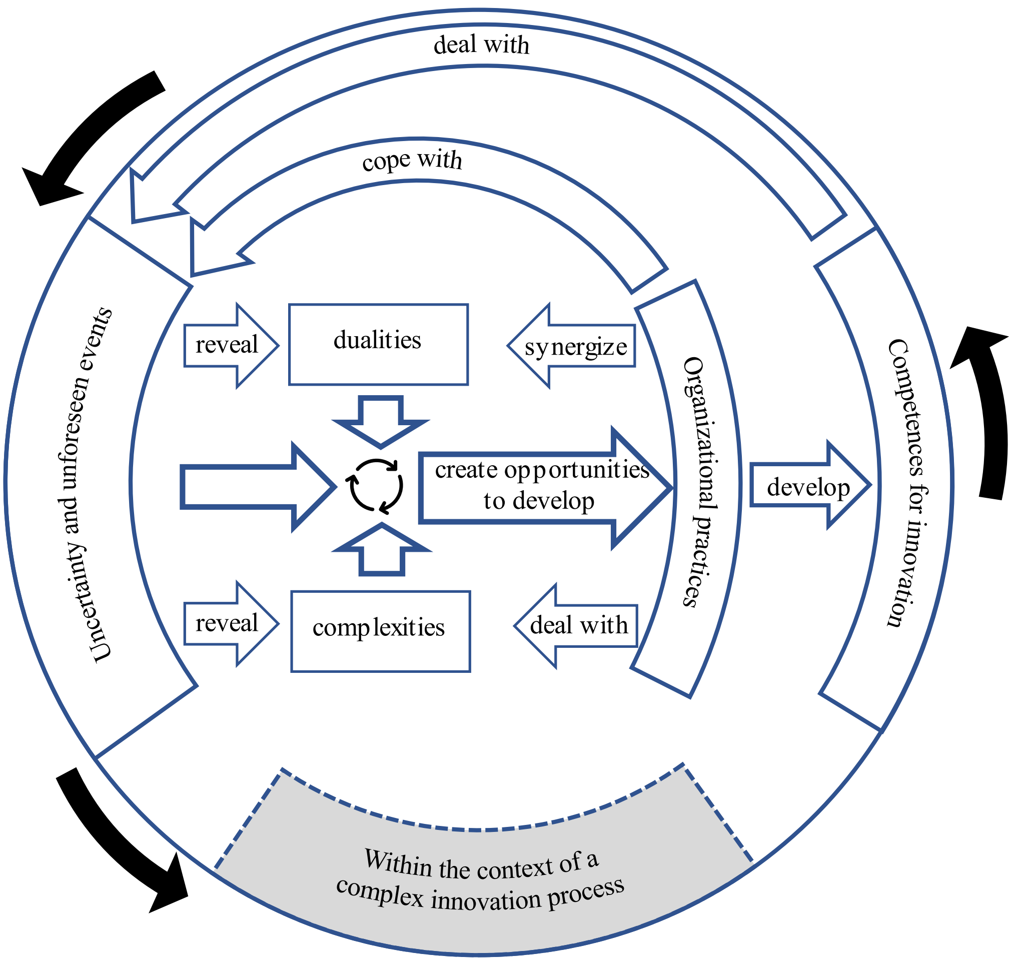

Figure 7 The dynamics of practicing the unknown, Part 3. Own figure

co-develop the interconnector (competence: mobilize networks), which ultimately dealt with the unforeseen event of the complicated interconnector steel.

By practicing the unknown, the complex configuration of the innovation process is being approached by dealing with unforeseen events when they appear in practice. Organizational practices establish and develop out of performative, continuously unfolding, and transforming arrangements that entail complexities, dualities, and uncertainty. In turn, those practices develop innovation competences and cope with unforeseen events within the context of a complex innovation process.

6 CONCLUSION

In closing, this thesis answers the question of how practices emerge from uncertainty to engage with unforeseen events and how this engagement stimulates the development of competences. It thematizes the relation among practices, duality, and complexity and provides evidence on how practices cope with unforeseen events within an innovation process.

By applying a case study method and utilizing qualitative research including interviews and secondary data analysis, the objectives of this thesis were achieved. The case of a Brazilian research group at a federal university and their development of two SOFC prototypes was chosen. This thesis analyzed practices that were identified by dealing with uncertainty within the innovation process and how they turned into competences, mapped the innovation process, detected and categorized uncertainties, identified and categorized practices, and analyzed how those practices when coping with uncertainty, turned into competences.

The findings of this thesis reveal a complex technology development project, which was confronted with unforeseen events along its process. The findings provide evidence that the organization coped with the uncertain environment by developing practices, which dealt with dualities and complexities, present in performative innovation processes. Furthermore, being confronted with unforeseen events and utilizing practices, led to individual and collective competence development within the organization and in turn support dealing with uncertainty.

The performative process and practice perspective of this work contributes to investigating the studied case with a holistic mindset, which reveals the intertwinement of practices and uncertainty while the process unfolds. By applying this perspective, we can observe how elements like duality and complexity are part of a performative world and, although creating relational and temporal tension and paradoxes they reveal opportunities and create synergy. This unfolding of the innovation process gives insight into how organizations can take opportunities in developing practices to cope with the uncertain environment and create spaces in which relational competences can emerge and develop.

This thesis contributes by revealing practices as a response to uncertainty and a source for competence development in innovation processes. By practicing the unknown, organizations have to possibility to embrace performativity, which reveals unknown events, complexity, and duality, and create opportunities for competence development. Organizational practices are key in developing competences and cope with the unknown of the innovation process.

During the elaboration of this thesis, I was constantly confronted with the juxtaposition of dualistic and existential ontology: rationalistic versus relational approaches to competence, dualism and duality, and synoptic versus performative process research. This active confrontation with different, however, complementing perspectives gave me the tools to engage with my research with an open-minded and holistic mindset. I observed performativity not only in the case and the innovation process of the prototype development but also in the way I did my research. The way I elaborated the literature background, the way I collected data, and the way I analyzed my results was a constantly becoming process that transformed with each piece of information and thought that was introduced. The unfolding of the research question is the best example for my efforts of incorporating the adapted theory not only into the investigated case but in the entire development of this thesis.

Instead of focusing on separate entities, the approach of this research was to investigate organizational practices by exploring relational and context-depended occurrences that incorporate a vast array of interacting elements. A beneficial aspect of this case study was that the practices, unforeseen events, and arrangements within the case could be investigated with a retrospective and were, therefore, completed and fully developed, which enabled me to identify and term them as ‘practices’ or ‘unforeseen events’. As the projects were finished, the interviewed participants had a holistic view of the process and their involvement in all interrelated elements of it.

This, however, brings me to some of the limitations of this work. When describing past events in the interviews, the possible presence of hindsight biases is not preventable. By cross-referencing responses of the participants with each other and with secondary data, the method applied in this thesis tried to delimit the occurrence of hindsight biases, however, it is never excludable. Furthermore, at the time of the interviews, the participation in the projects was for some participants more than 10 years ago, which impacted their ability to recall exactly the occurrence of certain events in detail.

The fact that this study was initiated after the case was completed brings me to the probably biggest limitation of this research. In the spirit of extended case methods, I attempted to incorporate a reflexive approach – an approach that “embraces not detachment but engagement as the road to knowledge" (Burawoy, 1998, p. 5). Engagement with my theoretical base but also the examined case and the investigated subjects. This, however, was only partially possible due to the termination of the projects and the dispersal of the group. An engagement with the entire organizational context by observing inter alia working processes, relationships, and dialog within a real-life setting is beneficial to fully comprehend the intertwinement and performative development of organizational elements. Research tools like observation were not possible, which would have enriched the possibilities of collecting data and contributed to a truly performative extended case method and data analysis.

Another limitation of this thesis was to further explore the relation between concepts of duality and paradoxes as well as the different types of complexity with competence development. The concepts of duality and complexity can contribute profoundly to the notion of competence as practice but was only touched slightly in this thesis. In the case of duality, the research focus can be directed towards contradictions within organizational processes to better understand the development of competences when confronted with those opposing, however, synergetic elements. In the case of complexity, studying the three types, defined by Garud and colleagues (2011, 2013) as adaptive, relational, and temporal could give insight into competence development when investigating each complexity more closely.

This brings me to possibilities of future research. This thesis introduces practice theory and practices as an approach to uncertainty in innovation processes. Introducing other research methods, like observational, to investigate the emergence and development of practices and their impact on unforeseen events can deepen the research on innovation studies. Furthermore, exploring more intensely the presence of contradicting elements and complexities within innovation processes and how they influence practices and competence development, for example by applying dialogical analysis, could enrich the discussion on how to approach uncertainty within innovation processes.

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APPENDIX

Appendix 1: Introduction page to the interview

Informações - projeto CEMIG-LAMPAC-SOFC

Entrevistador: Victor Bistritzki (Programa de Doutorado de Inovação tecnológica, UFMG)

Introdução

O objetivo geral da pesquisa é compreender o processo de inovação e como lidar com incertezas durante esse processo e como essas incertezas geram novas práticas.

A pesquisa é feita através de um estudo de caso dos projetos de desenvolvimento de SOFC do Lampac (UFMG) e CEMIG de 2004 a 2014 (50W e 1kW).

A metodologia requer mais de uma entrevista com cada pessoa para aprofundar os aspectos que emergem do diálogo com os participantes. Portanto, espero poder realizar mais de uma entrevista com você.

Definições importantes:

Organização "Projeto CEMIG-Lampac":

- Para esta pesquisa organização é a forma como se estruturam formas de trabalho e espaço físico entorno dos projetos. Isto inclui:
- O laboratório e sua estrutura, que inclui o ambiente de trabalho, equipamentos, recursos e espaço físico.
- Os participantes, que incluem coordenadores de pesquisa, estudantes, técnicos e qualquer pessoa envolvida no projeto.
- Todos os elementos da CEMIG que participaram dos projetos, incluindo pessoal e recursos materiais ou financeiros.

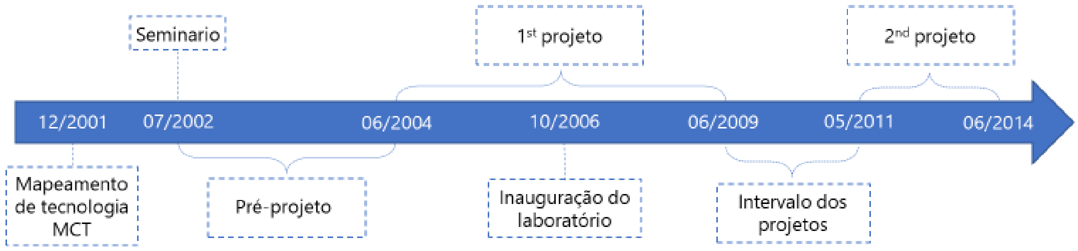
Prática:

Atividades coordenadas de indivíduos e grupos na realização de seu "trabalho real", conforme informado por um contexto organizacional ou de grupo específico.

Evento imprevisto / "Unknown unknowns":

Durante um processo de desenvolvimento, planejamos e esperamos certos resultados. Mas alguns eventos no decorrer o processo que não poderiam ter sido antecipados no planejamento do projeto. Esses eventos são chamados de “unknown unknowns” e só podem ser tratados quando aparecerem - não antes.

Desenvolvimento de “projeto CEMIG-Lampac”:



Tópicos da entrevista (Duração da entrevista aprox. 1 hora)

- Entrada no projeto, objetivos e integração ao grupo
- A estruturação dos projetos - práticas, rotinas, atividades fixas
- Práticas (atividades) estabelecidas e eventos imprevistos (unknown unknowns)
- Dificuldades, obstáculos e soluções encontrados.
- Eventos desconhecidos e como a organização lidou com eles.

Appendix 2: Script for interview “pre” with RL1 (03/09/2018)

Topics:

- Project origins
- Governmental technology prospection
- Workshop in Brasilia
- CEMIG project
- Project preparation & pre-phase
- Personal development (competence development)
- *Rede-Pacos*

Questions:

About governmental technology prospection

- How did you get to know about the technology prospection?
- What was it about?
- How did you get in contact with them?
- Why weren’t you included in the prospection?
- Why did they visit the laboratory?

About the visit of the technology projection team at UFMG

- What was the purpose of the visit?
- What happened at the visit? Topics?
- Who was invited to the visit? Why?
- How did you know the labs/companies/universities that were invited?
- What was the outcome?

About workshop in Brasilia

- How did you finance the trip?
- How did you get in contact with CEMIG?

About CEMIG

- Why was CEMIG interested in the research group?
- How did CEMIG hope for from the project?
- Did CEMIG already have competences in fuel cells?
- What is the group of excellence?
- What is the purpose of this group?
- What was included in the project description?

About project preparation & pre-phase

- How did the project development evolve with CEMIG?
- How were the steps of the project preparation?
- Who was involved in the project preparation?
- How did you know the other participants of the project? (Students, researcher, technicians).
- How were they selected?
- How were they trained for the project?
- Did they get paid? Did they receive scholarships? Who contracted?
- What happened with the trained workforce after the project?
- How did you collect knowledge on how to construct the laboratory and prepare the project?
- Did the fuel cell research and development during the pre-phase stop?

Personal development (competence development)

- How did the project influence the previous work tasks?
- What were your new job tasks?
- How did previous job task change or being influenced by the new ones?
- What competences did you develop?
- What competences are needed to successfully prepare the project?
- What competences are needed to successfully execute the project?

Rede-Pacos (RP)

- What is RP?
- When and how did RP start?
- Was the project connected to RP?
- How did it influence the project?
- Did it support the project? How?
- Where there any competence exchange through RP that helped the project?

Appendix 3: Questionnaire script - first round (01/05/2020 – 27/07/2020)

Definitions & Information:

- Methodology relies on multiple interviews of each participant
- Practice
- Unforeseen event / unknown unknown
- uncertainty

General background questions:

- Como você ficou sabendo do projeto?
- Por que você se juntou ao projeto e qual foi o seu principal objetivo de participar do projeto?
- Quais eram suas responsabilidades no projeto?

Case narration

- Conte-me sobre sua participação no projeto com o máximo de detalhamento possível
    - Dificuldades
    - Atrasos
    - Prorrogações
    - troca de equipe
    - troca de material
    - troca de tecnologia
    - busca por outros parceiros

"Começar do zero"

- Você estava familiarizado com a tecnologia ou teve que começar do zero?
- Estrutura da equipe. Para quem reportar?

Orçamento e equipamento

- Alguns participantes me falaram sobre dificuldades no processo de orçamento. O que você lembra disso?
- Alguns participantes mencionaram que foi muito difícil aprender a operar os novos equipamentos. Como o grupo aprendeu a usá-los?
- Houve algum problema com equipamento quebrado? Como foi resolvido?

Interconnector case

- Durante o projeto tinham dificuldades com o aço do interconector. O que você lembra sobre isso?

"Practice" questions:

- Como os participantes deveriam reagir quando tinham algum problema relacionado ao projeto (cadeia de comando)? Havia alguma orientação sobre isso?
  - Qual era o procedimento usual quando alguém da equipe não sabia o que fazer (reportar a quem)?
  - Isso foi seguido? A equipe seguiu as diretrizes ou reagiu de maneira diferente?
- Você estabeleceu algumas práticas?
  - Reuniões diárias, semanais, mensais, práticas sobre como se comunicar e com quem se reportar, atividades de solução de problemas, relatórios, atualizações etc.
- O grupo estabeleceu novas práticas devido à experiência que passou durante as fases do projeto?
  - O que mudou? Mais reuniões? Cadeia de relatórios diferente?
- Qual era o procedimento usual quando a equipe era confrontada com um evento imprevisto? Tente resolver ou relatar primeiro?
  - Como a equipe reconheceu o evento?
  - Como eles enfrentaram o evento incerto?
  - Eles resolveram isso? Se sim, como?
- O tratamento dos eventos incertos mudou alguma coisa nas práticas da equipe?
- Isso levou a novas práticas dentro da equipe?

Competence:

- Descreva-me o que é um aluno competente em um projeto como este? O que ele tem?
- Quais competências você desenvolveu durante o projeto?

Appendix 4: Questionnaire script - second round (21/08/2020 – 06/05/2021)

Topics:

T4: Time pressure

- Na última entrevista você falou que sentiu mais pressão do doutorado que do projeto CEMIG. Como você lidou com essa pressão?
  - Como respondeu a essa pressão?
  - Havia alguma forma de reduzir essa pressão?
    - se sim, qual ou quais?
  - A pressão do doutorado era diferente da pressão da CEMIG?
    - Se sim, como?

T5: Felt project responsibilities?

- Você realizou tarefas que não tinham a ver com seu doutorado, mas só com o projeto CEMIG?
  - Se sim, quais? Poderia dar exemplos?
- Como você lidou com essas tarefas?
- Elas interferiam umas nas outras (doutorado x CEMIG e vice versa)?
  - Se sim, como?
- Como você gerenciava isso?

T6: overtime

- Você ficou mais tempo trabalhando no laboratório do que o inicialmente esperado?
  - Se sim, por que houve essa necessidade?
  - Foi algo imposto ou voluntário?
  - Poderia dar exemplos?

T7: External help

- Além do laboratório você tinha apoio de fora do grupo?
  - Se sim, como você encontrou eles?
  - Por que você os procurava? Para resolver problemas?
  - Você procurava os contatos de novo?
  - Outros participantes usaram esses contatos também?

Difficulties & unks:

D2/u1: Did she have any difficulties with the order process of equipment or other materials?

- Quando você precisava algum material ou equipamento, como você fazia os orçamentos?

- Tinha alguns problemas com o orçamento?
    - Quais? Que tipo de problemas? exemplos
- Você sempre recebeu o que pediu?
    - Se não, o que você fez então?
- Chegou no prazo esperado?
    - Se não, o que você fez então, como isso foi tratado?

D3/p5: Broken equipment

- Você teve algum problema com equipamento quebrado?
- Se um equipamento quebrou ou teve problemas, havia um procedimento sobre como lidar com ele?
    - Se sim, você usou o procedimento?
    - Se sim, foi suficiente?
    - Se não foi suficiente, por quê?
    - Se não usou, por que não?
    - Pode dar exemplos?
- Quem foi responsável por resolver o problema?
    - Quem o acionou? Por que o acionou?
- O que você fez até o equipamento ser consertado?
    - Por que optou por esse curso de ação?

D4: how to learn to use an equipment?

- Em relação ao aprendizado dos novos equipamentos. Você mencionou que um técnico forneceu algumas informações básicas e que o grupo teve que preencher as lacunas de conhecimento. Como exatamente vocês fizeram isso?
- Você teve que fazer muitos experimentos, tentativa e erro?
- Você precisou ligar para pessoas de fora do grupo de pesquisa?
    - Como você conhecia essas pessoas?
    - Isso resolveu os problemas?
- Para entender o equipamento, havia uma pessoa responsável ou todo o grupo tentou encontrar informações sobre como usar o equipamento?

D6: Zirconia Powder synthesis PART3

- Um participante mencionou que houve um tempo em que vocês tinham um problema de sintetizar e filtrar o pó de zircônio. Você lembra disso?
- Se sim: Ninguém suspeitava que o problema poderia ter sido o controle contínuo do ph?
    - Se não, por quê?
    - Não havia relatos de literatura ou prática?
- Você suspeitava que poderia surgir algum problema com o processo de síntese quando você o conduziu pela primeira vez?

U2: Breaking of the anode / p7: Make more powder in advance in the case of something breaking.

- Um participante me contou sobre um problema vocês tinham com o ânodo quebrando no forno nas primeiras vezes vocês os testaram. Você lembra disso?
- Quando esses anodos saíram do forno, vocês imaginaram que vai sair todo quebrado?
  - Se não imaginou, por quê?
  - Se imaginou, como sabia que pode sair quebrado?
  - Você já tinha experiência com esse procedimento? Tinha lido sobre ele?
- Um participante mencionou que, em algum momento, decidiu fazer mais pó, caso tivesse que repetir o processo. Isso foi algo que você continuou fazendo em outras partes da pesquisa - preparar com mais antecedência e quantidade maior em caso de dificuldades ao longo do processo?
- Você precisava autorização para produzir mais pó, sem saber que o precisar?
- Outros participantes sabiam que você ia fazer isso?
- Outros participantes passaram a fazer isso?

Practice:

P1: Pass developed process to technicians

- Você mencionou que, quando desenvolveram um processo novo, vocês ensinaram aos técnicos ou estagiários como fazer o processo para se concentrar em outros desenvolvimentos. Você lembra disso?
- Como isso funcionou? Como você ensinou os técnicos pra replicar o processo?
- Essa era uma prática comum?
- Outros participantes fizeram isso também?

P14: Competence development and knowledge transfer

- Como esse tipo de aprendizado era desenvolvido na equipe?
  - Quando você aprendeu algo novo, você compartilhou?
- Como a transferência de conhecimento era realizada entre vocês?

P2: Equipment responsibility

- Você mencionou que todos eram responsáveis por um determinado equipamento. O que isso significava - ser responsável por um equipamento?
- O que era esperado do responsável?
- Isso continuou durante todo o projeto ou desapareceu com todos conhecendo melhor os equipamentos?
- Se não: Por que não continuou?

P3: Did novices *have to read? Why?*

- Você mencionou na última vez que os novos participantes tiveram que fazer uma revisão da literatura. Você estava envolvido com isso?
  - Se sim, como?
- Você foi solicitado a fornecer aos novos participantes materiais de leitura?
  - Se não, quem lhes forneceu isso?
  - Como a literatura era escolhida?
  - Já havia alguns artigos básicos?
  - A literatura era compartilhada entre todos, ou cada um procurava e lia da sua parte?
- Havia outras práticas para introduzir os novos participantes na tecnologia, no laboratório ou no grupo de pesquisa?
  - Se sim, quais?

P4: How was the research notebook handles?

- Foi-me dito que havia um caderno em que todos tinham que anotar se um equipamento fosse usado. Você se lembra daquele caderno?
  - Para que serve e como deveria ser usado?
- O caderno ajudou?
  - Se sim, em qual sentido?

P6: Meetings

- Estou muito interessado nas reuniões que tinha no LAMAPC cada semana. Você poderia tentar se lembrar se havia algum procedimento? Como eles foram estruturados?
- Talvez você se lembre de um específico e descreva-o em detalhes?
- Alguém foi responsável pela estrutura da reunião?
  - Quem conduzia a reunião?
  - Como era a sistemática das reuniões – todos apresentavam seus resultados ou só alguns?
  - Quem falava?
  - Quem comentava?
  - Como os problemas eram tratados nessas reuniões?
- Alguém fez anotações?

P8: Did you really start with a literature revision when you had a problem?

- Onde você começou a procurar uma solução quando tinha um problema a resolver?
- Por quê?
- Você pediu ajuda nos participantes do grupo de pesquisa?
  - Se sim, em qual forma?

P9: Procedimento Operacional Padrão (POP)

- Você lembra dos POPs (Procedimento Operacional Padrão)?
- Quem os apresentou e como funcionou?
- Na sua percepção, os POPS eram suficientes para realização das atividades? Era necessário algum conhecimento além do POP?
    - Você poderia dar exemplos?
- Na sua percepção, um aluno novo na equipe poderia replicar o POP apenas com a folha, sem nenhuma ajuda prática?

P11: Use comercial parts to test the own.

- Um outro participante contou o que o grupo usou ânodo, cátodo e eletrólito comerciais para testar seus próprios materiais em cima deles
- Qual era sua experiencia com isso?
- Ajudou o processo?
    - Como? Por quê?
- Isso era uma prática comum?

P13: Bricolage

- Outro participante mencionou que o grupo de pesquisa utilizou um selante de alimentos do Polishop ao invés de um profissional. Você se lembra se o grupo improvisava assim com frequência ou recombinou recursos para um novo propósito??
- Se sim, com que e por quê?
- Isso funcionou ou era uma solução provisório?

T12: Called back for p2?

- Você foi convidado a compartilhar experiências ou conhecimentos de qualquer forma para o segundo projeto?
- Se sim, quem chamou você?
- Como e para quais atividades?

Appendix 5: Complete participation list of the CEMIG-UFMG SOFC development projects I and II between 2004 and 2014.

Name	Affiliation	Years	Program	Study	Bolsa/funds
RL1	UFMG	2004-2014	-	-	UFMG
RL2	UFMG	2004-2014	-	-	UFMG
RC	UFMG, ANEEL	2004-2007	-	-	ANEEL
Participant	UFMG, ANEEL	2011-2014	-	-	ANEEL
Participant	CEMIG	2004-2009	-	-	CEMIG
Participant	CEMIG	2011-2014	-	-	CEMIG
Cíntia	UFMG	2005-2009	Doutorado	Química	CNPq
	UFMG	2009-2010	Pos-Doc	Química	CNPq
Part3	UFMG	2005-2009	Doutorado	Química	CNPq
	UFMG	2009-2011	Pos-Doc	Química	CAPES
Part2	UFMG	2002-2004	Mestrado	Química	CAPES
	UFMG	2004-2009	Doutorado	Química	CNPq
	UFMG	2009-2010	Pos-Doc	Química	CNPq
Participant	UFMG	2007-2008	Pos-Doc	Química	FAPEMIG
Tech	UFMG	2004-2007	Estágio	Química	ANEEL
Part5	UFMG	2009-2011	Mestrado	Química	FAPEMIG
	UFMG	2011-2014	Doutorado	Química	CNPq
Participant	UFMG	2003-2005	Mestrado	Química	CAPES
Participant	UFMG	2004-2006	Mestrado	Química	CNPq
Participant	UFMG	2005-2007	Mestrado	Química	CNPq
Participant	UFMG	2005-2007	Mestrado	Química	FAPEMIG
Participant	UFMG	2007-2009	Mestrado	Química	CNPq
Participant	UFMG	2010-2012	Mestrado	Química	CNPq
	UFMG	2012-2016	Doutorado	Química	CNPq
Participant	UFMG	2011-2013	Mestrado	Química	CNPq
Participant	UFMG	2011-2014	Tecnica/o	Química	ANEEL
Participant	UFMG	2012-2014	Mestrado	Química	CAPES
	UFMG	-2016	Outra natureza	Quimica	CNPq
Part4	UFMG	2009-2012	Doutorado	Química	CNPq
Participant	UFMG	2007	TCC	Engenharia Elétrica	-
Participant	UFMG	2004-2005	Iniciação científica	Química	-
	UFMG	2007	Iniciação científica	Química	-
Participant	UFMG	2005	Iniciação científica	Engenharia Química	CNPq
Participant	UFMG	2009	Iniciação científica	Engenharia Química	-
Participant	UFMG	2009	Iniciação científica	Química	CNPq
Participant	UFMG	2010	Iniciação científica	Química	CNPq
Participant	UFMG	2011	Iniciação científica	Química	CNPq
Participant	UFMG	2014	Iniciação científica	Engenharia Metalúrgica	-

Intern1	UFMG	2006-2007	TCC	Engenharia Mecânica	-
	UFMG	2008-2009	Mestrado	Engenharia Mecânica	CAPES
	Petrobras	2011-2014	-	-	-
Participant	CEFET	2007	Estágio	Ensino Médio	-
Participant	COLTEC	2007	Estágio tecnico	Ensino Médio	-
Participant	COLTEC	2009	Estágio tecnico	Ensino Médio	-
Participant	Polimig	2009	Estágio	Ensino Médio	-
Participant	COLTEC	2009	Estágio tecnico	Ensino Médio	-
Participant	UFMG, ANEEL	2011	Estágio	Ensino Médio	-
Participant	UFMG	2011	Tecnica/o	Química	ANEEL
Participant	COLTEC	2011	Estágio tecnico	Ensino Médio	-
Participant	COLTEC	2011	Estágio tecnico	Ensino Médio	-
Participant	UFMG, ANEEL	2012	Tecnica/o	Química	ANEEL
Participant	UFMG, ANEEL	2013	Tecnica/o	Química	ANEEL
Participant	UFMG, ANEEL	2014	Tecnica/o	Química	ANEEL
Participant	UFMG, ANEEL	2014	Tecnica/o	Química	ANEEL
Participant	UFMG, ANEEL	2014	Tecnica/o	Química	ANEEL
Participant	UFMG, ANEEL	2012	Tecnica/o	Química	ANEEL
	UFMG	2011	Monografia	Química	FAPEMIG
	UFMG	2010	Iniciação Científica	Química	FAPEMIG
Participant	UFMG	2012	TCC	Química	-
	UFMG	2012	Tecnica/o	Química	CNPq
Participant	UFMG	-2008	Iniciação Científica	Química	FAPEMIG
Participant	UFMG	-2016	Iniciação Científica	Química	-
Participant	UFMG	-2016	Iniciação Científica	Química	CNPq
Participant	UFMG	-2011	Outra natureza	Química	CNPq