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Mind the gap—managing boundaries in the fuzzy front end of production innovation

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Abstract

Purpose – The purpose of this paper is to increase the understanding about exploratory practices in the fuzzy front end (FFE) of production innovation.

Design/methodology/approach – The empirical findings are based on a longitudinal single-case study conducted at a multinational manufacturing company in the automotive industry. By using an ethnographic approach, our study analyzes the work of the production system development engineers. The unit of analysis is production system development in the FFE of production innovation.

Findings – The results reveal that little of exploration of new opportunities is taking place – i.e. limited time is spent by the engineers in the FFE – even within the development department, which was assigned the formal responsibility for elaborating concepts about what the future factory should look like. Whilst the exploration work in the FFE that do take place is individually carried "under the radar" by a few enthusiastic engineers, it is simultaneously being disregarded by an organization heavily favoring exploitation of the current practices.

Research limitations/implications – The research complements existing production innovation approaches with new insights on the production innovation process and how to manage exploration in the FFE.

Practical implications – The findings are particularly relevant for production engineers and plant managers interested in enabling and achieving more innovative and radical change.

Originality/value – This paper extends research on how to manage the early phases of production system development and, specifically, how to enable exploratory practices to emerge in this setting, thereby contributing to the theoretical discourse on managing exploration in manufacturing.

Keywords Production system development, Exploration, Exploitation, Fuzzy front end, Innovation, Manufacturing

Paper type Research paper

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1. Introduction

In recent decades, continuous improvements have been a hallmark for manufacturing organizations to stay competitive. In particular, Lean production has become the most widely accepted management approach and has been widely applied in industry (Marodin and Saurin, 2013). However, the business world currently faces a period of rapid change (Rothenberg and Ettlie, 2011; Stålberg and Fundin, 2016; Teece and Leih, 2016). Even products that revolutionized markets in the recent past are at risk of being obsolete today and recent new technologies are no longer considered state of the art. Emerging trends, such as digitalization and electrification, new technologies, and complex connected systems (Industry 4.0), are increasingly being studied, developed, and implemented. Increased market uncertainties place a higher pressure on the functional integration in the automotive industry with new technologies introduced through discontinuous innovation (Rothenberg and Ettlie, 2011). Thus, organizations previously characterized by stability and predictability now face risks in more dynamic markets (Eriksson *et al*., 2016; Teece and Leih, 2016). However, guidance for high-tech companies regarding exploratory innovation is still needed (Zhang *et al*., 2023; Troisi *et al*., 2024). This has implications on the fuzzy front end of production innovation due to new processes for complex projects (Zwikael and Gilchrist, 2024), new product portfolio practices (Ojiako *et al*., 2023), and a combination of plan-driven vs. agile methodologies (Mirzaei *et al*., 2024). As a result, manufacturing companies are under enormous pressure to innovate and improve their production systems to stay competitive (Stålberg and Fundin, 2016). Manufacturing companies need to improve and prioritize tools and structures that stimulate new ideas and to promote changes outside companies' comfort zones (Södergren, 2016). In other words, manufacturing companies need to become better at carrying out production innovation (Larsson and Romero, 2023). Production innovation is however a challenging task. Research shows a critical discourse with a micro-perspective of how dialogue enables knowledge creation and development for strategy implementation (Bellis *et al*., 2023). As a means how to facilitate the dialogue, Zasa and Buganza (2024) propose two groups of boundary object configurations such as product envisioning and product design in supporting innovation teams. In production environments with high expectations on predictability and takt time, introduction of new radical production concepts certainly requires skills beyond ordinary work processes.

Regarding a more specific focus on re-design and new creation, a lot of research has been undertaken in the business process management field during the last 3 decades using concepts such as business process re-engineering (Hammer and Champy, 1993), process innovation (Davenport, 1993), and kaikaku (the Japanese term for "radical change") (Yamamoto, 2013). Despite the inherent focus on re-design and creating new, little research has been undertaken on how to manage exploratory work in the fuzzy front end (FFE) explicitly. In line de Oliveira *et al*. (2024), one potential forthcoming scenario of front-end innovation is making the construct more coherent to overriding challenges. Further, in an analysis of 266 FFE studies (Park *et al*., 2021), strategies that emphasize explicitness and responsiveness by planned flexibility are needed. More specifically, in contexts with high complexity products, such as in the automotive industry and in a production system development (PSD) context, there is a need of more experimentation and prototyping to enable a design for manufacturability. In conclusion, there is a lack of research focusing on the early phases of production innovation (Kurkkio *et al*., 2011; Frishammar *et al*., 2013; Lager *et al*., 2013; Yamamoto, 2013; Ng *et al*., 2015), especially on how to enable exploration (Yamamoto, 2018) – e.g. production innovation in the context of this study.

Today, companies face increasing challenges as new products are frequently introduced, often with vastly different architectures and technologies from current offerings. For instance, it remains uncertain which type of fuel cells will ultimately provide a sustainable solution for the automotive industry: hydrogen, fully electric batteries, or hybrid options combining both. In a car manufacturing plant, production may even need to accommodate these emerging variants alongside existing models. This uncertainty creates significant hurdles for production

development engineers, who need to prepare for future production demands without a clear picture of what products they'll be required to manufacture. During transitional phases, the marketing and development departments often cannot confirm which car models will be produced, leaving production engineers in a difficult position. They must begin strategizing and investing in production capabilities without precise information, making long-term planning nearly impossible and increasing the risk of costly adjustments down the line.

These examples are only a small part of what happens in an assembly shop when new drive trains are introduced. Consequently, the production department must handle all these issues even though they do not know what products to be assembled in the future. This is a typical example of a FFE dilemma. Similar situations can occur in the body shop and paint shop when new lightweight materials such as aluminum, magnesium, carbon fiber reinforced panels or Sandwich panels are introduced. Spot welding cannot be used but depending on what material that is introduced there are several different assembly methods that might be better suited for this task. Which methods should a company start to explore in order to be ready to produce the products when production is started?

However, a review of existing literature shows that little attention has been given to the FFE of production innovation (Yamamoto, 2013; Ng *et al*., 2015; Ahlskog, 2019; Trolle *et al*., 2020). Although the FFE has been studied from an R&D, voice of the customer, technology opportunity and a process development perspective, such analyses are mainly in the context of process firms (Kurkkio *et al*., 2011; Kurkkio, 2011; Frishammar *et al*., 2013; Lager *et al*., 2010). The FFE has also been implicitly studied from a production system design perspective (Wu, 2001; Bellgran and Säfsten, 2010; Rösiö and Bruch, 2018). However, even though previous research partly focuses on managing the FFE, there is a lack of explicit focus on how innovative and explorative work is enabled in practice from a PSD perspective, and the conditions in which it is embedded.

In the development of new radical product innovations however, the FFE has been highlighted as a critical phase (Frishammar *et al*., 2013; Yamamoto, 2018; Kurkkio, 2011; Wikström, 2013), and represents the time that it takes for a new opportunity—a new product or process—to be realized through serious effort after it is first considered (Smith and Reinertsen, 1998). Lager *et al*. (2010) and Rösiö and Bruch (2018) indicate that this early stage of development is generally informal in nature, and as such, is characterized by ad-hoc decision-making, complexity, and a high degree of uncertainty. Therefore, it is also considered the most difficult phase to manage (Kim and Wilemon, 2002a). In theory, not only does FFE work require a high degree of freedom to explore new ideas, but more especially, the decisions made has a high leverage for the entire innovation process and its outcomes (Reid and De Brentani, 2004; Markham, 2013; Gassmann and Schweitzer, 2014). Consequently, it is reasonable to believe that the exploratory work done in the FFE is critical to the success even when running production development, especially when the objective is to boost production innovation (Yamamoto, 2018).

Thus, the research gap highlighted in current research lies in the limited focus on the front end of innovation (FFE) within the context of *production innovation*, particularly from a production system design (PSD) perspective. While existing studies have explored FFE from various angles, such as R&D, customer insights, technology opportunities, and process development, these analyses largely pertain to process firms rather than production-focused settings. Moreover, although some literature has indirectly addressed FFE within PSD, there is a lack of explicit focus on how innovative and exploratory work is practically enabled in PSD and the specific conditions under which it occurs. This gap is especially relevant given that FFE is recognized as a crucial yet challenging phase in developing radical product innovations, due to its informal, ad-hoc, and high-uncertainty characteristics. The need to explore new ideas with a degree of freedom in FFE and the high impact of early-stage decisions on the overall innovation process underscore the critical role of FFE in production innovation. Thus, this paper aims to address the gap by increasing understanding of exploratory practices in the FFE of production innovation with the following research questions:

RQ1. What characterize the FFE of production innovation?

RQ2. What are the prerequisites for exploratory practices to thrive in the FFE of production innovation?

The article is structured as follows. Section 2 presents a review of the literature related to the FFE, as well as exploitation and exploration. Section 3 presents the research methodology. Section 4 presents the empirical findings and addresses RQ1. Section 5 discusses the results, addresses RQ2, and concludes with implications and directions for further research.

2. Theoretical framework

The foundation of the theoretical framework used to analyze and discuss how exploratory practices are manifested in the front end of production innovation consists of two main pillars. The first subsection describes the FFE concept to understand the front end context in which production innovation is undertaken. The second subsection describes the concept of exploration and the characteristics of exploration practices.

2.1 The FFE concept as an enabler for production innovation

The FFE could be interpreted as an early phase of the product development process where ideas and concepts are generated, screened, and refined before formal development begins. Research in this area often centers on themes of innovation, creativity, uncertainty management, and the tools or processes that enhance clarity and efficiency during this stage.

The research foundation of the FFE can be described within four main contexts:

(1) *Conceptual Frameworks:* This context includes models that help define and structure the FFE (Ahlskog, 2019; Larsson and Romero, 2023). Koen *et al*. (2001) contribute foundational work with their New Concept Development (NCD) model, which provides a structure for FFE processes. Similarly, Reid and de Brentani (2004) examine FFE management in product innovation, especially under high uncertainty conditions.

(2) *Uncertainty and Ambiguity Management:* Research here focuses on strategies to navigate the inherent uncertainties of the FFE phase. Kim and Wilemon (2002a, b) present risk management strategies tailored for early-stage development, while Khurana and Rosenthal (1998) explore best practices by comparing successful and unsuccessful FFE approaches. More recently, Li *et al*. (2024) discuss how cooperative R&D network embeddedness and innovation resilience can moderate environmental turbulence during FFE.

(3) *Tools and Techniques:* This context addresses methods to support creativity and improve innovation quality in the FFE. Elmquist and Segrestin (2007) study how different FFE processes enhance creativity through specialized tools, while Zhang and Doll (2001) examine the link between early-stage design tools and their impact on innovation quality and speed.

(4) *Organizational Culture and Team Dynamics:* Research in this area highlights the influence of team structures and company culture on FFE success. Neukam (2017) investigates managing the FFE in multicultural teams, and Cooper *et al*. (2004) emphasize the role of cross-functional teams and organizational culture in driving successful FFE outcomes. Additionally, Kijkuit and Van den Ende (2007) examine how network dynamics within organizations affect the early stages of innovation.

Together, these research contexts provide a comprehensive understanding of the FFE phase, guiding strategies for managing complexity, fostering innovation, and optimizing early product development stages.

The FFE has been described by several scholars over the years (Smith and Reinertsen, 1991; Khurana and Rosenthal, 1997; Koen *et al*., 2001; Kim and Wilemon, 2002a). The term "fuzzy front end" was first coined and popularized by Smith and Reinertsen (1991) to describe how product development lead-time could be reduced in half. The authors referred to "pre-development," that is the time taken for work on an idea to start after its conception (Reinertsen, 1999). Since then, research on the FFE has predominantly been applied in the field of new product development (Kurkkio, 2011; Wikström, 2013), although some research has been undertaken in the process development domain (Frishammar *et al*., 2011; Kurkkio, 2011). In recent decades, research on this topic has been undertaken using many different terms besides the FFE, including "front end of innovation," "pre-development stage," "idea stage," "discovery stage," or simply, "the early stage" (Eling and Herstatt, 2017). Despite an increased sense of importance, the term "front end fuzziness" however still remains vague (Zhang *et al*., 2019). Prior research also emphasized the importance of the FFE. For instance, this stage was deemed critical, since substantial value tends to be created in the front end (Koen *et al*., 2001; Reid and De Brentani, 2004). Moreover, decisions made in this stage have high leverage for not only the subsequent development process, but more so, the overall outcome (Reid and De Brentani, 2004; Markham, 2013; Gassmann and Schweitzer, 2014).

The FFE starts with the identification of an opportunity (Eling and Herstatt, 2017). Specifically, the FFE starts when an idea is shared in a social setting among development participants, rather than residing in the mind of an individual (Khurana and Rosenthal, 1998; Frishammar *et al*., 2013). The FFE ends when a decision is made either to approve a formal development project or to reject it (Khurana and Rosenthal, 1998; Eling and Herstatt, 2017). The end result is typically a product or process concept (Khurana and Rosenthal, 1998; Kurkkio, 2010; Florén and Frishammar, 2012). The FFE comprises all activities that take place before the more formal and well-structured development process starts, such as the stage-gate within new product development (Koen *et al*., 2001).

The generally informal, complex, and uncertain nature of this early phase of development (Lager *et al*., 2010; Rösiö and Bruch, 2018) means that the level of formalization is generally low in the FFE, and the information tends to be informal and approximate (Kim and Wilemon, 2002a). Thus, it is often chaotic, unpredictable, and unstructured (Koen *et al*., 2001), further characterized by uncertainty and ambiguity (Zhang *et al*., 2019). The state of ideas tends to be fuzzy, and thus, it is easy to change or reject them in this stage (Kim and Wilemon, 2002a; Kurkkio, 2010). In general, there is no budget, or only a very small one (Kim and Wilemon, 2002a). In addition, the FFE is shown to be a crossroads of complex information processing, tacit knowledge, and conflicting organizational pressures (Khurana and Rosenthal, 1997). Due to the complex nature of the FFE it is considered the most difficult phase to manage (Kim and Wilemon, 2002a). In the front end, the nature of work is experimental and difficult to plan (Kurkkio, 2010), and thus, the management method is generally unstructured and experimental in nature, requiring creativity (Kim and Wilemon, 2002a). Hence, it is reasonable to assume that explorative work (exploratory capabilities) is a key characteristic and practice in managing the front end.

2.2 Exploration practices in production innovation

The concept of exploration is most easily described in relation to its antonym, exploitation. The two concepts have been widely researched since they were introduced in the early nineties (March, 1991). Exploitation includes refinement, choice, production, efficiency, selection, implementation, and execution; while, exploration involves aspects captured by such terms as search, variation, risk-taking, experimentation, play, flexibility, discovery, and innovation (March, 1991). The concepts aim to achieve different objectives, and thus, require different strategies, processes, capabilities, and structures, and may also have different impacts on the organization's overall performance (March, 1996). While exploitation aims to boost efficiency, reliability, and standardized processes, thereby applying a more short-term and

specific perspective, exploration aims to create new ways of doing things, and is often related to distant search and activities with greater risk for a company (Levinthal and March, 1993; March, 1996).

Thus, exploratory practices are about the pursuit of new knowledge and new ways of doing things (Levinthal and March, 1993; Benner and Tushman, 2002; Atuahene-Gima, 2005; Mom *et al*., 2007). This pursuit requires external (distant) search, rather than internal search (March, 1991; Ahuja and Katila, 2004). In fact, the more diversified the search is, the greater degree of exploration (Ahuja and Katila, 2004). Exploration is also about experimenting (March, 1991; Holmqvist, 2003; Bierly and Daly, 2007; Prange and Schlegelmilch, 2009), constantly testing, researching, and investigating new ideas. As businesses generally strive for the creation of new things, or even radical innovation (March, 1991; Benner and Tushman, 2003), a high degree of novelty of the ideas generated is called for (Atuahene-Gima, 2005). Therefore, in order to manage exploration, play (March, 1991), free association (Holmqvist, 2003), and the ability to make ample choices (Chaharbaghi, 2007) are highly advocated for success. In addition, team diversity (Perretti and Negro, 2006; Chaharbaghi, 2007), including variety in experience among participants (Holmqvist, 2003), is strongly recommended. Consequently, exploration involves a high level of risk-taking (March, 1991), and therefore, the end results are uncertain and non-predictable (Prange and Schlegelmilch, 2009).

Managing the FFE is a balancing act between exploiting existing capabilities and dynamically exploring new ones (O'Reilly and Tushman, 2004; Gassmann and Schweitzer, 2014). This issue has been discussed by scholars in terms of incremental and radical innovation, which is closely linked to the notion of exploitation and exploration. For instance, McLaughlin *et al*. (2008) state that incremental and radical innovation can arguably be considered as two different cultures, since their inherent mindsets are fairly different. While incremental innovation is characterized by exploitative initiatives focused on reducing costs and increasing profits, in a more formal and systematic structure as well as a culture of efficiency and low risk, radical innovation is characterized by exploration, and applies a more adaptive structure with a culture of risk-taking, speed, flexibility, and experimentation (O'Reilly and Tushman, 2004). For an organization to successfully master exploration, a culture of exploitation is considered a prerequisite. However, such a culture may simultaneously hinder exploration due to the inherent mindsets being so diverse (McLaughlin *et al*., 2008). Furthermore, it is well known today that manufacturing organizations tend to solely focus on operational day-to-day efficiency, continuously improving themselves through exploitation (Benner and Tushman, 2003; Hill and Hill, 2009). Thus, establishing exploration practices in an environment characterized by exploitation may be a challenge (Backström *et al*., 2017).

3. Research methodology

3.1 Research design

To gain in-depth knowledge related to the research questions, a single longitudinal case study with a qualitative research design was applied. This is a proper research design for many reasons: (1) it provides the opportunity to apply different sources of data-collection techniques, such as interviews, observations, and documents, thereby enabling a rich set of empirical data to be gathered (Voss *et al*., 2002); (2) it prevents relevant behaviors from being manipulated as contemporary events are being studied (Yin, 2013); (3) it is appropriate for developing theory and proposing new concepts (Voss *et al*., 2002; Eisenhardt and Graebner, 2007); and (4) it is preferable for studying the iterative and complex nature of the early phases of production innovation (Chang *et al*., 2007). Furthermore, single-case studies are often selected for their depth of insight into complex, dynamic processes that are difficult to capture with broader methods. They allow researchers to examine causal mechanisms, interactions, and developments over time in great detail, which can provide valuable theoretical insights. In this study, the justification for using a single case rest on the idea that the chosen organization is

representative of broader industry trends in the multinational automotive manufacturing sector.

The main sample criterion was to identify a manufacturing company that had the strategic intent to achieve production innovation. A large global manufacturing company in the automotive industry was selected, and more specifically, the production development department at one of the company's lead factories. During the case study, the department, whose core tasks included the long-term development of the production system at the factory, consisted of three to six development engineers and their manager (during the second part of the case study, three engineers were reorganized to other departments due to layoffs during a recession).

The case study was conducted over approximately 2 years in its natural environment, and meaningful and relevant empirical data were generated from observing the practice (Karlsson, 2009). One of the researchers (the first author) closely followed and interacting with the development engineers in their office space, discussing work-related issues and socializing together. This close encounter enabled the researcher to overhear discussions and arguments consistently. When conducting a case study over a long period of time in a social setting characterized by intensive work together with a few individuals drawn from that setting, the information derived is a form of "cultural description" (Van Maanen, 2011). Hence, this research could be described as an ethnographic-inspired approach (Kaijser *et al*., 2011; Van Maanen, 2011). To develop an in-depth and credible understanding of the social reality of the studied group, the following eight steps in the ethnographic approach have been used to enhance validity through-out the research process.

(1) Choice of research question and planning: The research approach started by formulating clear research questions and planning how to conduct the research study. This includes defining which society, group, or culture to be studied and what the researcher wants to understand and interpret.

(2) Fieldwork and establishing contact: The researcher (first author) entered the chosen environment to observe and interact with the participants. This way to establish trust and to build relationships to access more authentic information.

(3) Participant observation: In this phase the participants' behaviors and social interactions over time was observed and noted. This implied both participating in activities and observing them from a distance. Through this step, the researcher gained a deeper understanding of the group's everyday life, norms and values.

(4) Collection of data through various methods: In addition to observations, the research study was designed with interviews, informal conversations, workshops, department meetings, and project meetings. Diaries and logbooks were used to collect data. These methods helped to create an overall picture of the group's perspective.

(5) Data analysis: Once the data collection reached empirical maturity, the analysis was made to identify themes, patterns, and key insights. The analysis was iterative, with the researchers going back to field notes and data several times to deepen the understanding and interpretation.

(6) Theory development and interpretation: After the analysis, the new formulates theories was developed with interpretations to explain the phenomena observed. These were related to existing theory and research. The aim was to develop insights that can be applicable in a broader context than just the studied group.

(7) Writing and reporting: In this later phase the compilation of results was made to describe the observations, the identified themes and theories. Quotes and stories from the participants were included to illustrate the findings and to give the reader an insight into the group's perspective.

(8) Reflection on the role of the researcher and ethics: Finally, the researcher's own influence and role in the study was reviewed and discussed, as ethnographic research is subjective in nature and the researcher's presence could influence the participants.

3.2 Data collection

To achieve the research purpose, several data-collection techniques were applied, including semi-structured interviews, participant observations, reading internal documents, and field notes. Interviews were conducted throughout the case study; this is a preferable approach, as it is considered very efficient for obtaining rich empirical data (Eisenhardt and Graebner, 2007). In line with this being an inductive and exploratory case study, the interviews were conducted from the perspective of the traveler, implying an exploratory and free search in an unknown territory (Kvale and Brinkmann, 2014). As such, the interviews were conducted in a semi-structured manner based on topics of interest raised throughout the case study. Specifically, 21 interviews were conducted over 44 h at the case company, focused on four topics. (1) Role description—what does being a development engineer in the FFE entail? (2) Description of the production innovation process—how is the FFE of the production innovation process undertaken? (3) What are the main challenges of working in the FFE of the production innovation process? (4) How do exploratory practices manifest in the FFE of the production innovation process? All interviews were recorded and transcribed.

Participant observations were another main data-collection technique as 330 h were spent observing the practice under study, which was documented continuously by writing field notes on statements, ideas, and narratives. Given the vast amount of time spent at the company, including informal time spent with the engineers, attending meetings, and workshops, the field notes provided not only rich empirical data, but also served as the common thread in the data collection. The participant observations were derived from informal conversations, workshops, and meetings. The informal conversations were the result of the researcher spending about 185 h with the development engineers in their office setting, thereby enabling vast contextual and cultural understanding (Van Maanen, 2011). Second, a series of workshops were held consistently throughout the case study. In these workshops, the researcher made statements, proposed ideas, and posed questions, and participants discussed the topic. In total, 42 workshops were held, totaling 61 h. Throughout the workshops, a wait-and-see approach was applied, thereby allowing the participants to discuss issues among themselves; the researcher focused on posing further questions to keep the discussion going.

All comments and statements affecting the FFE of production development were noted, and important findings were documented in the field journal. In addition, meetings were attended consistently throughout the case study. The researcher attended 52 department meetings in which the development engineers discussed current and future projects, specifically, their main project ("the factory of 2030"), activity lists, and production innovation practice, relating to methodology and support. In addition, the researcher attended 12 project meetings, focusing on various forms of production development, such as new products introduced to the factory. In addition, the researcher scrutinized some internal documents on role descriptions, strategy, and specific projects as well as project model handbooks and activity lists. See Table 1 with a summary of the empirical investigation and data collection methods.

3.3 Data analysis

The empirical data were analyzed iteratively in five phases following the guidelines of Yin (2013). In the first phase, the data were gathered and compiled in a structured way using an Excel sheet, including transcribed data from interviews, observation protocols, document statements, and narratives from the field journal. In the second phase, the data were broken down into the general areas that were empirically explored (Miles and Huberman, 1994; Corbin and Strauss, 2008). Following, the authors decided on four codes to employ for the data

Table 1. Summary of the empirical investigation and data collection methods

Data collection techniques	Number of activities	Time
Interviews	21	44 h
Participant observations	Documented continuously	330 h
Informal conversations	Documented continuously	185 h
Workshops	42	61 h
Department meetings	52	52 h
Project meetings	12	12 h
Summary	127	684 h

Source(s): Authors' own work

analysis. Since the research focused on exploratory practices in the FFE of production innovation, the codes were derived from literature on exploration, and specifically, key exploration characteristics: (1) experimentation and play, (2) idea generation and novelty of ideas, (3) external search and discovery, and (4) pursuit of new knowledge. In the third phase, the data were reassembled according to the four codes. Hence, a new tag in the Excel document was created. In the fourth phase, the data were interpreted, and a comprehensive picture emerged. In this phase, first, the codes were analyzed separately, and the key findings related to the research questions were highlighted.

Second, the data in the four codes were reassembled into two themes: (1) "discovery of new opportunities," comprising the previous codes experimentation and play, and idea generation and novelty of ideas; and (2) "in pursuit of new knowledge," comprising the previous codes external search and discovery, and pursuit of new knowledge. Next, these two new themes were analyzed comprehensively, and an overall picture emerged. The findings were then synthesized accordingly. In the fifth and final phase, conclusions were drawn based on the previous interpretations and overall picture. Since the collected data were empirically rich, the voice of both the informants and the researchers was advocated, as doing so allowed for "*the kind of insight that is the defining hallmark of high-quality qualitative research*" (Gioia *et al.*, 2013, p. 18). As such, the empirical data can be presented transparently, including rich empirical descriptions and quotations. To create overlap between the data collection and data analysis, frequent discussions and preliminary analysis of emergent findings were conducted by the authors.

4. Findings – exploration in the fuzzy front end of production innovation

This section presents the empirical findings. First, this paper sets the scene by disclosing how the engineers, working at the production development department, engage in production innovation activities. Second, RQ1 "What characterize the fuzzy-front end of production innovation?" is discussed.

4.1 The production development department

The PSD department is a small unit consisting of a manager and three to six development engineers, organizationally placed as a part of the factory plant. The development engineers are selected based on their extensive experience in production development and engineering. According to the unit's functional description, it is both their responsibility and their purpose *"to optimize the current production system as well as to develop the future production system."* Therefore, the engineers engaged in a wide range of development activities. Elaborating on the department's responsibility during an interview, one of the engineers stated: "*The work differs tremendously in character. Some tasks are more exploitative, some constitute a mix, and some are more exploratory.*"

In fact, the development engineers described their day-to-day work to consist of a mix of projects, emphasizing that it was difficult to undertake only exploratory work in which "*you often find yourself fumbling in the dark*." During an interview, one of the engineers stated that they worked with "*optimizing current production versus creating new stuff about 50–50*". The projects related to "creating new stuff", that is, exploration of new opportunities, generally focused on new technology and/or new ways of working. For instance, one of the main projects the department was working on during this case study was "The factory of 2030." In this project, many considerations for the future had to be assessed, including emerging trends and new technologies, such as digitalization and electrification, and at the same time, the mix of current and new products, as well as their respective volumes had to be considered. Consequently, make-or-buy decisions had to be made accordingly. In addition, such issues as capacity, equipment, flow, and layout had to be investigated, thereby highlighting the complex nature of such an all-encompassing project.

At the case company, production innovation activities were mainly being initiated in two ways; by the development engineers at the PSD department themselves, or by top management. When new initiatives originated from top management, they already had legitimacy. However, when they were initiated by the PSD department, as was often the case, the ideas generally had to be discussed with top management before a decision was made regarding whether and how to proceed. This process consumed a lot of energy, and, according to the development engineers, also "*hinders radical change*." Consequently, the development engineers chose to engage in what they referred to as "*informal development*" instead, as pointed out during a workshop: "*Since we have to push through our own ideas, I like to work under the radar as much as possible.*" This statement was confirmed by the other engineers. According to the development engineers, working "*under the radar*" was characterized by a low level of bureaucracy with few requirements for management oversight, reporting, and administration in general and thus, enabled free scope. As the starting point of informal development was often a vague idea, there was generally no defined customer at this point. As such, the development was characterized by a high level of uncertainty. This is in contrast to formal development activities, which the development engineers defined as controlled, thereby including directives, time plans, responsibilities, approvals, steering groups, and cross-functional teams. As such, the development engineers stated that formal development activities were "*killing creativity*" compared to the informal development activities. Therefore, the engineers embraced the freedom derived from informal development, and chose to engage in working under the radar to a large extent. This was further explained by one of the engineers during an interview:

> "Most of us just want to work as freely as possible without any rules or administration. I don't think any one of us really wants steering groups and being required to report all the time. We want to work in peace."

During a workshop on informal development activities, a discussion about leadership arose. The engineers mutually praised the level of discretion they were granted within the department. One of them revealed, "*We have rather free scope as we can basically do as we like.*" One of the fellow engineers concurred: "*Yes, and I think this really contributes to our creativity.*" However, eventually, the informal development initiatives had to be run by top management, which, according to the engineers, "*hampers exploration a bit,*" as priorities then seemed to be skewed toward short-term optimization rather than innovation and long-term success.

4.2 Discovery of new opportunities

A critical element of radical innovation and production innovation is to discover new opportunities that later can be turned into a new future state of the production system. To discover such new opportunities, experimentation and idea generation practices become critical.

4.2.1 Various degrees of experimentation and play. During a workshop, one of the more experienced engineers referred to a successful example of experimentation. The task concerned the introduction of a new product, which required change in the assembly line. In this case, the engineers used new technology to experiment as they created material artifacts representing the future state. One of the engineers clarified: "*Since every article was physically 3D-printed it was easier to discuss how they were to be assembled in the future,"* followed by *"I can certainly see the value of it.*" However, aside from this example, the level of experimentation and play in the FFE process seemed to be rather low. In fact, during an interview, one of the development engineers stated that "*In general, we are very bad at experimentation*." This was further emphasized by an engineer who, during his interview, stated that they did not experiment much. As further illustration, he referred to an example:

> "We had ideas to use Lego in order to visualize the layout and production flows, experimenting with how machines and cells could be moved around and adapted to the future prerequisites. However, it never came to happen. Probably out of habit."

A possible explanation for the lack of experimentation was expressed by one of the engineers during a lunch break:

> "It is not only the development engineers who get themselves into distress when things become too fuzzy, it has to be communicated to others as well."

4.2.2 Idea generation—"too fuzzy" or "copy-paste"?. One of the engineers revealed that for production development projects, when discussing possible future solutions, many colleagues—mainly outside the production development department—tended to apply a "*copy-paste*" of the current set-up, if it was possible to do so. This was further emphasized in an interview in which another engineer argued that when conducting informal development, it was "*ok*" to deliver uncertain results. However, simultaneously, he revealed that "*outside of our department, when working in formal pre-studies, the acceptance is rather low.*" During an interview on formal versus informal development, one of the more experienced engineers stated that, "*In the case you have a formal project I don't think it is acceptable to not come up with a result, or something that is too fuzzy.*" This was further explained during a subsequent workshop on pre-studies, where the engineers generally constituted steering groups, by which these types of results were said to "*being picked up*" early on. Following this explanation, one of the engineers argued that, regarding this "control," "*we are probably locking ourselves into one specific solution way too early.*"

Fuzzy ideas whose perceived degree of novelty was higher tended to be initiated by the engineers within the production development department themselves. Regarding the methodology, brainstorming was their commonly used approach for idea generation, regardless of the objective of the exercise. This was emphasized by one of the development engineers:

> "As soon as we don't know what or how to do something, we return to our standard tool, the yellow-post-it practice. When there, we don't put too much effort into what to actually generate ideas about, but rather just say let's go!"

Moreover, considering idea generation, one of the engineers expressed that "*if you open up to new solutions, the fuzzier ideas you get, and the harder it becomes to evaluate*." He further clarified that, as a consequence, many ideas were "*discarded early on in the fuzzy stage, as you only evaluate them in your own head*," implying that the ideas were never actually shared in the development setting.

4.3 In pursuit of new knowledge

In regard to new knowledge, there are two types to pursue: specific and unbiased knowledge. In addition, there are in general two domains to search: internal and external domains.

4.3.1 Specific and unbiased knowledge. The pursuit of specific knowledge was rather common, as an engineer was introduced to a new assignment or project, thereby requiring new

knowledge on a specific topic, such as assembly, materials, and logistics. There was less pursuit of more unbiased knowledge, being "*up to date*" regarding trends that have an effect on the production system in the general sense, even though it was recognized by the engineers as an important prerequisite with regard to the department's responsibility for the long-term competitiveness of the factory. Within the department, this kind of activity was given low priority, and the respondents argued that it was more difficult to motivate for unbiased knowledge within the organization, as it not only took resources from an already streamlined organization, but also lacked clear purpose from an organizational point of view. This was explicitly stressed by one of the engineers, who stated that "*the company thinks that going to a trade fair without having a clear purpose is a waste of resources.*" He further defined "*clear purpose*" as new knowledge that could be capitalized in the short term, and that a trip without such a purpose "*sure would feel like a luxury trip.*" This issue was further emphasized by the department manager, who stated that "*we are way too poor in pursuing new knowledge.*"

Consequently, the pursuit of new knowledge was mostly undertaken within the plant, and to some extent outside the plant through company benchmarks or calling established contacts at consulting firms, partner companies, or universities. During an interview, one of the engineers explained that:

> "Personally, I google around for new knowledge. I try to find papers, theses, case studies, master's theses, etc., in order to get inspiration, and to immerse myself in the field of inquiry. In addition, I do some benchmarking too, not only for the sake of study, but to discuss with a third party as well."

At a later workshop, a fellow engineer stated that he was trying to keep close contact with the local university, but there unfortunately was low interest from the rest of the department. The engineer further explained that there were several PhD students working at the plant, and they sat close by, but had very little collaboration with the engineers.

> "I've had a little collaboration with a few of them, but that's because I personally think it is important, the company doesn't communicate it being of importance. This is not ok."

The most senior engineer shed further light on the issue during a lunch-break discussion. In despair, he vocalized what he considered to be a big problem: they saw such a big gap between research and practice, which resulted in them not fully seeing the point of working close together with the researchers.

4.3.2 External search and discovery—a non-priority?. It was entirely up to the development engineers themselves to decide what and how to undertake external search and discovery. During an informal conversation, one of the engineers stated:

> "For instance, when at a meeting with a steering group or management team, they never ask if we have been looking around to see what others do, or what the emerging trends are in a related area."

Thereafter, one of the engineers pointed out that, in fact, nobody undertook external search and discovery. In a later stage of the case study, one of the engineers explained that to travel, a clear purpose was generally required. He further said:

> "If it's aligned with a current project it is generally fine, but if it is more about just gaining a general understanding about what is going on in a field, not so much."

Travel for external search was recurrently referred to as being one of the activities that "*most easily is cut down due to prioritization reasons.*" In addition, for external search with regard to formal projects included "*inviting experts or visiting other companies within our company group.*"

During an interview, one of the development engineers said that some time previously he had been assigned a task to create a benchmarking plan, including such questions as "*What trade fairs do we need to attend*?" and "*How are we tracking what is happening in our sphere?*" However, he revealed that the task was not given priority, and subsequently, how the department operated did not align with its ambitions, indicating there was some willingness for

external discovery. This fact was emphasized throughout the case study. For instance, the department manager stated that:

> "In general, I think we lean towards internal search in our day-to-day business, but we probably ought to widen our perspective to look externally to a greater extent as well."

This finding might be explained by economic challenges, which were widely emphasized throughout the case study. During an informal conversation with two of the engineers, one of them stated that "*everything we do is controlled by the economy, and we are supposed to make money on everything we do . . . making a business case in the early stage is not that easy.*" Thus, exploratory practices appeared to be hampered by economic objectives, as further clarified by an engineer:

> "In general, we think that if something is costing money, it is always bad, even though it might be a great investment for the company."

4.4 Mind the gap – managing boundaries in the fuzzy front end of production innovation

Operating in the FFE is held as a critical phase in the development of new innovative opportunities, even in the context of innovative production development (Yamamoto, 2018). As the case in this study, "the future factory" is one of the PSD department's core tasks, it would be reasonable to expect that the FFE and innovative practices would emerge as key characteristics of the department. However, the empirical findings revealed that innovative and exploratory practices were not yet institutionalized or supported by a set of organizational routines (Nelson and Winter, 1982). On the contrary, the exploratory practices were very much carried out individually, and were simultaneously organizationally disregarded in favor of the strong exploitative practices that seemed to be deeply rooted within the organization. While the "individual carrying of exploration" was manifested through the informal development initiatives run by the development engineers as they worked "under the radar," the organizational disregard for exploration was displayed through the fact that routines, resources, mindsets of managers and employees outside the PSD department, and organizational support worked in favor of exploitation of current practices. Hence, there were few carriers of the exploratory practices.

Regarding routines, the empirical data revealed that the initiation process of new development initiatives clearly hampered exploration, as management and fellow departments only asked for exploitation, while exploration needed to be pushed through the system, and had to be heavily argued for. Consequently, the initiation practice systematically constrained exploration. Second, there was a total lack of methodology and guidance on how to undertake exploratory and innovative work in practice, and as a result, the engineers applied ad-hoc approaches in which they tended to fall back on methodologies and tools used for exploitation, as it was their go-to practice and what they knew best.

Regarding resources, the engineers stated that it was difficult to motivate within the organization for external search for unbiased knowledge as it not only consumed resources, but from an organizational point of view, also lacked clear purpose, that is, there was no short-term benefit associated with it. Thus, external search was systematically given low priority and often cut down early. In addition, there was an ongoing economic challenge to overcome. The respondents stated that the "general culture" required them to make money on everything they do. As a result, exploratory work, which is associated with unpredictable results and higher risks, was disregarded in favor of exploitation in which results are typically more predictable. Furthermore, the mindset displayed at the case company heavily suggested that exploratory work was held back in favor of exploitative work, as there seemed to be systematic and cultural mistrust toward what was perceived as "too fuzzy." While more novel ideas tended to be developed by the engineers in the PSD department, their colleagues outside the department generally applied a "copy paste" mentality when possible. Moreover, the empirical data

indicated that it was not acceptable to come up with an idea that was considered "too fuzzy" when working on formal projects, such as pre-studies. As a result, working with fuzzy ideas not only resulted in more work, but also created general distress. Thus, as a countermeasure, the engineers sometimes self-sensor and discarded their own ideas early on if they thought that their colleagues would perceive them as "too fuzzy."

Finally, the case clearly revealed a lack of organizational support toward exploratory practices. First, exploration was not even considered "real work" by several colleagues outside the PSD department. Thus, even though exploration was at the core of the engineers' job description, they constantly felt the need to justify this kind of work. Second, there was a big difference in what was claimed to be important, and what management complied with. While the case company emphasized the strategic importance of establishing exploratory and innovative practices, the empirical findings indicated the opposite situation in practice. (1) Exploration had to be "pushed through" the system, implying the challenges and difficulty with such projects and possible resistance to them. (2) When projects were initiated by management, they were typically aligned with exploitative work. (3) The engineers engaged in exploratory work argued that neither top management nor colleagues from other departments ever asked about new trends or what was generally happening in their sphere. Put simply, nobody showed any interest in exploration.

Linear project models are functioning when the engineers know what to do and what to achieve. However, in the fuzzy-front end, companies still do not know what the future direction is, and therefore a different set of ways of working are necessary allowing to search for the unexpected. The findings indicates that there is a challenge in keeping track of the fuzzy front end, that is, there is a struggle for the engineers to stick to the kind of exploratory work that contributes to future production innovation. Instead, they gravitate towards the exploitative tasks explicitly and implicitly required by management. To summarize, there is no (1) formal accepted innovation process in the organization, (2) Top management decisions drive a linear exploitative process, (3) there is no systematic structure for exploration in the FFE, and (4) there is an informal enacted process for exploration in the FFE. See Figure 1.

5. Discussion

Knowledge about how to manage the FFE in production innovation is scarce today, and this is especially true for how to enable exploration in a manufacturing context. Hence, the purpose of this paper is to increase the understanding about exploratory practices in the FFE of production innovation. The purpose is achieved by providing extended knowledge about how exploratory practices are manifested in a large manufacturing company (RQ1), and, also, what is required for exploratory practices to emerge and become established in this setting (RQ2). The case study revealed that even within the PSD department—which was assigned the formal responsibility for the future factory, there was a tendency to favor exploitative practices at the expense of exploratory practices. This finding could be explained by the fact that work activities related to exploratory practices were mostly disregarded by senior managers and staff outside the PSD department. Exploratory work tended to be undertaken individually by

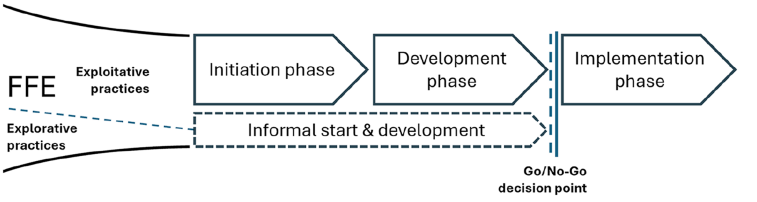

Figure 1. The boundaries between the FFE and the structured processes for production innovation. Source: Authors' own work

the development engineers themselves. In other words, there were few established structures or routines to support exploration of new opportunities, and the mindset of the mainstream engineers in the company was heavily influenced by exploitative logic. In conclusion, there was an obvious unbalance between exploration and exploitation even within the department where exploratory practices are expected to be the most vivid. To address RQ2, what then is required for exploratory practices to emerge and become established?

5.1 Balancing the unbalanced

Due to its complex and uncertain nature, working in the FFE of production innovation is very challenging, and thus, difficult to manage (Trolle *et al*., 2020). Managing the FFE is a matter of balancing exploitative and exploratory capabilities, and according to Gassmann and Schweitzer "It is the art of identifying and understanding contradictory and complementary forces, supportive and counterproductive influences, and of providing the necessary framework, resources, and conditions to cope with these forces and influences" (2014, p. 8). Thus, managing exploration requires active engagement by management to create a conducive environment for exploratory work to thrive. However, in practice, it is not easy to translate into managerial actions and practices. Even though previous research has explicitly addressed the need to become more innovative, creative, and exploratory in a production innovation context (Stewart and Raman, 2007; Yamamoto, 2013; Rosemann, 2014; Ng *et al*., 2015; Södergren, 2016), there are no definite objectives guiding what to pursue or the extent to which exploration is desired. From the outside, the level of exploration of new opportunities revealed in the case company may seem rather slim, but then again, how much exploration is actually required or desired in a production innovation context as it also has to be synchronized with the interrelated product design development (Larsson and Romero, 2023)? Is this case an example of failure? How does this company perform in comparison to its peers? Finally, what conditions are necessary for an exploratory practice to emerge in this context?

The findings clearly indicates that, to achieve a balance between exploitative and exploratory work, forces and incentives need to be balanced too. Based on the empirical analysis, we do not advocate for a 50/50 balance between the two practices, but rather argue that if an exploratory practice is sought to some extent, the forces and incentives ought to be aligned accordingly. Since exploitation is and likely ought to be the predominant practice in a production development setting, it comes down to balancing the unbalanced, that is, finding a way for both practices to co-exist in whatever distribution is considered appropriate. Given these contextual circumstances, how can the emergence of exploratory practices be supported in this context? According to Gassmann and Schweitzer (2014), it would require providing the necessary conditions to cope with the forces and incentives in play. This implies that routines, resources, mindsets, and organizational support need to be aligned with the balance of practices desired.

In reality, this denotes that the initiation process should not systematically hamper exploration. To avoid hampering exploration, our research suggests three broad categories of critical prerequisites to consider for exploratory practices to thrive in the FFE of production innovation:

Culture and training:

(1) Organizations should recognize and support informal development activities that allow engineers to explore new ideas without excessive bureaucratic constraints.

(2) Cultivate a culture that encourages experimentation and play, such as using 3D printing or other prototyping tools, to visualize and test new ideas. This can help in better understanding and developing future production systems. Encourage open communication and acceptance of "fuzzy" ideas to ensure they are shared and developed.

(3) Engineers and managers engaged in exploratory work should receive training on how to conduct it properly, preventing reliance on ad-hoc methodologies and the tendency to revert to exploitative practices.

Resources, practices and follow-up:

(1) Resources should be allocated based on strategic importance rather than convenience or established norms.

(2) Allocate resources and provide support for engineers to engage in external knowledge acquisition, such as attending trade fairs, collaborating with universities, and benchmarking against other companies. This can bring fresh perspectives and innovative ideas into the organization.

(3) Exploratory work must be evaluated according to its own characteristics rather than through the lens of exploitation. This means that, for example, business-case models or gate systems used in exploitative projects are not suitable for exploratory work.

An ambidextrous approach:

(1) Organizations need to raise awareness about the nature of exploration, fostering not only acceptance of "fuzzy" ideas but also an understanding of their role in product innovation. This is of utmost importance, as this case study reveals that ideas might otherwise be dismissed before even being shared among developers.

(2) Develop a balanced approach that values both exploitative and exploratory practices. This includes creating routines and methodologies that support exploratory work and aligning incentives to encourage innovation.

In conclusion, if exploration is considered strategically important for the company, it should not only be supported but actively required by the organization. The alternative, as shown in the case study, would likely lead to a steady decline in exploratory work. In a system designed for exploitation, only a few enthusiastic engineers engage in exploration. Over time, even their enthusiasm may fade—or worse, they may choose to leave. By considering the identified prerequisites organizations can better manage the fuzzy front end of production innovation, fostering a more balanced and innovative environment.

5.2 Practical implications – shifting organizational mindset and scaffolding FFE

The findings in this study are particularly relevant for production engineers and plant managers interested in enabling and achieving more innovative and radical change in manufacturing. The article provides practical implications that addresses two critical building blocks in managing exploratory work in PSD. First, the framework describes and defines the FFE from a PSD perspective. Second, explorative practices are described as a critical capability in managing exploratory PSD. Furthermore, the paper shows that little exploratory work is taking place, even in a production system with a high level of functional integration where exploration is expected to be the most vivid. The exploration that does take place is carried out in informal development initiatives "under the radar" driven by individual enthusiasm. Simultaneously, exploration is widely disregarded by the organization, displayed through the way routines, resources, mindsets and organizational support are heavily favoring exploitation. Moreover, the research indicates that, for exploratory practices to emerge in the FFE of PSD, it would require "balancing the unbalanced." Thus, managing exploratory practices in the FFE of PSD would not be about creating an even balance between exploitative and exploratory practices alike. Rather, it would entail creating the scaffolding conditions necessary to systematically run both practices in co-existence in whatever distribution desired.

Hence, to successfully shift the organizational mindset in managing FFE in production innovation, leadership must actively support exploratory practices, even though it might be for only a temporally limited part of the work. Without visible commitment, innovation efforts risk being deprioritized. Furthermore, engineers and managers need training in structured methodologies to avoid reverting to exploitative work. Establishing cross-functional collaboration can integrate exploration within mainstream development processes.

5.3 Conclusion and future research

The research contributes new knowledge and reasoning on (1) how FFE operates in relation with general PSD practices, but also (2) offering enablers for managing boundaries in the FFE before a PSD process begins. It rather depends on the organization's capabilities in managing boundaries between explorative and exploitative work in the FFE.

Theoretically, the research contributes to the ongoing discourse on FFE conceptual frameworks by building on the theoretical foundations of Koen *et al*. (2001) and their NCD model, but also to Reid and de Brentani (2004) regarding FFE management in product innovation under high uncertainty – in this study expanded to the context of production innovation (Larsson and Romero, 2023). While the article developing the context of FFE conceptual frameworks, it uses the context of organizational culture and team dynamics by illuminating how team structures and organizational culture shape the capability of in FFE phase. In line with Neukam (2017) it explores strategies for managing the FFE within diverse teams, offering new insights into the complexities and advantages of diverse team environments when the explorative work is preceding any stage-gate processes. Hence, it contributes to the discussion on innovation and stage-gate models (Cooper *et al*., 2004) in production innovation, by enriching this discussion through highlighting the positive impact of cross-functional teams and a supportive company culture on FFE outcomes, suggesting that well-integrated, collaborative teams can accelerate production innovation. Expanding on this, the article contributes to the research by Kijkuit and Van den Ende (2007) regarding analysing how internal network dynamics influence the early stages of production innovation, underscoring the role of organizational networks in fostering creativity and reducing uncertainty in the FFE. Together, current research study contributes with contemporary new perspectives on the interplay between organizational culture, team composition, and production innovation capability during the FFE phase.

Moreover, managing boundaries in production innovation also facilitates the long-term strategic PSD process by enabling early integration of novel ideas and feedback, ensuring alignment with customer and stakeholder needs (Ahlskog, 2019; Larsson and Romero, 2023). It fosters flexibility and adaptability, allowing production engineering design teams to adjust to new information and requirements. It promotes cross-functional collaboration, ensuring that departments are aligned with the production system's goals. Prototyping aids in testing new concepts, while early risk identification helps in mitigating risks. By allocating resources efficiently, it also aids in optimizing resource allocation. Fostering production innovation in the FFE can provide a competitive advantage and encourages sustainable, long-term PSD strategies.

While current research study is conducted in an automotive manufacturing PSD context, future research should involve original equipment manufacturer PSD to increase the understanding about how exploratory practices are manifested in this context. Second, more research is needed to address how to balance the co-existence of exploitative and exploratory practices in the PSD setting and on what level of exploration is desirable in this context. Future research should also incorporate data triangulation to enhance validity and reliability. By providing contextual depth to qualitative findings and supplementing them with insights from quantitative performance metrics—such as idea generation and screening metrics, production engineering insights metrics, resource and efficiency metrics, and speed and time-based metrics —future studies could better contextualize the results and identify underlying patterns in the FFE of production innovation.

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