The Front End in Radical Process Innovation Projects: Sources of Knowledge Problems and Coping Mechanisms

Simms, Christopher.[1.], Frishammar, Johan[2.]., and Ford, Nicholas.[1.]

[1.] Faculty of Business and Law, University of Portsmouth, Richmond Building, Portland Street, Portsmouth, PO1 3DE.
[2.] Lulea University of Technology, 971 87 Luleå, Sweden.

Corresponding Author Email Address and Telephone Number:
Telephone Number: +447813929115
Email: chris.simms@port.ac.uk

Abstract

When companies in process industries take radical leaps in product innovation, these new products often fall outside the "process window" of existing production processes and hence require extensive production line modifications and radical process change. Consequently, firms need to deal with high degrees of uncertainty, complexity, equivocality and ambiguity in the front-end. These four knowledge problems constitute important challenges to managers and engineers when a new process definition is created. Prior research into the front end of process innovation is limited, and for radical projects close to non-existent. We analyse six radical process innovation projects situated in the food processing industry in the United Kingdom and provide three key contributions. First, we uncover the underlying sources of knowledge problems, and the specific coping mechanisms used to address them. Second, we offer a framework that delineates the relationships between the sources of knowledge problems, the knowledge problems per se, and the coping mechanisms which enable more effective decision-making regarding the creation of process concepts and definitions. Finally, we extend prior studies of the front end by revealing the challenges faced with respect to ambiguity, thus providing a more granular understanding of fuzziness. Altogether, these findings provide important theoretical and practical implications.

Keywords: Process innovation; process industries; front-end; radical innovation

Highlights

- This paper investigates the front end of radical process innovation.
- Detailed analysis of the sources of knowledge problems are provided.
- Coping mechanisms to manage each type of knowledge problem is uncovered.
- A framework which enables more effective creation of process concepts and definitions is provided.

1. Introduction

Despite their important contribution to modern economies, the process industries have received a disproportionately low level of attention in the literature (Lager, 2017b). Process industries include chemicals and petrochemicals, mining and metals, mineral and materials, generic pharmaceuticals, pulp and paper, food and beverages and similar industries (Lager, 2010). The process industries are characterised by inputs and outputs that are materials or ingredients (Lager, 2000; Pisano, 1996) rather than assembled components. Critically, these industries are also characterised by high capital intensity and strong interrelationships between product and process innovation (Reichstein and Salter, 2006; Tang, 2006; Lager, 2002). The combination of high capital intensity and standardised product output often results in long product and equipment lifecycles and a reluctance to pass away prior investments (Novotny and Laestadius, 2014; Pisano and Shih, 2012; Upton, 1997). Current equipment is thus a source of lock-in and inertia, and represents a significant challenge when radical leaps in product innovation are required. New products need to be produced on existing production equipment, yet current equipment often does not meet their processing requirements.

For radical product innovations to occur, firms must radically innovate their existing production process. The significance of this to long-term competitiveness was highlighted by Aylen (2013), who found that over a period of over forty years firms in the wide strip mill industry extended and modified equipment multiple times in order to continue to deliver the new products sought. Yet, such innovation projects present significant challenges. Frishammar et al. (2012) revealed that radically new products typically break the current "process window", which refers to the set of boundary conditions for existing production development. Major changes to equipment are then required (Lager and Frishammar, 2012; Kurkkio et al., 2011). Moreover, the systemic nature of process innovation often results in wider changes in other parts of the firm, including reward systems, HRM policies and distribution channels (Damanpour and Gopalakrishnan, 2001). Managers are also required to pool the competencies of multiple actors collaborating across firm boundaries with multiple suppliers and others (Rönnberg-Sjödin et al., 2016; Hutcheson et al., 1995).

This paper examines the sources of knowledge problems and coping mechanisms used to address them within the front end of radical process innovation projects, i.e. projects that fall outside the current "process window". Prior research highlights the critical nature of front end activities to the success of product and process innovation (Kurkkio et al., 2011; Cooper and Kleinschmidt, 1994). The front end in radical innovation is characterised by high extents of 'fuzziness', which must be dealt with for effective decision-making to occur (Stevens, 2014;

Lane and Maxfield, 2005). We examine four distinct knowledge problems that characterise this fuzziness: uncertainty, complexity, equivocality and ambiguity (Zack, 2001). These problems form the hallmarks of the front end, especially in more radical projects (Stevens, 2014; Reid and Brentani, 2004).

The process innovation literature has demonstrated that such projects face problems and challenges that are conceptually rooted in these four areas (e.g. Rönnberg-Sjödin et al., 2016; Frishammar et al., 2011; Damanpour and Gopalakrishnan, 2001), yet it has neglected to examine them in detail. There is a relative deficit of research into the front end of process innovation, despite its unique characteristics and requirements (Kurkkio et al., 2011; Lim et al., 2006). Those studies that have been conducted have largely described the activities in the front end and offered initial understanding of successs factors (e.g. Frishammar et al., 2013; Kurkkio et al., 2011). Moreover, few insights into radical projects are evident (Frishammar et al., 2012; Kurkkio et al., 2011). As a result, studies have not yet examined the sources of the four knowledge problems in a front-end process innovation context, nor the specific coping mechanisms that firms can use to deal with them. An improved understanding of knowledge problems and coping mechanisms would provide important implications for the literature on process innovation and shed light on how managers approach ensuring projects survive these critical project stages.

In response to these shortcomings, the overall purpose of this study is to unravel the sources of knowledge problems and coping mechanisms in the front end of radical process innovation. We do so by addressing two research questions:

> RQ1: What are the specific sources of complexity, uncertainty, equivocality and ambiguity for front-end projects outside of the process window?
>
> RQ2: What are the coping mechanisms project members use to overcome or mitigate complexity, uncertainty, equivocality and ambiguity respectively?

Our study draws upon six in-depth cases from the food processing industry in the U.K.. We select this industry as an example of the need to deal with knowledge problems in the front end. Within the food processing industry, the successful management of development of radical products is challenged by low investments in R&D (Trott and Simms, 2017). Furthermore, firms face significant barriers when attempting to differentiate products (e.g. Simms and Trott, 2014). The cases selected for our study each involved projects that fall outside the process window.

The findings of our paper provide three contributions to the front-end and process innovation literatures. Our first and primary contribution is to uncover the different sources of uncertainty, complexity, equivocality and ambiguity in the specific context of radical process innovation projects, and unravel different coping mechanisms that are deployed to either reduce the levels of fuzziness or increase tolerance to it amongst decision makers. This detailed account extends prior literature (e.g. Rönnberg-Sjödin et al., 2016; Frishammar et al., 2011; Lager, 2002; Damanpour and Gopalakrishnan, 2001) and moves beyond simply identifying that the four problems exist, shedding new light on the front end of radical process innovation.

Our second contribution is to delineate which specific coping mechanisms are more or less appropriate for different knowledge problems within radical front-end projects. In particular, we present a new approach to mapping specific sources of problems to appropriate mechanisms, in the form of a descriptive framework and associated table, which extends prior literature (Stevens, 2014; Frishammar et al., 2011; Zack, 2001; Kurkkio et al., 2011). This new conceptualisation delineates how coping mechanisms are used to reduce fuzziness in front end activities, which enable more effective decision-making regarding the creation of process concepts and process definitions. In doing so, our study also responds to Townsend et al.'s (2018) call for further research examining how different knowledge problems are responded to by managers. Finally, we extend Stevens (2014) study of learning strategies as an approach to address problems by providing a more granular view on the reduction of fuzziness. Our findings highlight the need to analyse all four knowledge problems in the front end, and reveal specific challenges faced with respect to ambiguity.

The remainder of this article is organised as follows. Section 2 presents the theoretical background to our study. This is followed by our methodology. Section 4 reveals our analysis and results. Finally, Section 5 discusses the theoretical and managerial implications, followed by suggestions for future research.

2. Theoretical background

2.1 Process innovation and the "process window" concept

As industries mature, process innovation tends to be more pronounced (Linton and Walsh, 2008; Utterback and Abernathy, 1975). Firms then become tied to a path-dependent technical trajectory (Bunduchi and Smart, 2010) and bound by existing routines, investments and knowledge (Bauer and Leker, 2013; Henderson and Clark, 1990). This effect is particularly pronounced within process industries (Lager, 2017a; Hullova et al., 2016). Firms are also reluctant to pass away significant prior investments (Novotny and Laestadius, 2014;

Pisano and Shih, 2012; Upton, 1997). The lifetime of production equipment is frequently over 25 years (Novotny and Laestadius, 2014; Erumban, 2008). Long-term success is, however, dependent upon the development of new products (Lager et al., 2013; Reichstein and Salter, 2006), which often require major changes to production processes and equipment. Such changes break the current “process window” – e.g. the boundary conditions of existing production processes (Frishammar et al., 2012; Kurkkio et al., 2011). New products that cannot be produced within the boundary conditions of existing production processes are “outside of the current process window”. Once capital investment has been made, new products frequently have to be manufactured on existing production equipment. Thus firms tend to stay within the process window by utilizing existing resources with minimal changes, to maximize return on investment (Hullova et al., 2018; 2016).

Despite these challenges, process firms are frequently required to extend or break the process window. The need for new types of products or enhanced production volumes requires existing equipment to be modified (e.g. Ozman, 2011; Aylen, 2010; Lager et al., 2014; Hutcheson et al., 1995). A representative example is Aylen’s (2013) study of line ‘stretch’ in the wide strip mill industry in which he found that firms modified and extensively reconstructed production lines to develop and deliver new products. However, this study did not uncover how firms manage specific projects that require substantial changes to existing production equipment to deliver new and improved products.

2.2 The front end in process innovation

The literature contains multiple definitions of process innovation (Kurkkio et al., 2011; Lager, 2002), and the intertwined nature of product and process innovation often results in difficulties in drawing distinctions (e.g. Hullova et al., 2018; Lager, 2002). Following Frishammar et al., 2013 (p. 215) we consider process innovation to refer to ‘all-encompassing changes to the manufacturing process, such as the launch of a next-generation process for a new product’ (e.g. Reichstein and Salter, 2006; Pisano, 1997).

The front end in process innovation is an iterative trial-and-error based phase in which ideas are generated and refined, and where various forms of experiments at bench scale, lab scale and full-scale production allow firms to create new process concepts (Frishammar et al., 2013; Kurkkio et al., 2011). Trial-and-error plays an important role in the development of new product and process concepts and technologies (Pisano, 1994; Utterback, 1994). The “prototyping activities” evident in other industries are replaced with test runs and batches (Lager, 2016; Pisano, 1994). Bench scale, lab scale, and full scale testing have been found to be key front-end activities within process innovation projects that assist risk reduction

(Frishammar et al., 2013). Whilst bench and lab scale experiments play an important role, they have limited accuracy compared to real-world production realities (Pisano, 1996). Production trials and factory experiments reduce the problems known to occur at the point of scale-up, when different ingredients or materials may react differently to one another in larger volumes (e.g. Lager, 2017).

Tests in pilot plants can therefore play a particularly important role in early development projects (Hellsmark et al., 2016; Pettinau et al., 2015; Dinca and Badea, 2013). In other cases, trial-and-error occurs on the production line (Trott and Simms, 2017). However, factory experiments are costly, high risk and also bring the opportunity cost of revenues from saleable products (Pisano, 1994). Front-end activities also appear difficult, as these are often crowded out by day-to-day reactive problem solving (Kurkkio et al., 2011) and everyday priorities to keep production running (e.g. Tyre and Orlikowski, 1994). Decision-makers may also be concerned about the risk of major disturbances if the concept is not viable (e.g. Rönnberg-Sjödin et al., 2016). Establishing the legitimacy of proposed changes to the production line thus becomes a critical development task.

The production line is frequently relatively inflexible, with long changeover times and a pressure to achieve high volumes and levels of capacity (e.g. Ashayeri and Teelen, 1996). This creates a need for a clear process design (Aurich et al., 2008; Slack et al., 2007). Against this background, the importance of early product and process definitions have been identified as critical (Frishammar et al., 2013). Despite this, in projects involving higher degrees of newness, firms often need to deal with different types of knowledge problems. Reaching a stable process definition can then be more time consuming, and innovators may initially have to work with 'formative' definitions during the learning process (Verworn et al., 2008).

Against this background, front-end research in process innovation is scarce, and close to non-existent for projects outside the process window. Indeed, most prior research on the front end has addressed product innovation (Florén et al., 2018), while studies on process innovation focus on more incremental projects (Kurkkio et al., 2011). Frishammar et al. (2012), however, identified two distinct project types: projects involving the development of products that could be produced on existing production equipment, and those that could not. The latter were characterised by managers as more challenging, requiring investments in, and modifications to, existing production equipment, as they fell outside the process window, and the authors specifically called for more research on such projects. The following section reviews the specific challenges that such projects face, and the learning processes firms may use to manage them.

2.3 Complexity, Uncertainty, Equivocality and Ambiguity, and potential remedies for projects outside the process window

Front-end activities play an important role in project success. Dealing early with problems in designing and developing process definitions is much less costly than undertaking rework at later stages (Martinsuo and Poskela 2009; Verworn, 2009; Shen-Li et al., 2007). In moving outside the process window, firms need to deal with problems that have their roots in four different concepts: complexity, uncertainty, equivocality and ambiguity (Townsend et al., 2018; Zack, 2001). On a very general level, gathering and processing sufficient information or knowledge enables each problem to be mitigated or reduced, in different ways (Stevens, 2014; Florén and Frishammar, 2012). This information gathering and processing may be conducted in collaboration with equipment suppliers (Sjödin, 2019). By doing so, improved process definitions can be created and a better decision about whether to enter formal development or not can be taken (Florén and Frishammar, 2012; Kijkuit and van den Ende, 2007).

Complexity reflects the number of parts in a system, the interactions between these parts and any difficulties in predicting interactions (Stevens, 2014; Zack, 2001; Simon, 1969). Although complex situations are predictable rather than vague, the number and variety of elements and relationships involved make the situation difficult to comprehend. In prior literature, process innovation has been described as highly complex and “systemic” (Sjödin, 2019; Damanpour and Gopalakrishnan, 2001). Broadly, complexity is managed by processing further data and by decomposing a problem into smaller components (Huber, 1984; Simon, 1969; Stabell, 1978). However, specific insights into the management of complexity in the front end of process innovation are limited.

Second, uncertainty reflects a lack of sufficient information, understanding or knowledge (Stevens, 2014; Zack, 2001; Galbraith, 1973), and difficulties in understanding the probability of a desired outcome (Simon, 1969; March and Simon, 1958). Uncertainty is thus the size of the gap between the information needed to complete a task and that available (Galbraith, 1973). Uncertainty is managed by gathering and sharing more information within multifunctional teams (Stevens, 2014; Galbraith, 1973), and by the ability to use knowledge to predict, infer or estimate (Zack, 2001). To date, insights into potential coping mechanisms within process innovation are limited to Rönnberg-Sjödin et al.’s (2016) study, which suggested the use of early end-user involvement. That study, however, did not specifically focus on the front end of process innovation.

Equivocality, by contrast, reflects the potential for multiple interpretations of facts and information (March, 1994; Weick, 1969). Here, the problem is not so much a lack of information but rather different interpretations of it. Equivocality is at the heart of process innovation projects (Frishammar et al., 2011), especially when these involve multiple collaborating organizations or departments, as that gives rise to so-called representational gaps (Cronin and Weingart, 2007) due to differences in frames of references, thought worlds or opinions. Broadly, equivocality is managed by acquiring contextual knowledge, input from external expertise, and communication between departments (Crossan et al., 1999). Process innovation studies identify the roles of joint problem solving and the exchange of rich information to help negotiate joint understanding and resolve equivocality (Rönnberg-Sjödin et al., 2016; Frishammar et al., 2011).

Finally, ambiguity is the inability to interpret something. According to Zack (2001, p. 6), 'If uncertainty represents not having answers, and complexity represents difficulty in finding them, then ambiguity represents not even being able to formulate the questions. Low levels of ambiguity may signal a lack of interpretative knowledge, but ambiguity levels are likely to increase as a project moves further and further away from the current process window. However, to the best of our knowledge, ambiguity, has not been analysed in front-end studies in a process innovation setting.

In sum, innovation projects outside the process window are all likely to experience complexity, uncertainty, equivocality and ambiguity to considerable degrees. These projects are more innovative, and thus tend to be characterised by greater uncertainty and complexity (e.g. Bessant et al., 2014; O'Connor and Rice, 2013; O'Connor and Veryzer, 2004; Veryzer, 2004; 1998). They frequently involve unforeseen events, resulting in frequent setbacks and disruptions (Leenders et al., 2007). However, prior studies have largely been conducted in the domain of product innovation. For projects outside the process window, the literature has been helpful in establishing and describing the four knowledge problems. However, they fail to characterise the sources of complexity, uncertainty, and equivocality or the specific coping mechanisms firms use to overcome them. This informs our rationale for examining projects outside the process window.

3. Methods

The limited knowledge about the complexity, uncertainty, equivocality and ambiguity within the front end of new process development projects led us to adopt an abductive exploratory case study (e.g. Edmondson and McManus, 2007; Dubois and Gadde, 2002). Case studies are appropriate for the analysis of complex and poorly understood phenomena (Dodgson et al., 2008; Eisenhardt, 1989; Yin, 2012). Due to the dynamic nature of the front end, the unfolding of events in the environment play an important role in building explanations (cf. Aaboen *et al.*, 2012; Yin, 2012).

The abductive case study approach enables the researcher to benefit from the potential for an intertwined research process. Abductive research is appropriate where the objective is to discover "new things – other variables and other relationships" (Dubois and Gadde, 2002: p. 559). This non-linear approach is well suited to case study research, in which data collection and analysis frequently overlap, and provided the researchers with the ability to match theory with observations (e.g. Dubois and Gadde, 2002; Eisenhardt, 1989). Thus empirical findings were able to evolve along the theoretical frame which guided the study. Beginning with basic theoretical constructs, in the form of the four knowledge problems, the researchers iterated between observing and analysing the empirical phenomena and background theory. This process of analysis allowed us to uncover the sources of each knowledge problem, and their interrelationships with coping mechanisms used to address them. To enhance robustness of our theoretical development, we adopted a multiple case study, which also facilitated the identification of emerging themes and patterns (Eisenhardt, 1989).

3.1 Data Collection

Our research was conducted within the food processing industry. Our rationale for selecting this industry is twofold. Firstly, we consider the industry an appropriate context as it forms the largest manufacturing sector in the UK (FDF, 2019). In this industry, production processes and process innovation are of pivotal importance (see Hullova et al., 2018; Meyer and Dalal, 2002; Barnett and Clark, 1996;). In common with many process industries, the food industry is classified as low-tech (Lager, 2017). Further, new products typically have low margins and decision-making is risk averse (see Trott and Simms, 2017; Simms and Trott, 2014). This results in a relatively low number of innovative products (Steiner, 2004). Hence the key challenges presented by innovation outside the process window are further compounded. Secondly, two of the authors had undertaken research within this industry for over twelve years, including a total of five PhD projects. As previously mentioned, radical innovation is relatively uncommon in the industry. The researchers used their existing contacts to identify projects. Three of the projects resulted from existing links with organisations as part of ongoing collaborative knowledge transfer projects, in which one of the researchers visited each company on a weekly basis and thus the researchers possessed prior knowledge of the company and its operations. Following an approach adopted by prior studies (e.g. Frishammar et al., 2015; Hoegl and Wagner, 2005), discussions with senior managers enabled us to identify projects either recently completed or near to completion. This assisted with information retrieval and ensuring the key actors could be identified.

We sampled six new process innovation projects initiated as a result of a radical product innovation. Each project selected fell outside the existing process window, and thus required the introduction of novel equipment within an established production line, alongside complex change. Our classification of these projects as radical is consistent with Frishammar et al. (2012), as well as Garcia and Calantone (2002) with the process innovations new to product application and thus new to the firm. Furthermore, all projects involved organisations beyond the focal process firm, so external collaboration was an integrated part of each project. Table 1 provides a summary of the projects and interviewees.

Primary data was collected by means of forty-five semi-structured in-depth interviews with forty pertinent individuals. Our initial discussions with senior managers, and subsequent interviews that followed this, assisted in identifying pertinent individuals that were recognised as key persons either directly involved or with a heavy influence on the project (e.g. Miles and Huberman, 1994). Through this approach we captured the key actors and functions involved in each of the projects. Respondents included the project leader, other key managers and individuals involved in or responsible for aspects of the project, such as engineers, process operators and members of R&D or new product development teams. Where pertinent, equipment suppliers or other external collaborators, such as consultants, were also incorporated. Some differences in the respondents interviewed across each project were evident as a result of the approach adopted. This approach aimed to ensure we captured the different activities involved in the front end and associated knowledge problems. Including a range of actors allowed us to explore problems identified such as those resulting from the transfer of product opportunities into production.

The interviews were semi-structured and lasted between 1-3 hours. The interview guide focused on the process innovation process, the main stages, the sources of uncertainty, equivocality, complexity and ambiguity as perceived by each individual, as well as the learning processes and coping mechanisms through which these were addressed. The interview guide was adapted for the purposes of each case study, as well as on the basis of the individual's involvement and functional background (e.g. Yin, 2012; Nag et al., 2007). This guide was further adapted for subsequent follow-up interviews, in order to explore new themes as they emerged (e.g. Miles and Huberman, 1994). Additional detail is provided in Appendix I alongside example questions. Internal reports and company documentation helped further an in-depth understanding of the cases through 'triangulation' (Denzin and Lincoln, 2000; Eisenhardt, 1989; Flick, 1998). This information was compared to our interview data to help ensure a more complete understanding, and where necessary additional areas for interview questioning were identified and pursued.

3.2 Data Analysis

Our data analysis followed the abductive approach (Dubois and Gadde, 2002). We started in the literature by using the concepts of uncertainty, complexity, equivocality and ambiguity as 'sensitizing concepts' to help focus and guide the data analysis process. Hence these concepts provided us with suggested directions to look for patterns in data (Blumer, 1954). This enabled us to enrich our initial understanding from literature through observations of empirical patterns, which could subsequently be explored in further interviews (e.g. Dubois and Gibbert, 2010; Dubois and Gadde, 2002). Hence our understanding and application of the concepts were developed in parallel to the data collection and analysis, by means of "systematic combining". These concepts were not directly introduced to the informants, but rather utilised to assist the researchers in the development of theory. The abductive process aims to achieve a better fit between theory and empirical observations, as opposed to forcing a fit based on pre-existent categories (e.g. Dubois and Gadde, 2002; Glaser, 1978).

[Insert Table 1 here]

Subsequently our data was analysed in several steps according to the principles for thematic data analysis suggested by Braun and Clarke (2006). First, the interviews were recorded and transcribed, a process which made us familiar with the data. In this step, we read each transcript repeatedly. Second, we utilised our sensitizing concepts to generate initial codes by uncovering preliminary patterns in the data that were pertinent to our research question. These provisional codes were used to organise subsequent data, whilst seeking to identify new codes as they emerged. Hence the themes were driven by both theory and data. Third, we began to cluster the list of initial codes into categories, and made preliminary drafts of how the categories related to the theoretical themes. This was done by extensively elaborating the meaning, differences and similarities of codes and categories among the authors, and the result was a draft of a thematic map. This was initially conducted with a subset of data to ensure coherence. We then used the entire data set to ensure that the themes were both valid and complete. Fourth, we reviewed the labelling of codes, categories and themes, to ensure that these were clearly defined, named and mapped. At this stage, we devoted special attention to eliminating ambiguous codes and to eliminating conceptual and empirical overlap between categories.

4. Analysis and Results

Our empirical analysis expands upon better understanding of the knowledge problems in the front end of radical process innovation projects (e.g. Frishammar et al., 2013; Kurkkio, 2011). Each project was characterised, though to varying extents, by complexity, uncertainty, equivocality and ambiguity. Our informants described these problems as particularly acute, due to characteristics of the projects that are detailed in the sections that follow. We also observed project delays caused by difficulties in addressing these problems, as managers attempted to achieve a stable and corroborated process definition. We use these sensitising concepts to structure the following sections, which firstly capture the sources of these knowledge problems, and subsequently reveal the coping mechanisms used to overcome them. We capture our key findings through illustrative key quotes incorporated into the following discussion, while appendices A-H present further evidence to support our findings in the form of additional representative quotes. The final version of the thematic map is presented in Figure 1. To the centre of the Figure we capture the knowledge problems, to the left we present each of the sources of knowledge problems (relating to RQ1), whilst to the right we identify the coping mechanisms used to deal with them (relating to RQ2).

[Insert Figure 1 here]

4.1 Sources of Knowledge Problems

The first part of our analysis focuses on the sources of each of the four knowledge problems rooted within uncertainty, complexity, equivocality and ambiguity. These are presented in the sections that follow.

4.1.1 Sources of Uncertainty

Our analysis identified five sources of uncertainty. A high extent of technical risk resulted from the newness of process technologies, which were either new to the industry or required extensive modifications to meet the new product’s requirements. Uncertainty not only concerned the new equipment technology itself, but also how it would function when processing at large volumes. During scale–up interactions and changes to the ultimate characteristics of the food were described as inevitable but difficult to anticipate. These problems were evident in the following:

> *"no one really knew how it was going to work in production…. Using a new welding process on the bag was quite a risk and we would not know if it had worked successfully until we had packed a large batch, stored and tested it. The risk was that the process wouldn't seal the weld consistently and the acidity of the wine would eat through leading to tainting… Add to this, no one had filled at 2-3 litres of wine per second into a 1 litre bag[1]"* [Project D, I21: Packaging Manager]

The above problems were compounded by the nature of food processing, which was characterised by restricted development budgets, alongside the prioritisation of capacity and efficiency. Innovators had limited access to the existing production line in order to conduct testing. Pressure to maintain volumes were in opposition to the time required for testing radical changes. Within established factories, growing demands to increase capacity virtually removed any slack for testing that may have once existed in production schedules. Moreover, whilst prior studies have demonstrated the important role of pilot- and demonstration plants in radical process innovation (Hellsmark et al., 2016; Smith and Raven, 2012), within our findings innovators were frequently unable to benefit from such opportunities to learn. Ownership of pilot plants was uncommon in the food industry and tests at dedicated pilot plants were considered prohibitively costly. This was despite the significant technical challenge within each project. Finally, difficulties in predicting the potential length of time a production line may need to go off stream for testing further contributed to problems in gaining access. As a result, innovators struggled to gather the information required to reduce uncertainty. In turn, this caused problems in establishing the legitimacy of a proposed technical solution. For example:

> *"The test would require a significant shut down period, but it was not possible to know how long. The technology was new, and we would have a lot of other variables to consider and experiment with…. Even when you have a lot of background work, its impossible to say it will take x number of hours, you don't know and something can always go wrong.."* [I2, Project B: Production Engineer]

4.1.2 Sources of Complexity

Our cases revealed five sources of knowledge problems rooted in complexity. Firstly, our results reveal how the systemic nature of process innovation (Damanpour and Gopalakrishnan, 2001) influenced the front end. Innovators faced problems resulting from

[1] Interviewee refers to a fill rate resulting in a 1 litre bag being filled in fractions of a second.

the introduction of novel production equipment (also referred to as equipment hereforward) which would cause a chain reaction of effects on an existing production line. Here the complexity lies in comprehending the extent of effects, identifying each piece of equipment affected and grasping the set of possible solutions. For example, in Project D, the team initially failed to recognise the cascade of change resulting from the introduction of the new form-fill-seal system. Subsequently, the requirement for new equipment to both feed unfilled bags into the vertical conveyor and to box the sealed wine bags became apparent:

> *"we started to realise how many other changes we were going to need to make. It's an old [production] line and it wouldn't be able to feed the new bags and would require the adaptation to handle the filled boxes…. The need to introduce new equipment created a cascade of problems and considerations. The project became a bit of a monster."* [I22: Production Development Engineer]

Similarly, a failure to initially recognise the complexity of change was central to the failure of Project B. The team's initial analysis failed to capture the requirement for significant investments in new conveyor belts, coating equipment and packaging equipment needed to handle the new product. Secondly, new equipment was frequently incompatible with existing equipment and could not be simply bolted onto the existing line. This reflects the notion that new equipment can often be considered a substitute as opposed to a direct replacement (e.g. Robertson et al., 2012). The consequence of this was an expanded the scope of analysis to uncover such problems, identify potential resolutions and their cost. The existing software systems operating the line exemplify one such problem.

The above problems were particularly pronounced within ageing production lines. Within four of the six projects studied, the production line had been installed between ten and twenty years back. For example, in project C:

> *"Our analysis revealed that introducing the micro dosing of the concentrated sweetener was going to make the existing machine inoperable… you're talking about moving from a teaspoon to a microdot in your dosing, which the system isn't designed to handle… it's nearly 20 years old. Neither the software nor the machinery itself could easily accommodate the change"* [I17: Production Engineering Manager]

The third source of complexity resulted from the requirement for engineers to maintain production capacity and efficiency targets whilst also meeting the requirements of a challenging technical brief. Efficiency targets were frequently included within project briefs, which increased the scope of considerations. This challenge may in part result from the volume intensive and low margin nature of production in the food industry (e.g. Trott and Simms, 2017), in which compromises to efficiency were often unviable.

The final two sources of complexity extended beyond the line itself. The systemic nature of change required the analysis of its effects on the layout of the entire factory, requirements for additional space, and changes to the procedures, operation and management of the facility. Indeed, in Case C, the introduction of powdered sweeteners into a factory that previously only handled liquids brought with it the need to consider compliance with additional health and safety regulations. Finally, the production of new products alongside existing goods necessitated analysis of the implementation of changeover and the impact this would have on efficiency and output.

4.1.3 Sources of Equivocality

Frishammar et al. (2011) argued that equivocality is at the heart of process innovation projects. Our cases revealed how five key sources of equivocality influenced the front end. First, amongst members of both production operations and engineering, diverging perceptions on project viability and feasibility were evident. A few members were more receptive to change and tended to conceive innovation as possible. We refer to these individuals, as 'front runner' members of each team. By contrast, more 'traditional' members were characterised as lacking creativity and their cognitive frames emphasised efficiency. This effect was compounded within older factories, where the cognitive frames of long-standing personnel tended to predispose them against change, emphasising the potential disturbance to operations and associated risks:

> *"I found a problem with the more established members of the team, who have been operating the line for over a decade… Iterative change happens fairly regularly and is easy to justify and they can see where the next step is, and those comfortable with iterative change can be stretched for step changes. But even those relatively comfortable with step change struggle to implement an innovation... They just can't foresee how the line can be changed"* [Project D, I22: Production Development Engineer]

The problems of technologies 'congealing' has been documented in prior studies (e.g. Smith and Tushman, 2005; Denison et al., 1995; Walsh, 1995). Our findings highlight how this temporal influence on the cognitive frame of 'traditional' actors influences equivocality.

Secondly, product R&D and NPD personnel were described as key actors, as each project was initiated as a result of a new product innovation. However, their often limited understanding of production equipment (e.g. Rönnberg-Sjödin et. al., 2016; Lager and Frishammar, 2010), resulted in erroneous conclusions being drawn on the manufacturability of the product, its production implications and project requirements. Critically, they frequently had different ambitions to production and process actors. For example, this was exhibited in meetings, when conflicts arose as a result of product R&D and NPD's emphasis on the attractiveness of a product opportunity, whilst production evaluated its viability from a more operational perspective. However, in Project E, there was a consensus amongst much of the NPD team that the high cost of integrating the 'doy-pak' format into the existing line rendered the project unviable. This proved hard for the engineering actors to resolve.

Thirdly, equivocality resulted from differences in the perceived extent and potential viability of change between members of engineering and senior management. Where senior decision-makers thought that less extensive changes to production were necessary than was the view of engineering, this led to conflicts over project feasibility, scope, timescales and budgetary requirements. By contrast, where senior management considered that more extensive changes would be required, this held the potential to hinder progression. This presented a particular problem where potentially viable equipment solutions had been identified, yet teams struggled to gain support for the investments required to test and verify a proposed solution. As previously mentioned, this demonstrates a linkage with the uncertainty resulting from difficulties in testing potential solutions:

> *"… the problem lies in how you manufacture it at full-scale in a viable way, you can tell management it's possible but they want to see evidence before committing to implementing your proposed solution… You end up with the situation where they want to see how it will work, but they won't provide the investment to let you demonstrate that it does… It's a complete 'catch 22'."* [Project C, I14: Production Unit Manager]

High risks are associated with the development and implementation of new process technologies (Filippou and King, 2011). Once engineering became involved in each project, and the extent of production implications became clear, senior decision-makers became increasingly concerned over risks and hesitant to proceed further. Decision-makers were concerned over the legitimacy of a proposed solution, and innovators experienced challenges in maintaining support and persuading them to commit investments. Concerns were evident over the potential for investments to further escalate into something unmanageable. Such concerns were compounded by the fact that radical change had not occurred frequently within the company. Finally, new process technologies were developed externally (e.g. Bergfors and Lager, 2011; Reichstein and Saler, 2006). This formed a further source of equivocality, with different interpretations of the project requirements and scope becoming evident between the internal members of production and engineering, and the external developers of new equipment.

4.1.4 Sources of Ambiguity

Prior studies have revealed the ambiguity associated with radical innovation (Keizer and Halman, 2007). Despite this, insights into ambiguity in process innovation are lacking. We uncovered three sources of problems rooted in ambiguity.

The engineering teams experienced difficulties in identifying the new product's manufacturing requirements and translating these needs to equipment suppliers, resulting in the development of inappropriate solutions. Hence teams struggled to ask the 'right' questions when specifying equipment. Prior studies identify the importance of equipment suppliers' capabilities in process innovation projects (e.g. Reichstein and Salter, 2006; Arora and Gambardella, 1997). However, our findings revealed that suppliers used their experience and expertise to develop novel process solutions, and thus did not possess sufficient interpretive knowledge to raise pertinent considerations. For example, in Project D, the team failed to identify new requirements when moving to vertical filling:

> *"Initially it had seemed simple and we had a prototype machine that could form-fill-seal successfully on red and white wine…. But the team had overlooked a number of factors and didn't recognise the need to consult more people when specifying the equipment… Fluid dynamics had been overlooked, resulting in bubbles and surges, the consistency of fill was out… added to this the different Reynolds number of each wine variety had been overlooked, resulting in further inconsistencies"* [I23: Senior Development Engineer]

This led to the need for significant redevelopment of the prototype and further investment, which nearly resulted in the project's failure.

Secondly, production managers and engineers lacked an understanding of equipment capabilities. Their emphasis was on the day-to-day running of the factory (e.g. McAdam and Leonard, 2004; Benner and Tushman, 2003; Heller, 2000; Pisano, 1994). As a result, they lacked experience in managing larger change and the understanding required to accurately assess the capabilities of existing and new equipment. This risked viable new equipment opportunities and potential solutions being overlooked. For example, in Project A:

> *"We couldn't solve the problem initially as we didn't know what the problem was with the mixing, we didn't really know about different types of mixers, we just knew it wouldn't run through the machine."* [I2: Production Engineer]

Finally, the radical nature of each project meant that innovation teams were operating in unfamiliar territory. As a result, they faced difficulties in interpreting problems as they arose in the testing of new technologies, and formulating hypotheses as to how these problems might be resolved. When problems arose, such as poor product texture, it was difficult to understand whether this should be tackled through changes to the product or process.

4.2 Coping mechanisms used to deal with Knowledge Problems

The second part of our analysis focuses on the coping mechanisms used by managers to deal with uncertainty, complexity, equivocality and ambiguity. Differences between the coping mechanisms used reflect the different nature of each problem and the problems' unique knowledge processing requirements (e.g. Zack, 2001).

4.2.1 Coping mechanisms to deal with Uncertainty

Our findings uncovered five coping mechanisms used to deal with uncertainty. Each uncovers different approaches adopted in a process innovation context that enabled innovators to obtain more information in order to reduce uncertainty and increase the reliability of information, or the use of knowledge to predict and estimate (Stevens, 2014; Zack, 2001; Galbraith, 1973).

First, our interviewees identified the importance of 'upfront homework', which incorporated a number of trial-and-error testing processes enabling the collection of critical information for faster problem solving during scale-up. Whilst this included background data collection and simulations, informants emphasised the importance of small physical trials and tests, due to the newness of the process. Secondly, the incorporation of production expertise within early kitchen scale or laboratory tests enabled testing to be better informed by the likely differences at larger scales. This finding reflects the significance of underlying relationships between product and process development (e.g. Hullova et al., 2018).

Teams also exploited opportunities to undertake 'learning-before-doing' with equipment suppliers, with experiments and simulations undertaken jointly to assess potential relationships between the product and potential equipment technologies. Exploiting both firms' knowledge bases reduced technical uncertainty and improved the reliability of scale-up predictions. However, the radical nature of each production equipment technology meant teams possessed limited relevant prior knowledge to draw upon (e.g. Pisano, 1994). To address this, innovators sought opportunities for experimention with new equipment. Where possible, new solutions were initially tested in isolation from the line in which they would be installed. Whilst not fully recreating scale-up realities, this 'learning-by-doing' strategy enabled preliminary information to be captured on these new solutions' impact on the product's characteristics, resulting in better predictions and additional reference information, without disturbing operations:

> *"First we got the basic crisp right on the machine using the new ingredient, then we started to add in other ingredients for the nutritional profile, then we started to explore coating and baking…* [later] *This meant we knew that each time something went wrong we had a base point to go back to"* [Project F, I32: Head of NPD]

We observed two further responses to difficulties in gaining access to the production line. Teams identified, and subsequently partnered with, appropriate external organisations with capabilities to undertake larger scale testing aligned with the firm's resource constraints. These included utilising a more entrepreneurial equipment supplier's demonstration plants or specialist pilot plant contractors. For example, in Project A:

> *"We had to work with the OEM and persuade them to let us use other equipment at their test facility in order to undertake the basic test. We couldn't trial the entire line from start to finish, but the core processing part was able to be largely addressed… Their ability to develop a method of temporarily making the equipment work to test the processing and forming was key to helping us understand how it could work."* [I1: Head of Production]

Finally, we observed engineers adapting and modifying existing equipment in order to enable testing. Through entrepreneurial bricolage teams aligned testing solutions to budgets, exploiting existing resources for opportunities to learn.

4.2.2 Coping mechanisms to deal with Complexity

We observed five mechanisms employed to deal with complexity. Broadly, these reflected the processing of further data or breaking down of a problem into smaller components (Huber, 1984; Stabell, 1978; Simon, 1969). Firstly, innovators described their process of systematically decomposing the production line and analysing each piece of equipment:

> *"I mapped out the performance window of each part of the line and then assessed how the proposed changes would impact on each touch point.. from there I looked at what adjustments would be required or if it wouldn't work on that piece of equipment what would be needed"* [Project F, I40: Head of R&D]

This enabled the individual assessment of each manufacturing unit of operation and its relationship with both the new product and potential interactions with new equipment. Notably, such detailed assessment was absent in Project B, which was later suspended as the magnitude of systemic change became evident. Secondly, process decomposition enabled teams to utilise the specialist knowledge of external consultants and suppliers to assess the particular units of operation affected by the new equipment. Third, in response to the need to address both technical and compatibility issues, we observed a 'step-wise' approach to problem solving. Undertaking an initial analysis of technical issues enabled teams to reduce complexity. Subsequently, compatibility issues were managed in a number of ways, such as by designing bespoke equipment interfaces or working with IT specialists to resolve software problems.

When undertaking analysis within process design and specification, our cases revealed the importance of bringing together diverse knowledge from a variety of actors to interpret requirements and foresee problems. In Project C, a wide variety of actors were brought in, leading to the recognition of a number of questions that would need to be addressed:

> *"It was necessary to get as many people involved as possible to understand and test out the consequences... more detailed evaluation revealed considerations related to the tank size, dosing, turbulation, mixing and order of ingredients"* [I13: Senior Beverages R&D Manager]

Finally, building on studies identifying the benefits of early production involvement (e.g. Floren et al., 2017; Frishammar et al., 2011; Kurkkio et al., 2011), we found that incorporating expertise from production operations in process design and definition enabled a more detailed analysis of the implications of change to the factory and to operation of the line. This occurred through extensive site visits, discussions and the involvement of on-site teams:

> *"We had to work closely with the factory staff, the introduction of the doy pak would change their operations and require changeover. Therefore, when we examined solutions we had to incorporate their experience to analyse the impact on the factory and figure out how it was going to work. Then you get a better understanding of speed, volumes and capacity etc."* [Project E, I30: Technical Engineer]

4.2.3 Coping mechanisms to deal with Equivocality

Our analysis uncovered six coping mechanisms used to deal with equivocality. Each uncovers a specific approach to utilising communication, the exchange of rich information and negotiation to resolve diverging opinions (e.g. Frishammar et al., 2011; Crossan et al., 1999). Firstly, prior studies have revealed the lack of creativity and emphasis on productivity amongst many members of the production function (Aylen, 2013; Kurkkio et al., 2011). Building on this, our results revealed how informants from product innovation attempted to overcome potential resistance from production by initially approaching more innovative 'front runners' with a new product opportunity:

> *"We had to be persistent to find the right individual… The person we ultimately identified in production was more open-minded, not like the other production*

engineers we had talked to. If we hadn't found him, I do not think the project would have ever gained traction" [Project E, I27: Head of Packaging Design]

Secondly, throughout the front end it was necessary to maintain close interpersonal communications amongst key stakeholders. Engineering were responsible for managing the process innovation project and thus worked closely with product R&D and NPD actors to translate product requirements into a process concept. Managing equivocality within the process required close integration with other actors. Working closely with production operations improved innovators' understanding of the variety of interests, priorities and cognitive frames through which developments were evaluated. Discussions were then able to ensure alignment of perceptions on the viability of change, and focus on pertinent benefits from *"…the perspective of the manufacturing shop floor"* [Project E, I28]. Face-to-face communications and negotiation with senior decision-makers and key members of NPD and product R&D ensured that goals, priorities, and critically the scope and engineering implications, were mutually understood:

> *"We had to keep the stakeholders continually engaged ... It's all about communications and alignment…. I do not think we really followed our stage-gate process when compared to other projects; this would have only brought people together intermittently. It wouldn't have kept everyone on board"* [Project C, I15: Senior Engineer]

The above mechanisms reflect some of the approaches used by firms when managing external stakeholders within development projects, and thus reflect actions to identify, coordinate and align perceptions across different project actors through dialogue (e.g. Pellizzoni et al., 2020; Driessen and Hillebrand, 2013).

A number of our informants asserted the importance of demonstrating the results of tests and simulations, and presenting prototypes and other evidence, within update meetings and informal discussions. Studies of radical product innovation have identified the importance of gathering information to demonstrate viability and articulating information to key decision makers in order to gain support (Veryzer, 2004; O'Connor and Veryzer, 2004). In our study, the dissemination of tangible evidence of progress formed a critical mechanism through which innovators achieved a greater consistency of interpretations, and thus reduced equivocality amongst diverse actors. Further, we observed teams undertaking development work outside the scope of approved operations. These unfunded 'skunk works' enabled initial tests to be undertaken in order to gather information, and provided the evidence required to gain the approval to proceed and obtain funding for larger formal testing.

Innovators sought to identify and recruit influential actors from other functions within the organization as sponsors of the project. The use of sponsors in part reflects manufacturing's lower status as a non-dominant discipline (Leonard-Barton, 1992), thus engineering teams attempted to address this by recruiting members of other departments with greater influence. For example, in Project E the engagement of marketing and packaging personnel, who recognised the potential of the innovation, assisted the team in converging views and gaining approval for the investments necessary to proceed. Finally, interviewees identified the importance of developing a close partnership with equipment suppliers in order to reduce the probability of differences in the interpretations of project requirements.

4.2.4 Coping mechanisms to deal with Ambiguity

Ambiguity proved particularly challenging to address, due to its inherent nature. However, our analysis revealed four approaches through which innovation teams tried to reduce ambiguity. Firstly, intensive integration of production and product development expertise was considered critical in understanding the processing requirements of the new product. Jointly bringing to bear the contextual knowledge of the food processor and the technical equipment knowledge of the supplier, led to a greater recognition of the problems and considerations to be addressed. Secondly, innovators utilised consultants and KIBS to identify what they did not know. Acquiring this expertise enabled them to both recognise factors that had not previously been considered and develop hypotheses on potential appropriate solutions to them. Both of these mechanisms were evident in Project D. Following the failure of a prototype equipment solution, an external consultant was bought in. Subsequently, the need to assemble a wider team providing greater combined product and processing expertise was recognised:

> *"Our subsequent analysis revealed that a vertical filling system of this speed needed to account for the density, mobility and surface characteristics of each variety… The team had failed to consider this within the original equipment specification. I had worked on a few other projects and through working with the firm closely as a group we were better able to develop a hypothesis on the different factors we were going to need to address and how they might play out"* [Project D, I25: Consultant]

McDermott (1999) identified the use of informal networks in radical product innovation, and our cases highlighted that process innovators exploited such networks for the purposes of interpreting problems and recognising possible equipment solutions as they unfolded. This included other line managers, engineers, and existing contacts within different divisions and from other firms. For example, in Project B the production line manager drew upon the experience of a line manager from another plant to resolve problems with the mixing of ingredients that the team were struggling to comprehend, ultimately recognising the need for a blade as opposed to the existing screw mixer. Finally, our results identify the importance of moving beyond informal networks and expanding external searches to a broader variety of equipment suppliers, consultants and partners, in order to acquire additional understanding of potential equipment solutions when unexpected problems were experienced.

4.3 Towards a Framework for the Management of Knowledge Problems in the Front End of Radical Process Innovation

The preceding discussion and analysis reveal the specific sources of knowledge problems, as well as the coping mechanisms used to address them. This is captured in Table 2. Firstly, we distinguish between the four knowledge problems, separated by horizontal rows. Secondly, across the top of each of the four main sections of the table we identify the sources of knowledge problems uncovered. Thirdly, the table presents the coping mechanisms evident in the context of each knowledge problem (presented to the left). Finally, we capture the specific interlinkages between the source of each problem and the coping mechanism used to address them through the shading of the intersecting boxes between these two underlying components within the table.

[Insert Table 2 here]

Building on Table 2, which further underscores the distinct coping mechanisms innovators used to deal with the different sources of knowledge problems, we developed a framework that delineates the implications of our findings on these interrelationships in the front end (Figure 2). To the left of the framework, a radical process innovation project is initiatated as a result of a product brief that falls outside the current process window. Subsequently, this leads to the innovation activities being undertaken within the central part of our framework. On the basis of our findings and others (e.g. Kurkkio et al., 2011), key front end activities may be summarised as an initial study to generate ideas, evaluating technical equipment and factory requirements, initial lower fidelity testing, followed by larger higher fidelity tests, and a final analysis of feasibility and process requirements. Through the combination of these activities the emerging process concept is developed and refined. The decisions on this process concept are influenced by the different sources of knowledge problems relating to either uncertainty, complexity, equivocality and ambiguity (captured around the periphery of this process). Throughout this process, in response to each of the specific sources of knowledge problems, appropriate coping mechansims must be utilised in order to reduce the levels of these problems (fuzziness) and strengthen the ability for effective decision-making.

This culminates in the final process definition which, with sufficiently reduced levels of fuzziness, enables effective go or no-go decisions to be made.

[Insert Figure 2 here]

In presenting the framework we acknowledge that at times it may not be possible to reduce fuzziness, and it may be necessary to tolerate higher extents within radical innovation. Further, in some instances the knowledge problems may also have positive effects, such as leading to more information being gathered, improved communication, and improved consensus formation. Nonetheless, our results provided examples of the different difficulties and challenges that resulted where fuzziness was not sufficiently reduced; compromising effective decision-making. These findings demonstrate the significance of the interrelationships depicted in our framework.

5. Discussion and Implications

The front end of radical innovation forms an important area for research, due to a higher extent of prevailing fuzziness, limited understanding in development and relatively few strategies for effective management (Brentani and Reid, 2012). Within a process innovation context, despite the considerable importance of front end activities to project success, research on the early phases of projects is scarce (see Frishammar et al., 2013; 2012; Kurkkio et al., 2011; Lim et al., 2006; Pisano, 1996). In particular, studies examining the front end of radical process innovation, outside the process window, are to date virtually non-existent. An improved understanding of knowledge problems and coping mechanisms in the front end of innovation would provide important implications for the literature on process innovation and shed light on how managers approach ensuring projects survive these critical project stages.

Our research is a step towards closing this gap in the literature. Adopting a knowledge-based perspective, our research examined four knowledge problems (e.g. Zack, 2001) in the front end of six process innovation projects in the packaged foods sector. In doing so, we responded to calls to shed new light on the problems teams face in the front end of radical process innovation projects (e.g. Frishammar et al., 2012; Kurkkio et al., 2011).

Our results are of significance to managers and academics, who have sought to improve their understanding of the issues and challenges required to improve process innovation proficiency (e.g. Reichstein and Salter, 2006). While there are studies that have demonstrated that knowledge problems exist in the front end of process innovation projects, a detailed understanding of the sources of these problems and the coping mechanisms managers utilise to overcome them is lacking. The findings of our case study research have deepened the understanding of the specific sources of uncertainty, complexity, equivocality and ambiguity within the specific context of radical process innovation projects that fall outside the process window. Our findings on radical process innovation projects may be particularly important in light of the escalating environmental crisis which many branches of the process industry now address by major investments in new process concepts, process technologies and production processes outside of current process windows (see Hellsmark et al., 2016; Johnsson, 2011).

5.1 Theoretical Implications

Our study provides three theoretical contributions. Firstly, our research has adopted a knowledge based view (e.g. Zack, 2001) to examine the front end of radical innovation projects. This approach enabled us to study the distinct nature of four different sources of knowledge problems and the coping mechanisms used to address them. Our primary contribution is to the small but growing body of literature on the front end of process innovation. Here, whilst knowledge problems are broadly acknowledged (e.g. Rönnberg-Sjödin et al., 2016; Frishammar et al., 2012), the question of their specific sources in a process innovation context has remained open. This gap remains particularly evident in the case of radical projects, despite the recognition that management challenges are particularly acute in such projects (Kurkkio et al., 2011). Despite the need for managers to develop appropriate coping mechanisms based on the soure of particular problems, both the sources of problems and mechanisms have remained unclear. Responding to these limitations, our empirical analysis began by unravelling the specific origins of these problems, and subsequently revealed the coping mechanisms managers used to address them. Our findings on the coping mechanisms have important implications. Whilst prior research has focused more on the activities involved in the front end (e.g. Kurkkio et al., 2011; Frishammar et al., 2013), our study highlights the need to better understand how managers recognise and address knowledge problems. This study thus moves beyond describing development activities, to present a more detailed account of actions required to address knowledge problems. We have captured coping mechanisms not previously acknowledged, such as the important role of 'front runners', and the use of entrepreneurship and bricolage to test new equipment. These findings extend those of previous scholars, which have so far failed to provide a detailed account of their specific origins.

Table 2 conceptualises the relationships between the underlying sources of problems and the mechanisms that innovators employed to address them, and thus helps to disentangle the different approaches used by innovators to address the specific requirements of particular problems.

Our second contribution to the literature is a descriptive framework, which complements and adds to the understanding provided in Table 2. Building upon the basic activities involved in the front end of process innovation (e.g. Kurkkio et al., 2011), this framework illustrates that through reducing fuzziness, more effective decision-making is allowed to occur throughout the activities undertaken. Achieving this requires the use of coping mechanisms that are appropriate not only on the basis of the underlying differences in the requirements for each of the four knowledge problems themselves, but also to the distinct nature and associated challenges presented by each specific source. The above contributions respond to a criticism of prior research, which often fails to delineate between these four different types of knowledge problems (Townsend et al., 2018).

The framework is of significant importance because radical process innovations not only offer potential for firms to deliver improvements in production performance, but also in the context of radically new products (e.g. Pisano, 1997; Aylen, 2013). Yet, in contrast to the product innovation literature (e.g. Veryzer, 2004; O'Connor and Veryzer, 2004), little attention has been paid to understanding radical front ends in process innovation. Thus, our study provides critical insights into a number of specific problems that have not been previously illuminated. For example, the framework could be deployed to help address complexity resulting from the need to maintain production efficiency and capacity whilst delivering a process innovation appropriate to the product's requirements, and difficulties accessing pilot plant equipment to trail new solutions. These findings deepen the understanding of the specific challenges to be overcome in a process innovation context.

Our framework and Table 2 also complements the literature on agile stage gate Processes (Cooper and Sommer, 2016; Pellizzoni et al., 2019; Magistretti et al., 2019), which suggests that experimentation plays a key role in undertainty reduction. In the process innovation context, not only did innovators face relatively limited financial resources, but also critically they had to avoid or mitigate disturbance to production operations. This resulted in the use of a number of different forms of experimentation, including learning-before-doing with equipment suppliers, and offline learning prior to online testing. Dealing with the combination of constrained financial resources alongside difficulties in undertaking high fidelity tests (production trials) forms a challenge specific to the process innovation context. Accordingly, this issue needs to be highlighted as an important avenue for future research.

Finally, our study more broadly contributes to attempts to examine fuzziness in the front end of innovation. In particular, we have built upon Stevens (2014) study of learning strategies. Table 2 alongside the framework presented within our study reflect a novel approach to better understading fuzziness. Our findings reflect the need to analyse all four problems in the front end, and reveal specific challenges faced with respect to ambiguity which has not been discussed before. In addition, we examined the sources of problems and subsequently the coping mechanisms used to address each of them. In doing so, we moved beyond the identification of learning strategies as an approach to address problems. Thus, we have been able to provide a more granular view on the reduction of fuzziness in the front end.

5.2 Managerial Implications

Our empirical findings have a number of managerial implications that are applicable to process development managers, production managers, product innovation managers and senior decision-makers when initiating and managing radical process innovation projects. In addition, engineers and managers from equipment suppliers may benefit from these implications. Whilst our findings are generated from the food industry, right across the process industries, innovation managers commonly face many of the problems identified in our research, such as long-equipment cycles, difficulties in scale-up, and the need to utilise production equipment for testing. The results may therefore be valuable to other branches of the process industries.

Broadly, our characterisation of the knowledge problems and coping mechanisms provides a number of lessons and identifies actions required for managers attempting to succed in navigating the front end of projects outside the process window. The more finely grained understanding of the problems innovators face and the different approaches to addressing them can enable managers to foresee potential challenges and how they might be dealt with. Critically, the insights provided by Figures 1 and 2 provide specific support for managers by identifying the specific actions that they can take to reduce each distinct source of fuzziness. Managers can utilise both the framework and matrix to assist their efforts to facilitate radical process innovation projects as they unfold.

Radical projects tend to be relatively infrequent. When they occur they tend to be of great importance, however, and our findings help illuminate the problems teams are likely to face when such projects unfold. Identifying these potential challenges may help senior decision makers to recognise the need for long-term changes in order to reduce the likelihood of radical process innovation projects overrunning, failing, resulting in an unanticipated escalation of costs, or product definitions which fail to materialize as planned. In particular, as a result of the radical nature of each project a number of sources of ambiguity proced challenging, as a result of the teams venturing into unknown territory. Different formal and informal partners played a key role in reducing ambiguity, which highlights the importance of firms building and maintaining diverse process innovation networks that can be drawn on when radical projects come about. Such networks can help address the limitations of internal process knowledge which may develop a path dependent effect, constraining understanding to current processes.

One implication of particular relevance to senior managers is the problems innovators face in establishing the legitimacy and validity of process concepts amongst senior decision-makers, and how to deal with this issue. Teams struggled to secure approval for the access they required to test new equipment on existing production lines or funding for pilot testing until process innovations were demonstrated as viable. Yet, without funding or access to the line, convincing senior decision-makers of viability was challenging. This problem represented a paradox for innovators. Whilst senior managers clearly need to be convinced of the viability of projects prior to escalating investments or shutting down functioning production lines, particular attention needs to be paid to the potential for project failure as a result of these conflicting requirements. Decision-makers must consider the requirements they place on access to funding, and ensure production schedules do not become stretched to the point where time for testing proves challenging.

For senior managers, R&D- and NPD managers, we have also identified the need to distinguish between ‘traditional’ and ‘front runner’ members of the production functions. This proved significant, as ‘traditional’ members of the production function were less likely to recognise innovations, and proved more resistant to them, as a result of a combination of factors. These included temporal and efficiency cognitive frames, an emphasis on day-to-day running, and concerns over the impact of changes on the production line and its operations. By contrast, a few ‘front runner’ members were more receptive and often played a key role in dealing with problems. Whilst differences in the perceptions of these members causes knowledge problems, for innovation managers seeking out and recruiting front runners can prove decisive in ensuring project success. These team members often played a critical role in overcoming other knowledge problems, for example through skunk works or communicating closely with other functions to reduce equivocality.

5.3 Limitations and Future Research

This study employed a knowledge-based approach to understanding the sources of fuzziness within the front end of radical process innovation projects. Our results demonstrate that this method of analysis forms a useful analytical lens through which to uncover the sources of problems. This method also assists in understanding how each type of problem is linked to the different types of coping mechanisms employed by managers aiming to address them. However, several limitations are evident within our approach, and we identify a need for future research to extend our initial insights. This research should examine further process innovation projects both across different types of industries and across different project types.

Firstly, our research examined six cases of process innovation projects. Further research is required to validate our findings, including studies of other branches of the process industries. The cases studied included one failed project and one project that experienced significant problems, nearly resulting in failure and leading to the development of a sub-optimal solution. Future studies should extend our insights by comparing a greater number of successful and unsuccessful projects to uncover differences in the coping mechanisms deployed by teams and their impacts on project outcomes. Secondly, our study examined process innovation projects initiated as a result of a radical product innovation project, which presented a number of specific problems. Additional research is required to compare our findings across projects initiated as a result of other initiatives, e.g. major process restructuring to increase efficiency. Studies of radical projects required to deliver significant efficiency improvements, and in particular projects established to deliver improvements in environmental performance, may prove particularly valuable.

Further research is required beyond the specific context of our cases. In this respect our research was confined to a sampling of cases within a single low technology industry, which limits the generalisability of our findings (e.g. Yin, 2014). While similar characteristics are present across the family of process industries (e.g. Lager, 2017), a number of problems resulted from limited budgets for process innovation, and may reflect the specific context of both the industry and the firms concerned. Prior studies suggest this is common within process innovation (Robertson et al., 2012). Despite this, future studies should compare low- and high-technology industries in order to illuminate the extent to which such problems are more acute in low technology industries, and identify other potential differences depending on the industry context. Building upon our insights from radical process innovation projects, we suggest a need for further studies to examine radical product innovation projects, utilising knowledge management as a conceptual lens to understand the sources of key problems and the coping mechanisms employed.

A number of our specific findings warrant further investigation. For example, our identification of 'traditional' and 'front runner' members of the production team warrants further investigation. Future studies should examine each of these types of production team members and attempt to understand the roles that front-runners can perform in process innovation projects. Such research could draw on the product champion literature in order to identify both commonalities and differences. We have also identified the use of entrepreneurial bricolage within production innovation teams in order to test new solutions within budgetary limitations. Research is required to further understand how this occurs and the capabilities required within production teams. Finally, within Cases A, B and F, the outsourced nature of production further contributed to equivocality between senior-decision makers and the engineering. Future studies should examine how the outsourcing of production impacts on process innovation.

6. Reference List

Aaboen, L., Dubois, A. and Lind, F., 2012. Capturing processes in longitudinal multiple case studies. Industrial Marketing Management, 41, 2, 235-246. DOI: https://doi.org/10.1016/j.indmarman.2012.01.009

Arora, A., Gambardella, A., 1997. Domestic markets and international competitiveness: generic and product-specific competencies in the engineering sector. Strategic Management Journal, 18, 1, 53–74. DOI: https://doi.org/10.1002/(SICI)1097-0266(199707)18:1+<53::AID-SMJ919>3.0.CO;2-V

Ashayeri, J. and Teelen, A., 1996. A production and maintenance planning model for the process industry. International Journal of Production Research, 34, 12, 3311–3326. DOI: https://doi.org/10.1080/00207549608905092

Aurich, J.C., Wagenknecht, C., and Wolf, N., 2008. Process chains in cross enterprise production: a module based design framework. International Journal of Production Research, 46, 17, 4947–4962. DOI: https://doi.org/10.1080/00207540701241875

Aylen, J., 2010. Open versus closed innovation: development of the wide strip mill for steel in the USA during the 1920's. R&D Management, 40, 1, 67-80. DOI: https://doi.org/10.1111/j.1467-9310.2009.00576.x

Aylen, J., 2013. Stretch: how innovation continues once investment is made. R&D Management, 43, 3, 271-287. DOI: https://doi.org/10.1111/radm.12014

Barnett, B.D. and Clark, K.B., 1996. Technological newness: an empirical study in the process industries. Journal of Engineering and Technology Management, 13, 3-4, 263-282. DOI: https://doi.org/10.1016/S0923-4748(96)01009-0

Bauer, M., and Leker, J., 2013. Exploration and exploitation in product and process innovation in the chemical industry. R&D Management, 43, 3, 196-212. DOI: https://doi.org/10.1111/radm.12012

Benner, M. J., and Tushman, M., 2003. Exploitation, exploration, and process management: The productivity dilemma revisited. Academy of Management Review, 28, 2, 238-256. DOI: https://doi.org/10.5465/amr.2003.9416096

Bergfors, M., and Lager, T., 2011. Innovation of process technology: exploring determinants for organizational design. International Journal of Innovation Management, 15, 5, 1113–1140. DOI: https://doi.org/10.1142/S1363919611003635

Bessant, J., Oberg, C. and Triflova, A., 2014. Framing problems in radical innovation. Industrial Marketing Management, 43, 8, 1284-1292. DOI: https://doi.org/10.1016/j.indmarman.2014.09.003

Blumer, H., 1954. What is wrong with social theory? American Sociological Review, 19, 1, 3–10. DOI: 10.2307/2088165

Braun, V., and Clarke, V., 2006. Using thematic analysis in psychology. Qualitative research in psychology, 3, 2, 77-101.

De Brentani, U., & Reid, S. E., 2012. The fuzzy front-end of discontinuous innovation: Insights for research and management. Journal of Product Innovation Management, 29, 1,, 70-87. DOI: https://doi.org/10.1111/j.1540-5885.2011.00879.x

Bunduchi, R. and Smart, A., 2010. Process innovation costs in supply networks: a synthesis. International Journal of Management Reviews, 12, 4, 365–383. DOI: https://doi.org/10.1111/j.1468-2370.2009.00269.x

Cooper, R.G. and Kleinschmidt, E.J., 1994. Determinants of timeliness in product development. Journal of Product Innovation Management, 11, 5, 381-396. DOI: https://doi.org/10.1111/1540-5885.1150381

Cooper, R.G. and Sommer, A., 2016. The agile-Stage-Gate hybrid model: A promising new approach and a new research opportunity. Journal of Product Innovation Management, 33, 5, 513-526. DOI: https://doi.org/10.1111/jpim.12314

Cronin, M. A., and Weingart, L. R., 2007. Representational gaps, information processing, and conflict in functionally diverse teams. Academy of Management Review, 32, 3, 761-773. DOI: https://doi.org/10.5465/amr.2007.25275511

Crossan, M.M., Lane, H.W., and White, R.E., 1999. An organizational learning framework: from intuition to institution. Academy of Management Review, 24, 3, 522–537. DOI: https://doi.org/10.5465/amr.1999.2202135

Damanpour, F., and Gopalakrishnan, S., 2001. The Dynamics of the adoption of Product and Process Innovation in Organizations. Journal of Management Studies, 38, 1, 45-65. DOI: https://doi.org/10.1111/1467-6486.00227

Denison, D., R. Hooijberg, and R. Quinn., 1995. Paradox and performance: Toward a theory of behavioural complexity in managerial leadership. Organization Science, 6, 5m 524–540. DOI: https://doi.org/10.1287/orsc.6.5.524

Denzin and Lincoln, 2000: Denzin, N., Lincoln, Y., 1994. Handbook of Qualitative Research. Sage Publications, Thousand Oaks.

Dinca, C. and Badea, A., 2013. The parameters optimization for a CFBC pilot plant experimental study of post-combustion CO2 capture by reactive absorption with MEA. International Journal of Greenhouse Gas Control, 12, 269-279. DOI: https://doi.org/10.1016/j.ijggc.2012.11.006

Dodgson, M., Gann, D.M. and Salter, A., 2008. The management of technological innovation: strategy and practice, Oxford University Press.

Driessen, P.H. and Hillebrand, B., 2013. Integrating multiple stakeholder issues in new product development: an exploration. Journal of Product Innovation Management, 30, 2, 364-379. DOI: https://doi.org/10.1111/j.1540-5885.2012.01004.x

Dubois, A., and Gadde, L.E., 2002. Systematic combining: an abductive approach to case research. Journal of Business Research, 55, 7, 553–560. DOI: https://doi.org/10.1016/S0148-2963(00)00195-8

Dubois, A., and Gibbert, M., 2010. From complexity to transparency: managing the interplay between theory, method and empirical phenomena in IMM case studies. Industrial Marketing Management, 39, 1, 129–136. DOI: https://doi.org/10.1016/j.indmarman.2009.08.003

Edmondson, A.C., and McManus, S.E., 2007. Methodological fit in management field research. Academy of Management Reviews, 32, 4, 1155–1179. DOI: https://doi.org/10.5465/amr.2007.26586086

Eisenhardt, K., 1989. Building Theories from Case Study Research. Academy of Management Review, 14, 4, 532–550. DOI: https://doi.org/10.5465/amr.1989.4308385

Erumban, A., 2008. Lifetimes of machinery and equipment: Evidence from Dutch manufacturing. Review of Income and Wealth, 54, 2, 237-268. DOI: https://doi.org/10.1111/j.1475-4991.2008.00272.x

FDF (Food and Drink Federation), 2019. The Food and Drink Industry: Economic Growth and Growth Opportunities, London.

Filippou, D. and King, M.G., 2011. R&D prospects in the mining and metals industry. Resource Policy, 36, 3, 276–284. DOI: https://doi.org/10.1016/j.resourpol.2011.04.001

Flick, U.,1998. An Introduction to Qualitative Research, Cambridge, UK: SAGE Publications.

Florén, H. and Frishammar, J., 2012. From preliminary ideas to corroborated product definitions: managing the front end of new product development. California Management Review, 54, 4, 20–43. DOI: https://doi.org/10.1525/cmr.2012.54.4.20

Floren, H., Frishammar, J., Parida, V. and Wincent, J., 2018. Critical success factors in early new product development: a review and a conceptual model. International Entrepreneurship Management Journal, 14, 2, 411-427. DOI: https://doi.org/10.1007/s11365-017-0458-3

Frishammar, J., Ericsson, K. and Patel, P.C., 2015. The dark side of knowledge transfer: Exploring knowledge leakage in joint R&D projects. Technovation, 41-45, 75-88. DOI: https://doi.org/10.1016/j.technovation.2015.01.001

Frishammar, J., Florén, H., and Wincent, J., 2011. Beyond managing uncertainty: insights from studying equivocality in the fuzzy front-end of product and process innovation projects. IEEE Transactions on Engineering Management, 50, 3, 551–563. DOI: 10.1109/TEM.2010.2095017

Frishammar, J., Lichtenthaler, U., and Kurkkio, M., 2012. The front end in non-assembled product development: a multiple case study of mineral- and metal firms. Journal of Engineering and Technology Management, 29, 4, 468–488. DOI: https://doi.org/10.1016/j.jengtecman.2012.07.001

Frishammar, J., Lichtenthaler, U., and Richtner, A., 2013. Managing process development: key issues and dimensions in the front end. R&D Management, 43, 3, 213-226. DOI: https://doi.org/10.1111/radm.12011

Galbraith, J. R., 1973. Designing Complex Organizations, Reading, MA: Addison Wesley Publishing Co.

Garcia, R. and Calantone, R., 2002. A critical look at technological innovation typology and innovativeness terminology: a literature review. Journal of Product Innovation Management, 19, 2, 110-132. DOI: https://doi.org/10.1111/1540-5885.1920110

Glaser, B. G., 1978. Theoretical sensitivity. Mill Valley, CA: Sociology Press.

Heller, T. 2000. If only we'd known sooner: Developing knowledge of organizational changes earlier in the product development process. IEEE Transactions on Engineering Management, 47, 3, 335–359. DOI: 10.1109/17.865902

Hellsmark, H., Frishammar, J., Soderholm, P. and Ylinenpaa, H., 2016. The role of pilot and demonstration plants in technology development and innovation policy. Research Policy, 45, 9, 1743-1761. DOI: https://doi.org/10.1016/j.respol.2016.05.005

Henderson, R.M., and Clark, K. B., 1990. Architectural innovation: the reconfiguration of existing product technology and the failure of established firms. Administrative Science Quarterly, 35, 1, 9-31. DOI: 10.2307/2393549

Hoegl, M. and Wagner, S., 2005. Buyer-supplier collaboration in product development projects. Journal of Management, 31, 1, 530-548. DOI: https://doi.org/10.1177/0149206304272291

Huber, G. P., 1984. The Nature and Design of Post-Industrial Organizations. Management Science, 30, 8, 928- 951. DOI: https://doi.org/10.1287/mnsc.30.8.928

Hullova, D. Simms, C., Trott, P. and Laczko, P., 2018. Critical capabilities for effective management of complimentarity between product and process innovation: cases from the food and drink industry. Research Policy, 48, 1, 339-354. DOI: https://doi.org/10.1016/j.respol.2018.09.001

Hullova., D., Trott, P. and Simms, C.D., 2016. Uncovering the reciprocal complementarity between product and process innovation. Research Policy, 45, 5, 929-940. DOI: https://doi.org/10.1016/j.respol.2016.01.012

Hutcheson, P., Pearson, A.W., and Ball, D.F., 1995. Innovation in process plant: a case study of ethylene. Journal of Product Innovation Management, 12, 5, 415-430. DOI: https://doi.org/10.1111/1540-5885.1250415

Johnsson, F., 2011. European Energy Pathways: Pathways to Sustainable European Energy Systems. Energy Technology, Chalmers University of Technology, Gothenburg.

Keizer, J. A., and Halman, J. I., 2007. Diagnosing risk in radical innovation projects. Research-Technology Management, 50, 5, 30-36. DOI: https://doi.org/10.1080/08956308.2007.11657459

Kijkuit, B., and van den Ende, J., 2007. The Organizational Life of an Idea: Integrating Social Network, Creativity and Decision-Making Perspectives. Journal of Management Studies, 44, 6, 863-882. DOI: https://doi.org/10.1111/j.1467-6486.2007.00695.x

Kurkkio, M., Frishammar, J. and Lichtenthaler, U., 2011. Where process development begins: a multiple case study of front end activities in process firms. Technovation, 31, 9, 490–504. DOI: https://doi.org/10.1016/j.technovation.2011.05.004

Lager, T. 2000. A New Conceptual Model for the Development of Process Technology in Process Industry A point of departure for the transformation of the “process development process” into a formal work process? International Journal of Innovation Management, 43, 3, 319-346. DOI: https://doi.org/10.1142/S1363919600000159

Lager, T. 2002. Product and process development intensity in process industry: A conceptual and empirical analysis of the allocation of company resources for the development of process technology. International Journal of Innovation Management, 6, 2, 105-130. DOI: https://doi.org/10.1142/S1363919602000537

Lager, T. 2016. Managing Innovation & Technology in the Process Industries: Current practices and future perspectives. Procedia Engineering, 138, 1, 459-471.

Lager, T. 2017a. A conceptual framework for platform-based design of non-assembled products. Technovation, 68, 20-34. DOI: https://doi.org/10.1016/j.technovation.2017.09.002

Lager, T. 2017b. A conceptual analysis of conditions for innovation in the process industries and a guiding framework for industry collaboration and further research. International Journal of Technological Learning, Innovation and Development, 9, 3, 189-218. DOI: https://doi.org/10.1504/IJTLID.2017.087403

Lager, T. Blanco, S., and Frishammar, J., 2013. Managing R&D and Innovation in the Process Industries. R&D Management, 43, 3, 189-195. DOI: https://doi.org/10.1111/radm.12018

Lager, T and Frishammar, J., 2012. Collaborative development of new produces technology/equipment in the process industries: in search of enhanced innovation performance. Journal of Business Chemistry, 9, 2, 67-84.

Lager, T., Rennard, J.P., Bruch, J. and Bellgran, M. 2014. Integrated portfolio planning of products and production systems. Journal of Manufacturing and Technology Management, 25, 155-174. DOI: https://doi.org/10.1108/JMTM-09-2013-0126

Lane, D.A. and Maxfield, R.R. 2005. Ontological uncertainty and innovation. Journal of Evolutionary Economics, 15, 1, 3-50. DOI: https://doi.org/10.1007/s00191-004-0227-7

Leenders, R.T., Kratzer, J. and van Engelen, J.M., 2007. Innovation team networks: the centrality of innovativeness and efficiency. International Journal of Networking and Virtual Organisations, 4, 4, 459–478. DOI: https://doi.org/10.1504/IJNVO.2007.015726

Leonard-Barton, D. 1992. Core capabilities and core rigidities: A paradox in managing new product development. Strategic management journal, 13, 1, 111-125. DOI: https://doi.org/10.1002/smj.4250131009

Lim, L.P.L., Garnsey, E. and Gregory, M., 2006. Product and process innovation in biopharmaceuticals: a new perspective on development. R&D Management, 36, 1, 27-36. DOI: https://doi.org/10.1111/j.1467-9310.2006.00413.x

Linton, J.D., and Walsh, S.T., 2008. A theory of innovation for process-based innovations such as nanotechnology. Technological Forecasting & Social Change, 75, 5, 583–594. DOI: https://doi.org/10.1016/j.techfore.2007.02.005

Magistretti, S., Trabucchi, D., Dell'Era, C., and Buganza, T., 2019. A New Path Toward a Hybrid Model: Insights from PwC's Italian Experience Centre. Research-Technology Management, 62, 5, 30-37. DOI: https://doi.org/10.1080/08956308.2019.1638223

March, J. 1994. A Primeron Decision Making: How Decisions Happen. The Free Press, New York, NY.

March, J. G. and Simon, H.A., 1958. Organizations, New York: Wiley.

Martinsuo, M. and J. Poskela, 2009. Use of Evaluation Criteria and Innovation Performance in the Front End of Innovation. Journal of Product Innovation Management, 28, 6, 896-914. DOI: https://doi.org/10.1111/j.1540-5885.2011.00844.x

McDermott, C. M., 1999. Managing radical product development in large manufacturing firms: a longitudinal study. Journal of Operations Management, 17, 6, 631-644. DOI: https://doi.org/10.1016/S0272-6963(99)00018-2

McAdam, R., and Leonard, D., 2004. Reengineering based inquiry into innovation in the front end of new product and service development processes. International Journal of Product Development, 1, 1, 66–91. DOI: https://doi.org/10.1504/IJPD.2004.004891

Meyer, M.H., and Dalal, D., 2002. Managing platform architectures and manufacturing processes for non-assembled products. Journal of Product Innovation Management, 19, 4, 277–293. DOI: https://doi.org/10.1111/1540-5885.1940277

Miles, M. B. and Huberman, A. M., 1994. Qualitative data analysis: An expanded sourcebook, Sage.

Nag, R., Hambrick, D.C. and Chen, M.J., 2007. What is strategic management really? Inductive derivation of a consensus definition of the field. Strategic Management Journal, 28, 9, 935-955. DOI: https://doi.org/10.1002/smj.615

Novotny, M. and Laestadius, S., 2014. Beyond papermaking: technology and market shifts for wood-based biomass industries – management implications for large-scale industries. Technology Analysis and Strategic Management, 26, 8, 875-891. DOI: https://doi.org/10.1080/09537325.2014.912789

O'Connor, G.C. and Rice, M.P., 2013. A comprehensive model of uncertainty associated with radical innovation. The Journal of Product Innovation Management, 30, 1, 2-18. DOI: https://doi.org/10.1111/jpim.12060

O'Connor, G.C. and Veryzer, R.W., 2004. The nature of market visioning for technology-based radical innovation. The Journal of Product Innovation Management, 18, 4, 231-246. DOI: https://doi.org/10.1111/1540-5885.1840231

Ozman, M., 2011. Modularity, industry life cycle and open innovation. Journal of technology management and innovation, 6, 1, 26-34. DOI: http://dx.doi.org/10.4067/S0718-27242011000100003

Pellizzoni, E., Trabucchi, D., Frattini, F., Buganza, T., and Di Beneditto, A., 2020. Leveragng stakeholders knowledge in new service development: a dynamic approach. Journal of Knowledge Management, 24, 2, 415-436. DOI: https://doi.org/10.1108/JKM-10-2019-0532

Pettinau, A., Cali, G., Loria, E. Miraglia, P. and Ferrara, F., 2015. The Sotcarbo gasification pilot platform: plant overview, recent experimental results and potential future integrations. Applied Thermal Engineering, 74, 2-9. DOI: https://doi.org/10.1016/j.applthermaleng.2013.12.079

Pisano, G., 1994. Knowledge, Integration and the Locus of Learning: An Empirical Analysis of Process Development. Strategic Management Journal, 15, 1, 85-100. DOI: https://doi.org/10.1002/smj.4250150907

Pisano, G. P. 1996. Learning-before-doing in the development of new process technology. Research Policy, 25, 7, 1097-1119. DOI: https://doi.org/10.1016/S0048-7333(96)00896-7

Pisano, G., and Shih, W., 2012. Producing Prosperity: Why America Needs a Manufacturing Renaissance. Boston: Harvard Business Review Press.

Reichstein, T. and Salter, A., 2006. Investigating the sources of process innovation among UK manufacturing firms. Industrial and Corporate Change, 15, 4, 653-682. DOI: https://doi.org/10.1093/icc/dtl014

Reid, S. and de Brentani, U., 2004. The Fuzzy Front End of New Product Development for Discontinuous Innovations: A Theoretical Model. Journal of Product Innovation Management, 21, 3, 170-184. DOI: https://doi.org/10.1111/j.0737-6782.2004.00068.x

Robertson, P., Casali, G.L. and Jacobson, D., 2012. Managing open incremental process innovation: absorptive capacity and distributed learning. Research Policy, 41, 5, 822-832. DOI: https://doi.org/10.1016/j.respol.2012.02.008

Rönnberg-Sjödin, D., Frishammar, J. and Eriksoon, P.E., 2016. Managing Uncertainty and Equivocality in joint process development projects. Journal of Engineering and Technology Management, 39, 13-25. DOI: https://doi.org/10.1016/j.jengtecman.2015.12.001

Sjödin, D. 2019. Knowledge processing and ecosystem co-creation for process innovation: Managing joint knowledge processing in process innovation projects. International Entrepreneurship and Management Journal, 15, 135-162. DOI: https://doi.org/10.1007/s11365-018-0550-3

Shen-Li, C., Chih-Yuan,C., and Shyh-Chyi,W., 2007. Conceptualizing, assessing and managing front-end in innovation/npd projects. R&D Management, 37, 5, 469–478. DOI: https://doi.org/10.1111/j.1467-9310.2007.00489.x

Simms, C. D., and Trott, P., 2014. Barriers to the upgrade cycle in a commodity process industry: Evidence from the UK packaging industry. R&D Management, 44, 2, 152-170. DOI: https://doi.org/10.1111/radm.12047

Simon, H.A. 1969. The Science of Artificial. MIT Press.

Slack, N., Chambers, S., and Johnston, R. 2007. Operations Management. Essex, UK: Prentice Hall.

Smith, A. and Raven, R., 2012. What is protective space? Reconsidering niches in transitions to sustainability. Research Policy, 41, 6, 1025-1036. DOI: https://doi.org/10.1016/j.respol.2011.12.012

Smith, W. K., and Tushman, M. L., 2005. Managing strategic contradictions: A top management model for managing innovation streams. Organization Science, 16, 5, 522–536. DOI: https://doi.org/10.1287/orsc.1050.0134

Stabell, C. B. 1978. Integrative Complexity of Information Environment Perception and Information Use. Organizational Behavior and Human Performance, 22, 116-142. DOI: https://doi.org/10.1016/0030-5073(78)90009-0

Steiner, R. L. 2004. The Nature and Benefits of National Brand/Private Label Competition. Review of Industrial Organisation, 24, 2, 105–127. DOI: https://doi.org/10.1023/B:REIO.0000033351.66025.05

Stevens, E., 2014. Fuzzy front-end learning strategies: Exploration of a high-tech company. Technovation, 34, 431-440. DOI: https://doi.org/10.1016/j.technovation.2013.12.006

Tang, J., 2006. Competition and innovation behaviour. Research Policy, 35, 68-82. DOI: https://doi.org/10.1016/j.respol.2005.08.004

Townsend, D.M., Hunt, R.A., McMullen, J.S. and Sarasvathy, S.D., 2018. Uncertainty, knowledge problems, and entrepreneurial action. Academy of Management Annals, 12, 2, 659-687. DOI: https://doi.org/10.5465/annals.2016.0109

Trott, P. and Simms, C., 2017. An examination of product innovation in low- and medium-technology industries: cases from the UK packaged food sector. Research Policy, 46, 3, 605-623. DOI: https://doi.org/10.1016/j.respol.2017.01.007

Tyre, M.J. and Orlikowski, W.J., 1994. Windows of Opportunity: Temporal patterns of technology adaptation in organisations. Organization Science, 5, 1, 98-118. DOI: https://doi.org/10.1287/orsc.5.1.98

Upton, D.M., 1997. Process Range in Manufacturing: An Empirical Study of Flexibility. Management Science, 43, 8, 1047-1188. DOI: https://doi.org/10.1287/mnsc.43.8.1079

Utterback, J.M., 1994. Mastering the Dynamics of Innovation, Harvard Business School Press, Boston.

Utterback, J. M., and Abernathy, W. J., 1975. A dynamic model of process and product innovation. Omega, 3, 6, 639-656.

Verworn, B., 2009. A Structural Equation Model of the Impact of the ‘Fuzzy Front End’ on the Success of New Product Development. Research Policy, 38, 10, 1571-1581. DOI: https://doi.org/10.1016/j.respol.2009.09.006

Verworn, B., Herstatt, C. and Nagahira, A., 2008. The Fuzzy Front End of Japanese New Product Development Projects: Impact on Success and Differences between Incremental and Radical Projects. R&D Management, 38, 1, 1-19. DOI: https://doi.org/10.1111/j.1467-9310.2007.00492.x

Veryzer, R.W., 1998. Discontinuous Innovation and the New Product Development Process. Journal of Product Innovation Management, 15, 4, 304-321. DOI: https://doi.org/10.1111/1540-5885.1540304

Veryzer, R.W., 2004. The Roles of Marketing and Industrial Design in Discontinuous New Product Development. The Journal of Product Innovation Management, 22, 1, 22-44. DOI: https://doi.org/10.1111/j.0737-6782.2005.00101.x

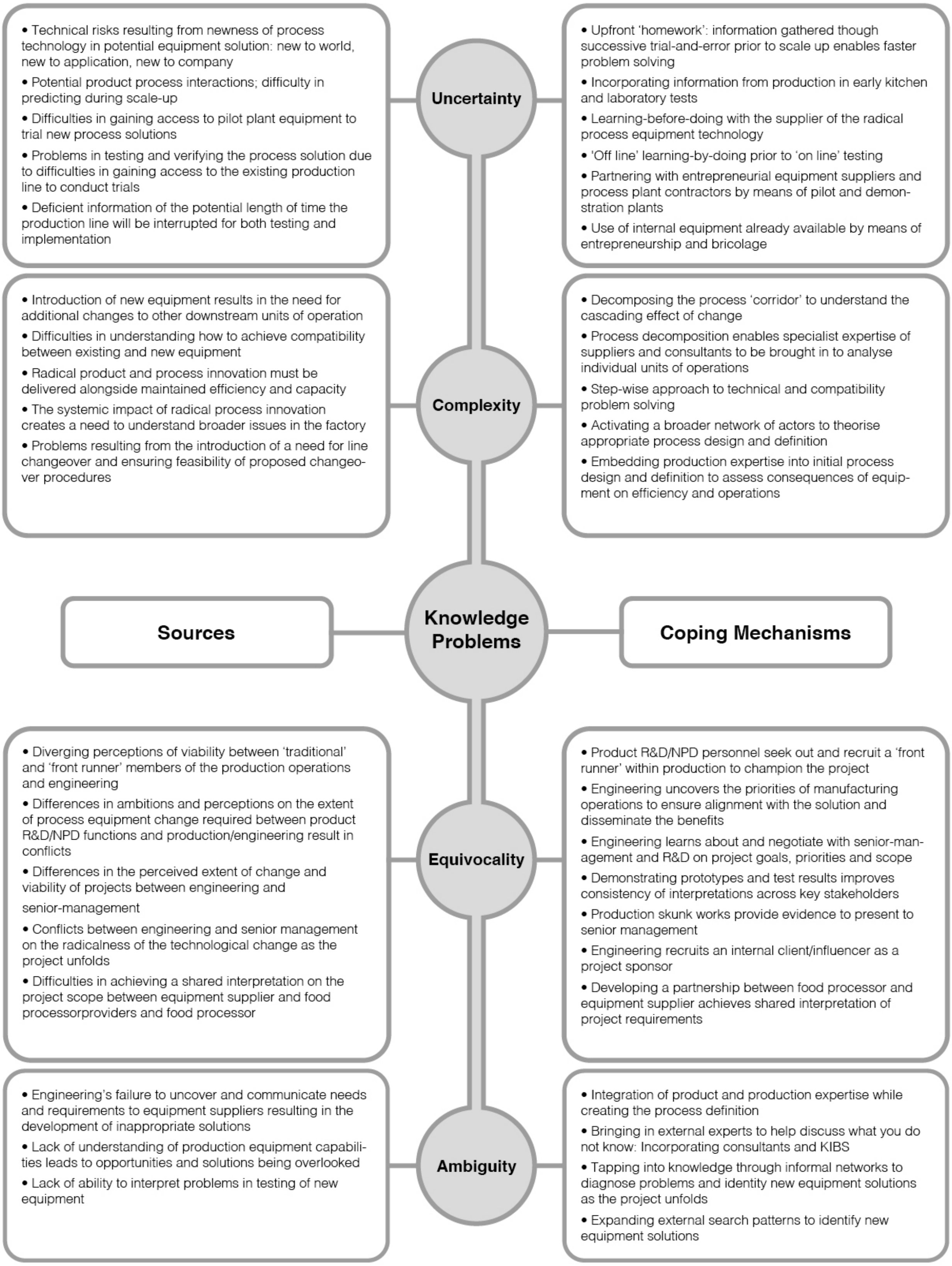
Walsh, J. P., 1995. Managerial and organizational cognition: Notes from a trip down memory lane. Organization Science, 6, 3, 280–321. DOI: https://doi.org/10.1287/orsc.6.3.280

Weick, K.E., 1969. The Social Psychology of Organizing. McGraw-Hill, NewYork, NY.

Yin, R. K., 2012. Applications of case study research (3rd ed.). Washington DC: SAGE Publications, Inc.

Zack, M.H., 2001. If managing knowledge is the solution, then what’s the problem?. In: Malhotra ,Y. (Ed.), Knowledge Management and Business Model Innovation. Idea Group Publishing, London, 16–36.

Figure 1: Coding tree with sources of knowledge problems to the left, with aligned coping mechanisms used to address the problems to the right



Knowledge Problems
Sources
Coping Mechanisms
Uncertainty
• Technical risks resulting from newness of process technology in potential equipment solution: new to world, new to application, new to company
• Potential product process interactions; difficulty in predicting during scale-up
• Difficulties in gaining access to pilot plant equipment to trial new process solutions
• Problems in testing and verifying the process solution due to difficulties in gaining access to the existing production line to conduct trials
• Deficient information of the potential length of time the production line will be interrupted for both testing and implementation
• Upfront 'homework': information gathered though successive trial-and-error prior to scale up enables faster problem solving
• Incorporating information from production in early kitchen and laboratory tests
• Learning-before-doing with the supplier of the radical process equipment technology
• 'Off line' learning-by-doing prior to 'on line' testing
• Partnering with entrepreneurial equipment suppliers and process plant contractors by means of pilot and demonstration plants
• Use of internal equipment already available by means of entrepreneurship and bricolage
Complexity
• Introduction of new equipment results in the need for additional changes to other downstream units of operation
• Difficulties in understanding how to achieve compatibility between existing and new equipment
• Radical product and process innovation must be delivered alongside maintained efficiency and capacity
• The systemic impact of radical process innovation creates a need to understand broader issues in the factory
• Problems resulting from the introduction of a need for line changeover and ensuring feasibility of proposed changeover procedures
• Decomposing the process 'corridor' to understand the cascading effect of change
• Process decomposition enables specialist expertise of suppliers and consultants to be brought in to analyse individual units of operations
• Step-wise approach to technical and compatibility problem solving
• Activating a broader network of actors to theorise appropriate process design and definition
• Embedding production expertise into initial process design and definition to assess consequences of equipment on efficiency and operations
Equivocality
• Diverging perceptions of viability between 'traditional' and 'front runner' members of the production operations and engineering
• Differences in ambitions and perceptions on the extent of process equipment change required between product R&D/NPD functions and production/engineering result in conflicts
• Differences in the perceived extent of change and viability of projects between engineering and senior-management
• Conflicts between engineering and senior management on the radicalness of the technological change as the project unfolds
• Difficulties in achieving a shared interpretation on the project scope between equipment supplier and food processorproviders and food processor
• Product R&D/NPD personnel seek out and recruit a 'front runner' within production to champion the project
• Engineering uncovers the priorities of manufacturing operations to ensure alignment with the solution and disseminate the benefits
• Engineering learns about and negotiate with senior-management and R&D on project goals, priorities and scope
• Demonstrating prototypes and test results improves consistency of interpretations across key stakeholders
• Production skunk works provide evidence to present to senior management
• Engineering recruits an internal client/influencer as a project sponsor
• Developing a partnership between food processor and equipment supplier achieves shared interpretation of project requirements
Ambiguity
• Engineering's failure to uncover and communicate needs and requirements to equipment suppliers resulting in the development of inappropriate solutions
• Lack of understanding of production equipment capabilities leads to opportunities and solutions being overlooked
• Lack of ability to interpret problems in testing of new equipment
• Integration of product and production expertise while creating the process definition
• Bringing in external experts to help discuss what you do not know: Incorporating consultants and KIBS
• Tapping into knowledge through informal networks to diagnose problems and identity new equipment solutions as the project unfolds
• Expanding external search patterns to identify new equipment solutions

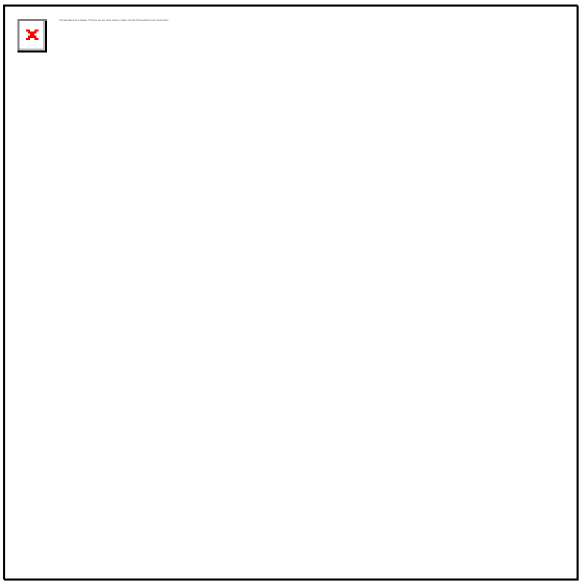

The linked image cannot be displayed. The file may have been moved, renamed, or deleted. Verify that the link points to the correct file and location.

Figure 2: Coping Mechanisms for Effective Decision-Making in the Front End of Radical Process Innovation

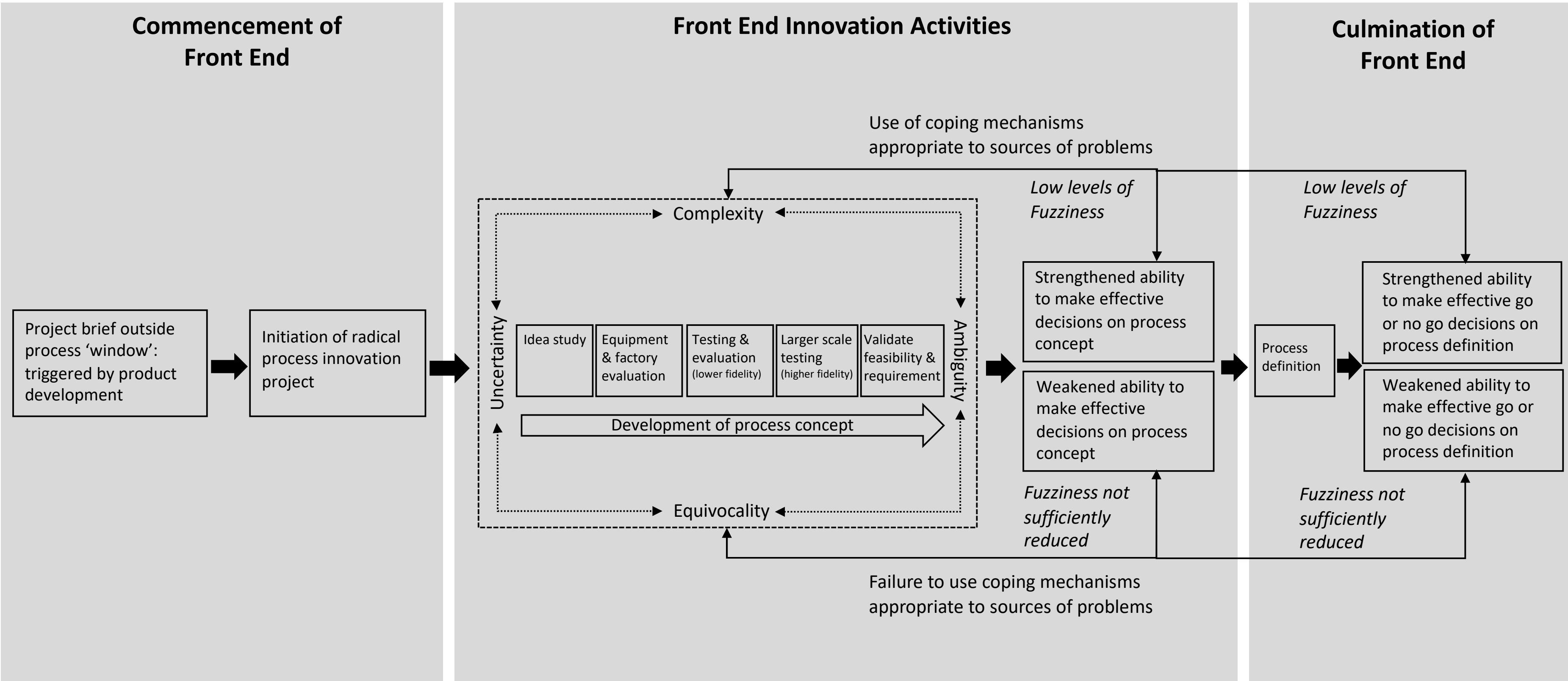


Table 1: Overview of Firms, Process Innovation Cases and Interviewees

Project and Firm Details	Project Overview/Summary	Process innovations & equipment technology newness	Interviewees
Project A: Protein bar Medium sized firm: UK outsourced snack manufacturer	Background: Marketing recognised opportunity for novel healthy protein and fruit breakfast bar. Aim: To manufacture a new to market high-protein breakfast bar format with novel carbohydrate and fruit paste. External Collaborators: Manufacturer within firm's local network, OEM and supplier of blade mixing equipment. Process Window constraints: New ingredients and shape incompatible with existing equipment. Duration: Spring 2015 to Spring 2016	New version of blade mixing equipment (non-OEM) custom developed and designed to bolt into existing machinery and novel purpose-built cutting and shaping tool, creating need for extension to current forming equipment and introduction of requirement for production line changeover.	*Food Processor/:* (I1) Head of Production (Group), (I2) Production Engineer, (I3) Technical Director, (I4) NPD Manager, (I5) Line Manager. *Snack Foods Brand owner:* (I6) Head of NPD, (I7) NPD Manager, (I8) COO, (I9) CEO, (I10) Packaging Development Manager, (I11) Head of Sales. *Equipment manufacturer:* (I12) Demonstration plant manager/engineer.
Project B: Filled protein sphere	Background: Marketing identified opportunity for premium filled version of existing product. Aim: Manufacture premium version of existing product, in a new to market liquid paste-filled sphere format. External collaborators: Filling/extrusion equipment supplier, equipment supplier, OEM. Process Window constraints: No filling capability. Duration: Late 2015 to Early 2017	Extensive line reconstruction to introduce novel purpose-developed extrusion filling equipment (new equipment developed from model previously used for chicken kiev) purpose-built tubing apparatus, conveyor belts, automatic product topping, and new packaging equipment.	
Project C: Naturally Sweetened Cordial Large firm: European beverages manufacturer & brand owner	Background: Consumer demand necessitated introduction of natural sweeteners into product. Aim: To replace liquid artificial sweeteners with lower cost powdered natural sweeteners in the manufacturing of an existing cordial product, introducing novel sweetener to product category. External collaborators: Pre-slurry equipment supplier, specialist engineering consultancy. Process Window constraints: Existing equipment designed for liquid slurry and unable to handle or process powdered ingredients. Duration: Mid 2014 to Late 2016	Extensive line reconstruction to enable the introduction of a novel compact two-phase pre-slurry mixer with dosing system, purpose-designed to interface with existing line (internally referred to as 'injection system'), combined with need for changes to complete filling and packaging line to accommodate smaller packaging. IT hardware and software changes required.	*Food processor:* (I13) Senior Beverages R&D Manager, (I14) Production Unit Manager, (I15) Senior Engineer (Process), (I16) Product scientist, (I17) Production Engineering Manager. *Equipment supplier:* (I18) Technical sales manager. Engineering consultancy firm: (I19) Engineering R&D manager.
Project D: Wine bag-in-box Medium sized firm: European beverage producer	Background: Marketing identified opportunity for a 1-litre bag-in-box wine packaging format. Aim: Introduction of novel vertical 'form-fill-seal' packaging system to produce compact bag-in-box with faster fill rate. External collaborators: Specialist equipment supplier. Process Window constraints: Existing equipment used a large and slow horizontal filling process only able to fill a single bag size. Project Duration: Eighty nine weeks from initiation to commencement of production. Duration: Late 2010 to Early 2013	Replacement of horizontal filling system for pre-formed bags with new flexible vertical form-fill-seal system, this equipment was new to market requiring significant redesign to apply to beverages application). Production developments required for insertion and welding of single piece tap on production line.	*Food processor:* (I20) Technical Operations Manager, (I21) Packaging Manager, (I22) Production Development Engineer, (I23) Senior Development Engineer (Process). *Equipment supplier:* (I24) Process engineer. *Consultancy firm:* (I25) Consultant.
Project E: Chocolate spread in 'doy pack' Large firm: International FMCG; food and beverages	Background: Recognition of market opportunity for a squeezy packaging format for spread. Aim: Introduce novel 'doy pack' format into product category, applying within existing process. External collaborators: Separate non-EU SBU manufacturing site, packaging equipment supplier. Process Window constraints: Existing production equipment designed for pre-formed tub. No 'form-fill-seal' capability for doy pack. Duration: Late 2012 to Early 2014	Extensive reconstruction of packaging line to enable the introduction of new form-fill-seal packaging equipment to enable the line to produce 'doy pack' alongside traditional tub format. This introduced the need to design and introduce processes for line changeover.	*Food processor:* (I26) NPD Manager Confectionary, (I27) Head of Packaging Design (confectionary), (I28) Technical Development Manager: production, (I29) Line Manager, (I30) Technical Engineer, (I31) Engineering Project Manager.
Project F: Pea based snack food Medium sized firm: UK private label (outsourced) snack foods manufacturer	Background: Client brief to develop a new to market crisp product manufactured from pea flour. Aim: New process to achieve desired texture profile at full-scale production speed. External collaborators: Supplier and engineering consultancy firm. Constraints of process window: Introduction of novel dual screw extruder required replacement of main production equipment module. Process window constraints; Existing 'single screw' extruder unable to produce the required texture or shape using pea-based flours. Duration: Early 2015 to Late 2016	Replacement of existing extrusion machinery with novel new to market dual screw extrusion equipment technology providing greater pressure in moulding and initial baking process.	*Food Processor:* (I32) Head of NPD; puffed snacks, (I33) Line Manager, (I34) Senior Production Engineer, (I35) Technical director, (I36) Head of Production and Engineering. *Brand owner:* (I37) COO, (I38) Head of Marketing, (I39) Operations Manager (UK). *Engineering Consultancy:* (I40) Head of R&D (Trained Process Engineer).

Table 2: Linkages between sources of knowledge problems and coping mechanisms

	Knowledge Problems				
Coping Mechanisms					
	Sources of Uncertainty				
	Newness of process equipment	Product process interactions; scale-up	Difficulties accessing pilot plant equipment	Difficulties accessing production line	Deficient information on line interruption
Upfront ‘homework’: successive trial-and-error					
Incorporating production information in lab tests					
Learning-before-doing with the equipment supplier					
'Off line' learning-by-doing prior to ‘on line’ testing					
Partnering with entrepreneurial suppliers & plant contractors					
Use of equipment by entrepreneurship & bricolage					
	Sources of Complexity				
	Change extending throughout the line	Achieving equipment compatibility	Maintaining efficiency and capacity	Systemic impact on factory, facilities and procedures	Introduction of line changeover and proposed procedures
Decomposing the process ‘corridor’					
Suppliers and consultants analyse individual units					
Step-wise approach to problem solving					
Activating a broader network of actors					
Embedding production expertise to assess consequence to operations					
	Sources of Equivocality				
	Between members of engineering/ production	Between R&D/NPD & production actors	Between engineering & senior management	Radicalness of change as the project unfolds	Between equipment supplier & food processor
Product R&D/NPD seek out and recruit a ‘front runner’					
Uncovering the priorities of manufacturing ops.					
Learn about & negotiate with senior-management & R&D					
Demonstrating prototypes & test results					
Production skunk works					
Recruit internal client/ influencer as a sponsor					
Developing a partnership between food processor & equipment supplier					
	Sources of Ambiguity				
	Failure to uncover & communicate needs to suppliers	Lack of understanding of equipment capabilities	Lack of ability to interpret problems in testing		
Integration of product and production expertise within concept definition					
Bringing in external experts					
Tapping into knowledge through informal networks					
Expanding external search patterns					