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On the Treatment of Uncertainty in Innovation Projects

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Abstract

Innovations encounter a relatively high level of uncertainty in their lifecycle path. As innovations are about implementing a new idea, they suffer from a shortage or lack of knowledge dependent on and directly proportional to the radical quality of novelty. They lack information to predict the future and face (high) uncertainty in the background knowledge used for the risk assessment. Incomplete information causes innovation risk analysts to assign subjective assumptions to simplify system models developed for innovation risk assessment. Subjective and non-subjective assumptions as uncertain assumptions are part of the background knowledge and source of uncertainty. This thesis tries to assess and treat innovation assumptions uncertainties by proposing a hybrid model which comprises the semi-quantitative risk assessment (SQRA) approach, extended semi-quantitative risk assessment (EQRA) approach, and knowledge dimension method. SQRA and EQRA highlight the criticality of assumptions and present a systematic approach to assess and treat assumption uncertainties. SQRA applies probabilistic analysis to conduct an assumptions risk assessment, and EQRA provides innovation managers with guidance on developing strategies to follow up uncertain assumptions over the process implementation. The knowledge dimension technique evaluates and communicates the strength of background knowledge applied in assumptions risk assessment to innovation decision-makers expressing whole uncertainty aspects in the background knowledge (assumptions, data, models, and expert judgment). The model can effectively contribute to innovation risks and uncertainties management during the project execution.

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Abbs

SoK: Strength of Knowledge

QRA: Quantitative Risk Assessment

SQRA: Semi-quantitative Risk Assessment

EQRA: Extended Semi-quantitative Risk Assessment

QSS: Qualitative Screening Scheme

ABP: Assumption-Based Planning

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1. Introduction

In this chapter, the thesis approach towards dealing with the topic is explained. First, background information leading to form the thesis intention is described. The thesis objectives clarify the reader the purpose of this thesis. Then, research questions and how the thesis organization addresses these questions follow. Finally, imposed limitations on the work are introduced to the reader.

1.1 Background

The definition of risk in the ISO 31000 standard on risk management is the "*effect of uncertainty on objectives*" (The British Standards Institution, 2018). The formal definition of uncertainty analysis is, determining the uncertainty related to the results of an assessment that stemmed from existing uncertainty in the analysis inputs (including applied methods and models in assessment) (Helton et al., 2006).

More agreement has developed on the view that "*sustainable development*" is not achievable without system innovation. System innovation means all change processes in production and consumption systems, including social relationships, roles division, and official regulations and values, as well as preceded technical products and infrastructure that have co-developed with prior "*unsustainable*" production and consumption processes (Geels, 2004; Grin & van Staveren, 2007; Rip & Kemp, 1998). Research has been conducted, and theoretical descriptions have been developed to represent system innovations with high uncertainties, undesired results, and unpredictable events from a reductionism perspective (Prigogine & Stengers, 1990; Rotmans et al., 2005).

Probabilistic analysis is predominantly used to deal with the uncertainty in risk assessment (Helton, 2011); however, other uncertainty representations and treatment approaches have been proposed criticizing the probability analysis (Flage et al., 2014). To treating innovation uncertainty, there are many types of research in the innovation management context for specific subjects such as dam, for innovation uncertainty aspects such as technological uncertainty, or innovation type like disruptive innovations. But, analyzing dealing with innovation uncertainty considering innovation uncertainty characteristics and uncertainty representations in the risk assessment context is of this thesis interest.

1.2 Thesis objectives

The main intention of this thesis lies in characterizing innovation uncertainties and adapting a method to treat them from the risk perspective reducing risks involved in these projects as a significant contribution to their objectives' achievement. To reach this goal, innovation definitions and descriptions analysis led to characterizing innovation uncertainty in the risk assessment context. Also, examining current uncertainty representations contributed to finding an appropriate approach to treat these processes' uncertainties.

1.3 Research questions and structure of the thesis

To reach thesis targets, the topic 'on the treatment of uncertainty in innovation projects', was addressed by the following questions.

1- What is innovation?
2- What is uncertainty generally and from the risk perspective?
3- How can uncertainty be described in innovations? What are possible aspects of uncertainty in innovations?
4- Discuss how can innovation uncertainties be characterized in the risk assessment context?
5- What approach(es) can treat innovation uncertainties from the risk assessment perspective?

Moving from the first question to the last one and clarifying the content of each question formed the thesis path and chapters. The thesis was structured into seven chapters as follows.

1- Introduction outlines the thesis problem presentation, objectives, limitations, research questions, and structure.

2- In chapter two, the first question of the research is addressed. Innovations definitions and classifications which describe these types of projects are explained in this chapter.

3- The concept of uncertainty from a general and the risk perspective (question 2) is described in chapter three. Also, existing uncertainty representations from the risk assessment context are introduced.

4- The purpose of chapter four is to deal with questions 3 and 4. Due to describing innovation uncertainties, a frame is suggested by the author. Then, regarding innovation description, the nature and dimensions of uncertainty in innovations, also uncertainty concepts in the risk assessment context are explained to introduce targeted innovation uncertainty for treatment from the risk perspective.

5- In chapter five, research question 5, is answered. Based on the selected innovation uncertainty for treatment and reviewing uncertainty representations for this type of uncertainty, a model founded on the semi-quantitative approach for innovation uncertainty treatment is recommended.

6- Chapter six, discussion, explains some reflections, the limitations of the model application, and recommends a need for future work.

7- A summary of what has been done and learned constitutes the conclusion.

1.4 Thesis limitations

This thesis encountered some limitations. The first one is the generality of innovations comprised of a wide range of business areas from a service provider such as mental health providers to industries like air space and nuclear power. Placing restrictions on innovative process areas would contribute to more clarification and description of uncertainty dimensions in these projects. Diversity in innovation definition and classifications (defining innovations from different perspectives) also put an obstacle to explaining innovation uncertainties based on the most agreed unified framework. Another limitation was the lack of research on innovation uncertainty treatment in the risk assessment context. Unavailability of expert judgment and data was another constraint that prevented implementing the recommended model by a practical case. Finally, the time limit obliged the thesis to avoid analysing different aspects of uncertainty treatments in the risk assessment perspective and concentrate on epistemic uncertainty treatment derived from risk assessment inputs.

2. Literature Review

Innovation has been defined from different points of view and with different expressions though expressing one concept, implementing a new idea. In the following comes these definitions and innovation classifications with more diversity than its definition.

2.1 Definitions of innovation

Joseph Schumpeter, as a pioneer in innovation concept diffusion, describes innovation as a linked phenomenon to the firm's context which modifies the industry existing production systems through exploiting new idea or invention leading to new technology capable of offering new product or production process fulfilling the market requirement by new products (Schumpeter, 1942).

Innovation is defined as new technology or a combination of technologies that bring global benefits. It is not crystal clear from this definition that to what extent current practices are distinct from new ones (R. D. Dewar & Dutton, 1986; J. E. Ettlie et al., 1984; J. E. Ettlie, 1997). Major innovations require fundamental capabilities such as understanding the classification of the market, new skills, large changes in processing abilities, and systems across the organization. Then, an innovation development requirement may draw a clear distinction between activities of introducing a new product to the market and existing products within the company (Utterbak & Linsu, 1985).

Rogers (1995) believes that innovation is the first effort to implement an invention defined as a first idea of a new product or process. Also, an idea, practice, or object perceived by those who adopt it as new is an innovation (Rogers, 2003). This concept shows that the notion of innovation refers to something added to or entirely substituted with something else which already exists. The purpose of adding or giving up is to improve the current status quo. Therefore, innovation can be an idea, practice, or object that is perceived by its adopter as new or an improvement. This definition implies three considerations as assumptions. Firstly, an idea, practice, or object not adopted and not implemented is not regarded as an innovation. Secondly, the innovation novelty depends on the adopter's point of view. In some context what is known to be an innovation, seems to be routine for some other contexts. Thirdly, although the concept of innovation implicitly presents a change in an organization, as all changes are not new, they are not considered as innovation (Jalonen, 2011).

Defining innovation as "*novelty in action*" (Altshuler & Zegans, 1997) implies that it is a process from initiation to implementation (Rogers, 2003). Initiation includes problem definition and alternatives evaluation. Implementation; however, means selecting the optimum options and putting the process into action (Jalonen, 2011) . Schumpeter (1911, 1942) believed that innovation is an idea of seeing and doing 'things' differently, meaning creating and destroying current structure bringing about continuous progress, which Schumpeter named 'creative destruction'. The destructive process replaces new power stemmed from technological, organizational, regulatory, and economic models with the previously developed processes (Jalonen, 2011).

Doing and seeing things differently expressing 'creative destruction' represents innovation as a particular type of change process. Innovation is a change because it is about to break and discontinue from the past (Drucker & Noel, 1986). Managing turning new ideas into new practice is of a firm's managerial capabilities forming the foundation of the change process. Innovation is recognized by its economic and social contribution if it can be changed from an idea to a product and disseminated to other parties beyond its explorers (Garcia & Calantone, 2002). Nevertheless, it should be emphasized that the creative destruction process does not have a linear or causal relationship between its phases (Smits, 2002) it just replaces an old system with a new one- " *a process of success and failure*" (Jalonen, 2011). Foster, (2010) thinks that in societies with continuous changes and a degree of complexity innovators cannot be assured of the rationality of their decision due to uncertainty engaged. Consequently, this novel movement may fail or succeed, but both outcomes are considered important (Foster, 2010).

Furthermore, based on Keeley et al. (2013), "*innovation is the creation of viable new offering*". They believe that the word innovation has lost its actual meaning due to hype, misusing, overusing, and excitement. The process and its consequent product are sometimes confused, and everything is described excitedly, whether it is a breakthrough outcome of market activities or a modest development of a product. In order to define innovation, four aspects should be considered. Firstly, innovation differs from invention. Innovation may include an invention, but there are other things involved in innovation. For instance, it is required a deep understanding of whether innovation is a strong desire of customers or their requirement, how it can be provided and delivered through other parties' cooperation, and how it will return the spent capital as time goes on. Secondly, innovation should be viable, meaning that it must be a sustainable process paying for itself over time. In fact, innovations have to bring value to the business so that one day putting another one into practice is privileged. Novelty is the third important feature of innovation even if, it is very little. However, as Biologist Francesco Redi established the maxim: "*every living thing comes from a living thing*", this fact is often disregarded that every innovation is founded on the previous enhancement. In other words, innovations are new to a market or industry, not to the world. Finally, innovation is more than creating a new product. New ways of conducting business and earning money, new products and services systems, and establishing new forms of involvement and interactions with customers, are also regarded as innovations (Keeley et al., 2013)

2.2 **Classifications of innovation**

Innovations have been classified from different perspectives. To cover most categorizations, some of them will be described in the following.

2.2.1 Schumpeter's five classifications of innovation

Schumpeter classified five types of innovations: new products, new ways of producing, new supply sources, development of new markets, and new techniques of organizing the business. Nonetheless, the two first kinds of innovation have received more attention in economics (Fagerberg, 2018). For instance, the distinction between the two terms "*product technology*" and "*production technology*" was discussed by Schmookler (1966), emphasizing the criticality of differences in the understanding of innovations. He described product technology as knowledge about product creation or improvement process, and production technology as knowledge about the product production process. Likewise, the term "*product innovation*" and "*process innovation*" characterize the phenomena of creating or improving a product or service and improvement activities to produce these products, respectively (Henderson & Clark, 1990). Differences between the impact of product and process innovation on society and economy often cause an argument about to what extent these innovative practices are distinct. To throw light on this argument formation, consider an obvious and positive impact of introducing new goods or services on economic growth (income and employment). As process innovations are capable of cutting costs, it has been argued that they may result in a more ambiguous consequence (Edquist et al., 2001). In spite of an organization's or industry's ability to distinguish their distinction clearly, this differentiation remains obscure at the overall economic level, since the output of a firm or industry may be applied to produce products in another company or industry (Fagerberg, 2018).

Diffusion of product and process innovation should not cause ignoring the impact of other types of innovations. For instance, the United States could make swift progress ahead of other countries with a similar economic framework with organizational kinds of innovations creating new forms of production and distribution processes during the first fifty years of the last century (Fagerberg, 2018). To throw light on the importance of different categories of innovation, Edquist et al. (2001) have recommended splitting up the process innovation into" technological process innovations" and "organizational process innovations", the former is referred to new types of production equipment, and the latter to novel methods of organizing work. Nevertheless, organizational innovations not only refers to establishing new forms of organizing production processes but also, it as Schumpeter (1934) has used, constitutes arranging all activities over the companies such as reestablishment of organization management. Moreover, as mentioned in the above example about the USA economic boost, most of the organizational novelties had affected the distribution in a way that brought profound impact on many industries (Chandler & Hikino, 1990).

2.2.2 Incremental and Radical innovations

Considering Schumpeter's work, innovations can also be classified based on how radical differences they have compared with existing technology (Freeman & Soete, 1997). From this point of view, continuous improvement is referred to as "*incremental*" or "*marginal*" innovation, by contrast, there exists "*radical*" innovation such as offering completely new machinery or "*technological*" innovation like a cluster of novelties leading to a profound effect (Lundvall, 2010). Dosi (1988) believed that most innovations have incremental nature presenting production line extension or current product modifications. As most ideas are derived from the marketplace, incremental innovations are categorized as market-pull novelties. Moreover, they are mostly expected to be originated from market-leader organizations, since these firms have extensive expertise in collecting, transforming, spreading, and responding to data received from the market (Kohli & Jaworski, 1990). With regard to this fact that incremental innovations are within existing business activities and do not have a considerable deviation from them, they are about to improve current internal skills through providing opportunities for competent individuals to develop their capabilities (Tushman & Anderson, 1986). On the contrary, radical innovations are described as new and creative products whose original attributes look highly new to their users and organization technology. These radical or discontinuous innovations (Veryzer, 1998) are developed beyond new product development (NPD) processes which require optimization and planning. They seek, for example, a discovery, 'try and learn' (Sommer & Loch, 2004), learning and novel managing capabilities (Christiansen et al., 2005), or creation ability (Badke-Schaub et al., 2010). The discontinuity attribute of radical innovation by Veryzer (1998) refers to a significant change in product and technology capabilities, i.e. when commercial and technological product discontinuity occurs (Arrighi et al., 2015). Similarly, radical innovations are said to be competence-destroying, often making present abilities and knowledge no longer useful (Tushman & Anderson, 1986). In addition, managing these novelties often differ from existing practices (G. O'Connor C., 1998; Rice et al., 1998). As radical innovations are likely to be originated from the scientists, they are classified as a technology-push novel notion (Dosi, 1988; Green et al., 1995; G. O'Connor C., 1998; Workman, 1993). These novelties usually impose a high level of risk on the business because their commercialization causes substantial difficulties. Nonetheless, they play a significant role in long-run business success, since new technology is applied in their development, and some of them might affect current market structures (Veryzer, 1998). Radical innovation can also result in consequent incremental opportunities (J. Ettlie & Rubenstein, 1987).

It seems that as radical innovations destroy present business processes, they can be new to both the world and the firm (Barczak & Wileman, 1991; Green et al., 1995). Nevertheless, new-to-the-world novelties involve either a ground-break idea or a novel combination of existing technologies, while new-to-the-firm innovations might not (Darroch & McNaughton, 2002).

Furthermore, Bessant et al. (2014) described incremental innovation as 'do what we do but better' and the radical one as 'do different '. According to them, the incremental innovation takes a low level of risk as these improvements benefit from established knowledge, meaning widespread employees' engagements in developing the new product or process when the scale of experiment and problem solving is small and controlled. Also, incremental innovations are created based on the interaction of organizations with existing business partners as integration of pre-found exchange with them (Hallén et al., 1991). Radical innovation, however, is recognized as an exploration practice with a high level of risk and linked to a nebulous knowledge basis. Expert judgment is often required here and although engaged activities are different, establishing iterative behavioral patterns and giving support to structures are possible. For instance, in setting up a major new product process, a devoted team and strategic analysis may be involved, regarding the importance this fact that the change process requires substantial planning, participation, and managing the change (Leifer et al., 2006; G. C. O'Connor & Veryzer, 2001).

There is another approach for presenting incremental and radical innovation. Tushman & O'Reilly (1996) stated that organizations essentially require two forms of innovations, exploitative and exploratory, to sustain and develop their economic prosperity, although their different knowledge management systems bring extensive pressure (March, 1991). From Atuahene-Gima's (2005) perspective on exploitation innovations, these novelties enhance and broaden existing knowledge, searching for higher productivity and improvements to make incremental innovations practical. Exploration, on the other hand, demands new knowledge generation and puts it into practice to promote diversity and creativity required for a higher level of novelty in radical innovation. Therefore, the challenge that existing enterprises face can be rooted in how they frame the innovation management activities and the environment they have set up to function within those frames (Bessant et al., 2014). Figure 1, shows such framing based on the categorization of Bessant et al. (2014), and the following explanation of what characteristics each zone has is also according to this reference.

Zone 1 indicates innovations with exploitation perspective in innovation study, which assumes a steady and common frame, "*business model or architecture*", within which incremental plans are established. Firms search, for instance, systematical technology development, incremental product improvement techniques, and market research capabilities to enhance the product with given emphasis on customers feedback and input, also to improve processes using management methods like Kaizen.

On the contrary, zone 2 represents the 'exploration' domain in innovation literature and can be termed as 'bounded exploration', while it is defined and carried out in a pre-established framework, 'business as usual'. There may be strategic discussions about selecting a radical novelty among other alternatives, but it is still established in a known environment. Strategies here are explored but dependent, following a particular company's direction (Pavitt, 1984).

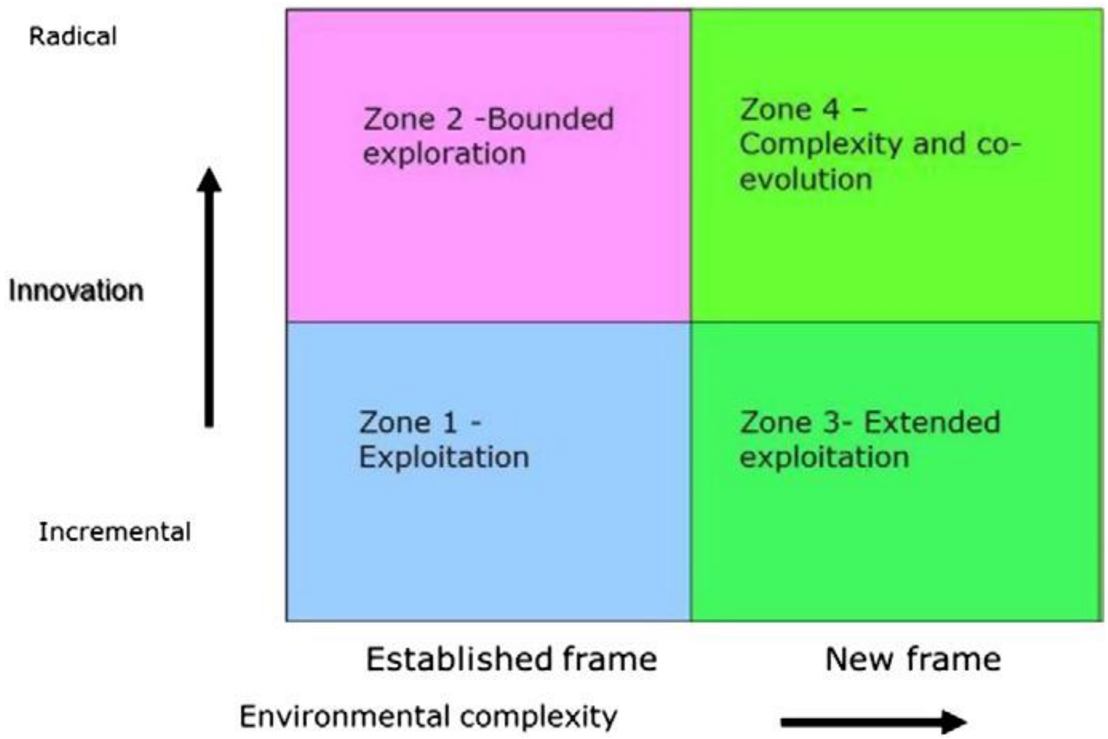


Figure 1, Simplified Map of Innovations Framing, derived from Bessant et al. (2014)

Zone 3 and 4, nonetheless, extend the cognitive framework outside the 'normal' frame and incorporate new and different elements such as new markets, technology, and actors. Innovations here have a degree of reframing and affect searching, selecting, and implementing routine activities. Enterprises on the right side of the presented model in Figure 1, will encounter complicated challenges with well-entrenched pre-set up frameworks which act as barriers to these novelties. In zone 3, innovations involve the creation of new frames in which existing practices adapt to new conditions. These extended explorations are searched by incumbent organizations adopting open strategies to take some risks on emerging notions. Stakes are high for innovations taking place in zone 4, encompassing a much higher level of uncertainty when many interactions exist among actors in these novelties. Because of dependencies amongst actors and elements forming this environment, predictions become more and more difficult, which causes higher complexity, the 'edge of chaos', for innovations in this space.

2.2.3 Innovation classification of Organization for Economic Co-operation and Development

The output of innovation can be divided into three categories: product, process, and organizational (managerial) innovation (OECD, 2010). The main purpose of product innovation lies in offering new or dramatically improved goods or services to the firm's market, consequently, affecting sales and the quality of product significantly compared with other performance indicators of the business (Rosenbusch et al., 2011). However, in process innovations, new production techniques by which different business operation measures (e.g., quality of product, costs of production, and productive capacity) may be influenced, are introduced (Tavassoli & Karlsson, 2016). Finally, organizational innovations make changes in managing obtainable resources and routines of existing company activities. Therefore, productive capacity, efficiency, and product quality performance indices are affected among others (Goedhuys & Veugelers, 2012; Polder et al., 2010).

2.2.4 Ten types of innovation

Keeley et al. (2013) have defined (in the book 'Ten Types of Innovation') a class of ten innovations introduced in three main categories as shown in Figure 2, derived from this book. The left side of this intuitively defined framework (configuration, offering, and experience) involves internal firms' activities and inaccessible to end-users. Moving towards the right side makes them more evident for customers. Metaphorically it can be said, the left side of the framework is backstage while the other side is onstage. In configuration class including profit model, network, structure, and process innovations, the enterprise focuses on innermost functions and its system. Offering classification, referring to product performance and product process innovations, consists of a core product or service innovations or a group of its goods and services innovations. In the last, namely, the experience category involving service, channel, brand, and customer engagement innovations, the customer-focused attributes of an enterprise and its business systems are taken into consideration (Keeley et al., 2013). In continue, innovations accessible by end-users are described based on the Keeley et al. (2013) accounting.

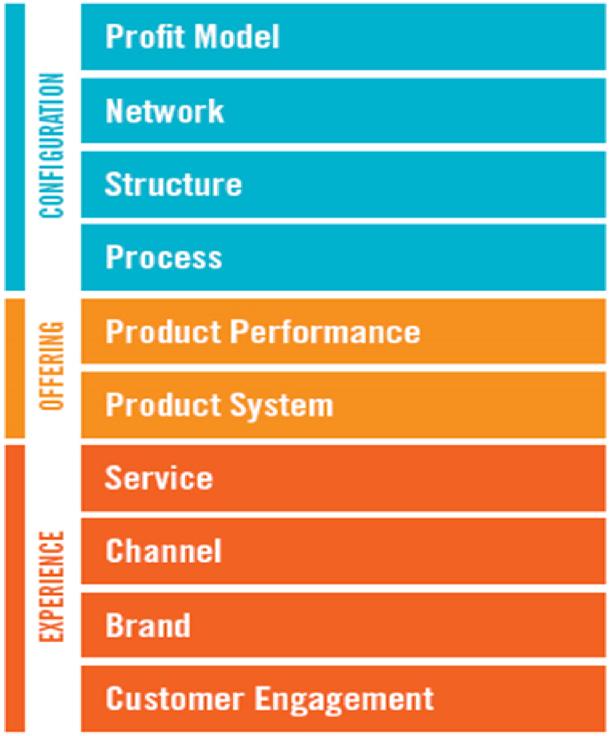


Figure 2, Ten Types of Innovation, taken from Keeley et al. (2013)

Profit model innovation

The main purpose of profit model innovations is to convert available offerings and value sources of the enterprise into cash through finding new opportunities. More successful innovations of this kind are founded on perceiving what end-users strongly desire and finding new increasing revenue, Or pricing methods. Innovative profit models often try to pose a challenge to an industry's present assumptions about "*what to offer, what to charge, or how to collect revenue*". They gain their power from the fact that the most influential assumptions have been "*unquestioned*" for many years. To exemplify, premium prices and auctions can be considered, which in the former companies know how to price their products and services more intelligently than their competitors while in the latter, the market determines the offerings. There is a wide range of ideal profit models depended on the context and industry. A new start-up may establish an easy-to-adopt products profit model for their customers, while a present firm may design a model difficult for its end-users to change. Overall, in order to be successful in carrying out this innovation, the profit model must have close alignment with the targeted innovative intention and organization broadscale strategy.

Network innovation

The main aim of network innovation is to make a connection with others creating value for an enterprise. In the current hyper-connection world, companies cannot or should not carry out everything on their own. Network innovations provide companies with opportunities to benefit quite well from other organizations' processes, technologies, products, services, channels, brands, and every single part of a business in a form of partnership, consortia, or affiliation. In fact, network innovations mean an enterprise's capability to utilize its strengths effectively while controls and employs the benefits of other external sources. In addition, this novelty contributes to companies' directors establishing a risk-sharing framework in new offerings or business development. The length of this collaboration can be short or long, and they can be formed between close business partners or even steadfast competitors. As an example, making a secondary market to attract other customers is a network innovation.

Structure innovation

In structure innovations, the challenge is how to apply firms' talent in an innovative way to create value from organizing its tangible and intangible assets. This novel method can be diverse from an original intelligent management system to a creative layout of high valuable machinery. Improving costs and processes can also be planned and implemented through structure innovations across departments such as Human Resources, IT, and R&D. Moreover, a desirable novelty of this kind can help absorb genius to the company by building a working environment with admirable productivity or promoting quality of performance far away from competitors' abilities to reach. Some examples of structure innovation can be developing incentive systems inspiring workers to pursue determined objectives, setting standards reducing operational costs and complexity, or building a university corporation targeting state-of-the-art continual training programs. These novel changes in an organization's structure cannot be imitated by competitors, as they essentially require fundamental changes in the related company and (or) investment expenditure. So, these novelties can form a basis for lasting success.

Process innovation

All activities and functions required to deliver a company's offerings are organized in process innovation. The distinction of these innovations with structure ones is that in the former, the challenge is to put ways of using assets into actual practice, nevertheless, in the latter inherent features of the company's intelligence and properties are organized. Process innovations target significant change which is radical from current business activities and provide the organization with opportunities to utilize its unique strengths, operate productively, set rapid adaption, and lead margins in the relevant market. Consequently, they often create a dominant capability for firms that may bring "*patented or proprietary*" benefits for the enterprise over several years. In other words, they are "*special sauce*" that the enterprise can use, but the competitors cannot copy. One of the noted examples of this kind of novelty is "lean production" through which system expenses and waste are decreased by managers. Standardizing processes and prediction analysis are other examples of process innovations enabling companies to "*design, price, and guarantee their offerings accordingly*". In the former, existing practices are improved to lower the costs and complexity, and in the latter, historical data are analyzed to forecast future events.

Product process innovation

This class of innovations distinguishes the values, attributes, and quality of a firm's offerings. Product performance novelties constitute both new products and line improvements (updates and extensions) that put an added value on the organization. It is frequently easy for competitors to imitate these innovations. Toothbrushes or baby strollers are examples of copied product performance innovations. Those successful in long-run competitive deliveries can be excepted from normal innovations of this kind. Nonetheless, product performance novelties are a valuable source of customer delight and economic growth. For instance, "*simplification*" is a product performance innovation that makes goods' and services' application easier, "*sustainability*" provides products without detrimental damages to the environment, or "*customization*" presents products customized according to desirable characteristics of customers.

Product system innovation

Connecting or bundling products and services together and creating a sturdy and expandable system are root practices in product system innovations. This is encouraged by cooperation, making modules, integration, and other approaches capable of creating connections between different offerings despite their distinction and disparity. Product system innovations are a great contribution towards building a business environment capable of attracting end users' attention, maintaining them delightful, and protecting a company against competitors. Selling several relevant products in a package exemplifies a frequent innovation of this type. In the twenty-first century, technology organizations have applied this kind of innovation as an opportunity to inspire others developing goods and services for them like application shops and kits developers. Other types of product system innovations consist of extending present products, combining goods and services, and complementing offerings that solely operate perfectly but can produce a considerably better result if they work together.

Service innovation

Service innovations are to ensure and improve product application, performance, and evident value. If a company originally provides services, the specifications and functions of its offerings are categorized as Product Performance (regardless of the word 'product'). Service innovations constitute all support and improvements the firm provides for its core offerings. These innovations even customers' journey path by solving their problems, making a product to be tested, used, and enjoyed easier, also reveal attributes or operations that customers might miss. Further than doing this job well, they raise dull and moderate offerings to enthralling experiences that customers would like to repeat. Product application improvements, maintenance plans, customer support, warranties, and guarantees are common examples of service innovations. Although human resources play a central role in these innovations, they are presented growingly with non-human intervention systems such as electronic interface, technological automation, and distant connections. Service can be seen as a most significant and striking part of customers' experiences or an unseen "*safety net*" that they require but never find.

Channel innovation

Channel innovations refer to all means by which an enterprise delivers its offerings to customers and users. In spite of lately emerged e-commerce as a powerful and influential force, convenient distribution channels are still crucial, especially the target is to create extensive experiences. Skillful innovation creators often seek different alternatives but complementary ways to connect their goods and services to customers. The purpose is to get assured of what users require, also when and how they want products with the minimum tension and expenses and maximum level of delight. These novelties are industry-context and customer-behavior-oriented. Flagship stores, for example, can be seen as a value-creation channel innovation arranging and holding a showcase offering the company products. On the contrary, selling directly by e-distribution means or others can decrease overhead expenses and increase marginal and cost benefits. Or one might follow up an indirect channel or multi-layer marketing by hiring others to promote and deliver an offering to the end customer.

Brand innovation

These novelties help organizations to promote their products and business and ensure that their customers and users recognize, remember, and prefer their goods and services to other providers. More successful brand innovations create and present an appealing and completely different entity after distilling an idea. They are typical consequences of spending time, attention, and expertise on adopting, developing, and implementing precise strategies over processes involving communications, promotions, service interactivities, channel systems, and workers' behavior of organizations and their business partners. This group of innovations can convert outputs to valuable offerings and bestow concept, intention, and value on an enterprise and its products. Moreover, these novelties can offer new goods and services as "extensions" under the current brand name. Besides, they may pursue another approach and inspire firms to express clearly and consistently a unique idea or set of values as their beliefs. The scale of brand innovation is not limited to manufacturers or producers who have direct contact with consumers. It also means branding " components" and advertising their values to the end-users gaining the power of preference and bargaining.

Customer engagement innovation

The target of these innovations lies in perceiving customers' driving ambitions for the firm and developing a "*meaningful*" connection between the enterprise and its end-users. Great customer engagement innovations provide more opportunities for more discoveries and encourage compelling interactions with users making more enthralling, unforgettable, satisfying, delightful, and even magical experiences for them. The continuous rise in substituting old means of communication such as TV or radio with more personal and mutual interactive connections to customers indicates these innovations approach towards users. It is also can be seen that some organizations utilize technology to simplify interactions in highly complicated areas, providing their customers with easier life and attracting their trust. Nonetheless, as is expected, technology is just a tool. Simple techniques like appealing and instinctive packaging can make customers come back again, also lengthen their experience with a firm long after the first purchase.

2.2.5 Open and close innovation

Chesbrough's thesis that many business leaders are experiencing an evident decline in innovation benefits when so many promising and novel ideas emerge everywhere lies in a change in how organizations innovate. Chesbrough recommends presenting a shift in creating innovations and "*commercializing industrial knowledge*" as a movement from "*closed*" to "*open*" innovation. Closed innovations comprise inbound technological developments for internal applications that are established by research and development (R&D) departments integrated vertically across a firm. As the system elements (input, output, and processes) of these innovative practices exist within the entrepreneur, process targets are achievable. In recent years, four elements reduced closed innovations' effectiveness gradually. The first one includes enormous highly educated and skillful individuals equipped with extensive and in-depth laboratory knowledge. Second is the growing accessibility of people with substantial capabilities, competencies, and experiences moving everywhere. Expanding private capital having expertise in innovating organizations "*to commercialize research*" is the third factor. Finally, is the ending life span of technologies and progressive increase in competition with non-US companies (Durmusoglu, 2004).

Chesbrough firstly defined open innovation as "*a paradigm that assumes that firms can and should use external ideas as well as internal ideas, internal and external path to market, as the firms look to advance their technology*" (Chesbrough, 2003). Afterwards, West & Gallagher (2006, p. 1) described open innovations with other words: inspiring and discovering internal and external opportunities for innovations as much as possible, consistently incorporating the exploration into the enterprise abilities and resources, and widely exploiting those opportunities by different distribution channels. In the same year, Chesbrough amended the OI definition as "*the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively*" (Chesbrough, 2006). After presenting this definition, efforts to define openness were commenced (e.g., Dahlander & Gann, 2010; Vrande et al., 2010), giving prominence to out-house source of novelties by both references (Laursen & Salter, 2006), also with an emphasis on invisible in-house ideas (Henkel, 2006). Dahlander & Gann (2010) define the role of openness in innovation as "*permeability*" of a firm's boundary to let "*ideas, resources, and individuals follow in and out of organizations*".

In contrast to advocates of OI, several authors (Dahlander & Gann, 2010; Groen & Linton, 2010; Oakey, 2013; Trott & Hartmann, 2009) maintain that open innovation is not a novel concept. They make reference to a history of painstaking research in which the consequences of opening up a firm's working environment to external boundaries have been analyzed (Chandler & Hikino, 1990; Freeman, 1974; Pavitt, 1984; von Hippel, 1986). In addition, considerable overlap between the concept of open innovation and present supply chain management has been accounted for thoroughly (Mowery, 2008). Following these critics, Chesbrough & Bogers (2014) redefined OI and presented a universal paradigm of it as a shared innovation process established based on a purposefully managed flow of knowledge over an organization environment, which applies "*pecuniary or non-pecuniary*" techniques consistent with each organization's economic strategy.

However, Remneland-Wikhamn (2013) believes that despite acknowledging the OI definition by researchers of multidisciplinary origins, forming a powerful and united community of OI researchers who have one practical and all-agreed OI concept is fiendishly difficult and these innovations can be formulated broadly in different-and not always matched- ways.

2.2.6 Innovation categories based on degree of novelty

Based on Burgelman et al. (2009), "*by leaps and bounds*" innovations (radical innovations) can differ noticeably from "*step-by-step*" innovations (incremental ones). The quality of innovations is a multifaceted criterion. Generally, the innovativeness of innovations is closely corresponded to and affected by the propagation of the below factors (Salomo et al., 2007):

- Technology dimension. This aspect manifests to what extent the novelty is uncertain. If technological knowledge of innovation has not been completed or required before its creation, a high degree of novelty is involved.

- Market dimension. When a firm's target lies in satisfying (till this point has not been satisfied) or introducing new needs for its users, a radical quality is diagnosed for that novel idea from the market perspective.
- Organizational dimension. Innovations can entail a necessary change in an organization. A drastic and major change indicates a high level of novelty in an innovation.
- Innovation environment. The degree of innovation novelty increases if it can influence its environment dramatically so that the consequent change like creating a new channel of distribution is distinguished as radical.

Figure 3, shows the interrelation between novelty dimensions of innovations. Every aspect of innovativeness for a radical idea depicts a "*strong profile*" representing a higher level of uncertainty. While incremental improvements have a low to medium profile in each dimension (Gaubinger et al., 2015).

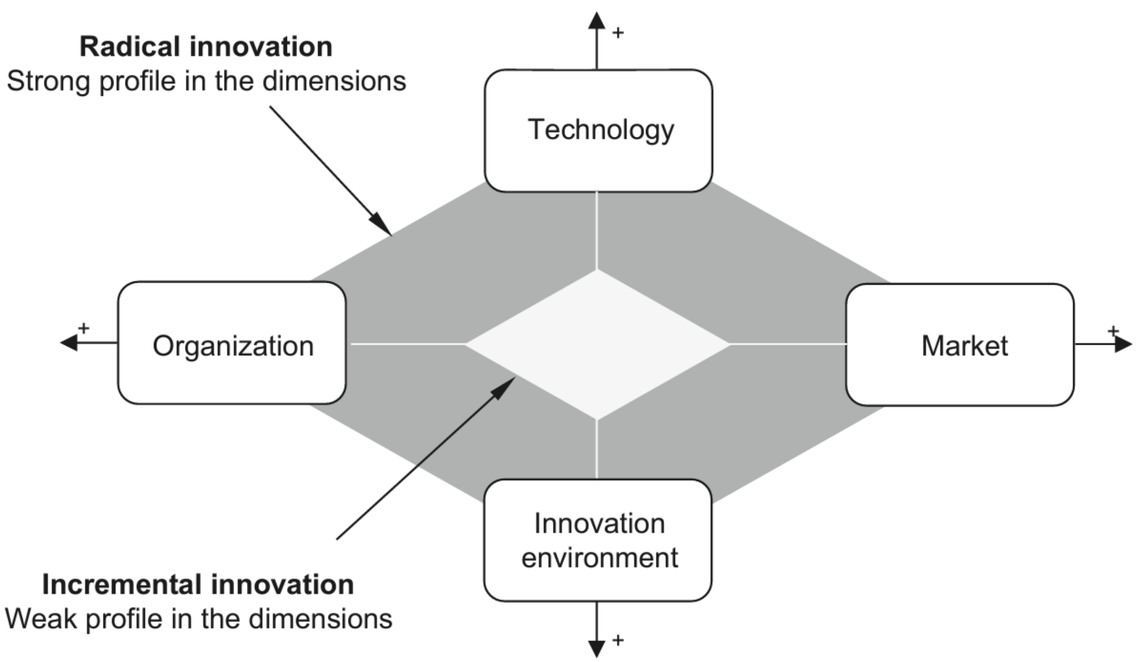


Figure 3, Dimensions of Degree of Novelty, Source: Gaubinger et al. (2015)

The following classification of innovations can be defined, considering their degree of novelty (Pleschak & Sabisch, 1996):

Fundamental innovations

Fundamental innovations feature the highest level of novelty. In order to implement a new technological innovation, new forms of operation should be processed, leading to a radical product or process generation. As examples of fundamental innovations, the steam engine, the jet engine, or the microprocessor are innovative triumphs bringing about enormous successive innovations (Vahs & Brem, 2013a).

Disruptive innovations

Disruptive innovations on the contrary to so-called "*preserving innovations*", constitute products and services that cause an interruption to current improvement processes and introduce completely new performance factors. Therefore, their degree of novelty is high and have radical feature. Despite inferior characteristics in performance compared to existing innovations at the time they are launched, disruptive innovations can grab a group of customers' attentions with basic needs of goods and services, but very careful about prices. These innovations gradually experience improvement; consequently, they are valued by established users and distinguished a danger for those suppliers who did not welcome these novelties (Christensen, 1997). Disruptive innovations have three key specifications: affordable, simple, and unexpectedly replace large enterprises with new and small beginners. Cassette tapes can be exemplified, which were replaced by compact discs and these discs gave their place to MP3 later (Chandra & Yang, 2011).

Quality – improving innovations

This type of innovation is identified as novelties with lower novelty quality compared with the fundamental innovations. Though usually manifest a revolution improvement, quality-improving projects make changes in their application parameters when preserving key functions constant (Vahs & Brem, 2013a).

Adaptive innovations

These innovations, unlike radical innovations, have incremental innovation nature as they present an adapted solution for the particular demand of their customers (Pleschak & Sabisch, 1996).

Imitations

Imitations utilize other organization’s current solutions. Imitations are *“tarnished by the odor of lacking imagination”*; however, the possibility of employing imitations should be regarded by a rigorous business management framework (Hauschildt, 2004).

Fake innovations

Fake innovations involve changes in goods or services which lack new utility for users and are diagnosed by low or zero degrees of innovation (Vahs & Brem, 2013b).

3. The Concept and Representations of Uncertainty

Frank Knight is one of the pioneers in defining uncertainty (Jalonen, 2011). He defined 'risk' as an unknown measure to which assigning probabilities is applicable and 'uncertainty' as risks to which assigning probabilities is not practical (Knight, 1921). For Galbraith (1977), the gap between the amount of required information for carrying out a task and available information in an organization defines the uncertainty, although he believed that "*a great deal of uncertainty exists about the concept of uncertainty*". Parallel with the previous opinion, Brashers (Brashers, 2001) maintains that uncertainty is manifested when situations have a quality of complexity and ambiguousness, when information is not accessible or consistent, and when applied knowledge cannot be secured by their sources. Also, scant or no information as an uncertain situation implies that by increasing the accessibility of information the certainty can be increased (Galbraith, 1977; Daft & Lengel, 1986). Nevertheless, Ellsberg,(1961) adopts the 'known uncertainty' concept. It means a situation in which important parameters and outcome probabilities are known while their real quantities are not. In such circumstances, probabilistic analysis sounds suitable to estimate different possible outcomes (Bullen et al., 2006; York & Venkataraman, 2010).

Further, the absence of knowledge about the existence of all variables and outcomes in addition to their real amount causes a more complicated situation (Jalonen, 2011). For this situation which Ellsberg (1961) expresses as 'unknown uncertainty' lies a "*lack of clarity of cause-effect relationships, lack of agreement among involved parties and the difficulty of identifying appropriate sources of information*" (Gales & Mansour-Cole, 1995). Also, different interpretations and conflicting views about them bring about unknown uncertainty (Daft & Lengel, 1986). While probabilistic analysis can be applied to decrease 'known uncertainty', such calculation is not applicable for a situation with 'unknown uncertainty' (cf. Bullen et al., 2006). Based on (Reddy, 1996), uncertainty includes a future vision with a high degree of fundamental indeterminacy precluding analysis of probabilities. Sartorius (2006) states that ignorance in novel and basically unpredictable situations cause unknown uncertainty. According to Teubal (2002), 'fundamental uncertainty' is stemmed from unpredictable events because translating all events into 'states of nature' and their relevant probabilities is not practical. Likewise, Spash (2002) introduces the term ‘strong uncertainty’ representing situations in which we are unable to predict the result of events and determine which event will consequently bring a future change.

3.1 Uncertainty in risk assessment context

In risk assessment of complex systems with limited knowledge about the behavior of these systems, one significant issue is finding the best way of expressing risk and communicating related uncertainties meeting decision makers’ and stakeholders’ requirements. In the risk assessment, most analysts would consider uncertainties associated with parameters in probability models. Based on statistical analysis, uncertainties are represented using confidence intervals or following Bayesian theory epistemic uncertainties about parameters are expressed by subjective (knowledge-based) probabilities. This typical uncertainty analysis is a non-segregated part of risk assessment (Aven et al., 2014). Nonetheless, uncertainty is presented independently of risk assessment (Morgan et al., 1990). Formally, uncertainty analysis is defined as a process of determining uncertainty about an analysis’s results stemmed from existing uncertainty in an analysis’s input, such as involved methods and models (Helton et al., 2006).

Uncertainty analysis can be indicated by defining a model g(X) in which function g depends on input variables X. The model g(X) generates desired quantity, Z. Uncertainty assessment of Z relies on X uncertainty analysis and input ‘propagation’ through the model g, as Figure 4 shows (Aven et al., 2014). The model structure g, can also impose uncertainty as an error equal to Z-g(X) which its uncertainty assessment is generally conducted in a different way (Baraldi & Zio, 2010; Devooght, 1998; Zio & Apostolakis, 1996). Elements g(X) and Z constitute the major basis of frameworks development for uncertainty assessment and management (Aven et al., 2014).

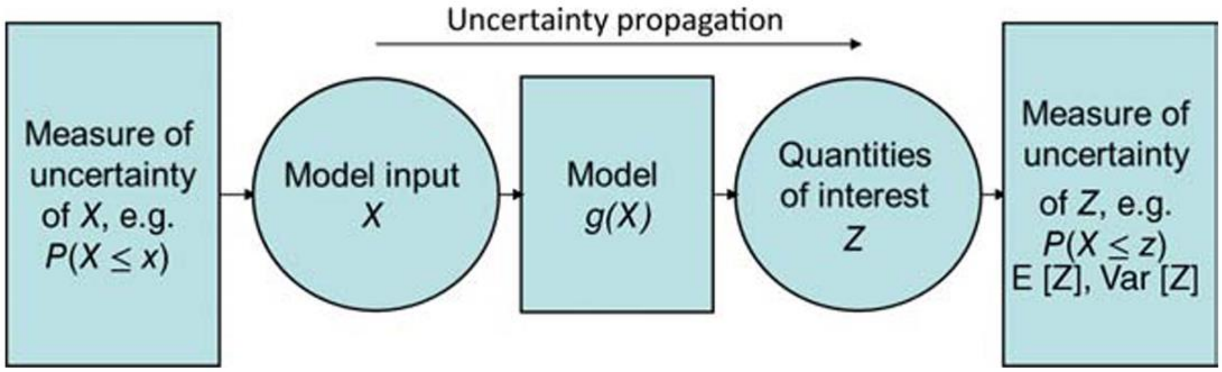


Figure 4, Basic Features of Uncertainty Analysis, taken from Aven et al. (2014)

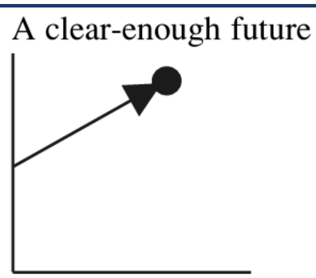
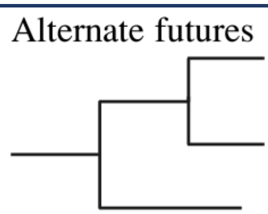
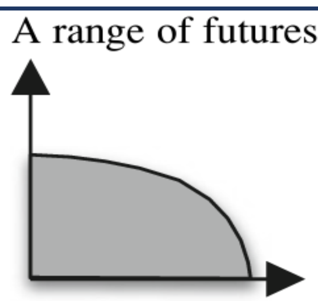
In engineering risk management, aleatory uncertainty is widely differentiated from epistemic uncertainty (Apostolakis, 1990; Helto & Burmaster, 1996). The word aleatory was originated from the Latin word "*alea*", meaning the rolling of a dice and the word epistemic was derived from the Greek "*επιστημ*" (episteme), meaning knowledge (Kiureghian & Ditlevsen, 2009). Aleatory uncertainty denotes 'variation in populations' and epistemic uncertainty manifests 'lack of knowledge' in an event. The former refers to uncertainty about parameters of a probability model describing variation in a phenomenon. This uncertainty is generally applied for describing frequentist probability. Although reducing epistemic uncertainty is possible and feasible, aleatory uncertainty is not and is sometimes called irreducible (Flage et al., 2014; Helto & Burmaster, 1996). Considering aleatory conceptualization, it is commonly known as stochastic uncertainty (e.g., Helto & Burmaster, 1996) randomness, (random) variation (Aven, 2010), (random) variability (e.g., Baudrit et al., 2006). In theory, an infinitely large group of *"similar"* and non-identical population units is required to describe variation uncertainty. For instance, a population of teenagers, a population of produced cars, or a sequence of multiple-choice question's answers. However, the concept of epistemic uncertainty is developed based on subjective uncertainty (e.g., Helto & Burmaster, 1996), complete or partial lack of knowledge (e.g., Aven, 2010), or partial ignorance (Ferson & Ginzburg, 1996).

3.2 **Level of uncertainty**

Based on uncertainty description, it is a product of limited cognition. Cognition as a process aims to reduce uncertainty. Therefore, knowledge particularly, scientific knowledge, is regarded as antithetical to uncertainty. Nevertheless, making decisions and taking actions are not just according to what is known, but also to what is not known, to what is expected, to what is believed, and to what is trusted (Motet & Bieder, 2017, Chapter 4).

Courtney et al. (1997) classified uncertainty into four levels and established a framework in which the levels of uncertainty existing in organizations' decision-making have been determined. They believe that unknown patterns and factors can often be identified and known if an in-depth analysis is conducted. Other uncertainties called 'residual' are categorized into four levels (Courtney et al., 1997). This grouping is described more in detail in Table 1, which is based on Courtney (2003) and developed according to Gaubinger et al. (2015).

Table 1, Levels of Uncertainty, inspired by Courtney and Gaubinger et al. (2003; 2015)

Level	Characteristic	Description
1		Quasi deterministic: Only a single forecast of the future exists with a slight variation on the uncertainty that does not affect the strategy. Obviously, the future is not thoroughly predictable, but developed foreseeing can be utilized for managing the innovation processes
2		A limited number of future outcomes is possible to completely identify, while each scenario probability analysis is problematic. The best adaptive approach relies on which one will really happen
3		A range of potential future alternatives can be identified, with a limitation on the number of key factors, but outcomes are within the large boundaries. Similar to level 2, the best strategy may change in case of future predictability

4	True ambiguity 	No future prediction is possible, even no means to identify a range of potential events. Identifying related variables defining the future sounds impossible. Multiple uncertainty dimensions are interrelated, creating an uncertain environment more or less impossible to forecast

3.3 Uncertainty representations

Probability has been fundamentally used to analyze and treat the uncertainty in the context of risk assessment appropriate for both aleatory and epistemic uncertainty. It is also employed to quantify uncertainties and margins involved in analyses for predicting a complex system behavior using calculation techniques (Helton, 2011). From the risk assessment perspective, the frequency and subjective interpretation of probability are mostly applied. Relative frequency interpretation is distinguished widely as the best-suited concept to denote variation in a large population and represent aleatory uncertainty, similar to advocates of other uncertainty approaches (e.g., Baudrit et al., 2006; Ferson & Ginzburg, 1996). In addition, the subjective interpretation, expressing probability as a degree of belief and describing epistemic uncertainty, is broadly used in risk assessment (Bedford & Cooke, 2001). Moreover, in the Bayesian framework as a formal tool for representing epistemic uncertainty, the probability is interpreted as a "*subjective measure of uncertainty*". In this theorem, judgmental probability and knowledge-based probability are also referred to as subjective probability (Flage et al., 2014).

Nonetheless, probability as epistemic uncertainty representation has been drawn criticism from a vast number of scholars. Other means of epistemic uncertainty representations introduced by Flage et al. (2014) are summarized in Table 2, appended with probabilistic analysis. In chapter 5, these ways of representing and assessing uncertainty are described in more detail.

Table 2, Uncertainty Representation and Analysis Alternatives

Technique type	Technique name	Technique description
Single-valued Probabilistic Analysis	Frequentist Probability Analysis	Single-valued measure for uncertainty representation of an event A, as P(A)>0 Frequentist probability as one of the most applied probability interpretations from the risk assessment perspective represents variation in a large population (aleatory uncertainty) (Aven et al., 2014).
	Subjective Probability Analysis	A knowledge-based probability describes its assigner's uncertainty (epistemic) according to his or her 'background knowledge'. The probability of an event, A is the degree of belief of the assessor about the event A occurrence. The assigned probability is a quantitative representation of the assessor's knowledge rather than a feature of the "*real world*" (Aven et al., 2014).
Two-valued Probability and Non-probability Analysis	Probability-bound Analysis	A probability-interval analysis approach, named as probability-bound analysis. The purpose is to describe uncertainty in a risk assessment context about some model parameters θ_i (θ a function of θ_is such as $\prod \theta_i$). Interval analysis is used for parameters where the precise estimation of aleatory uncertainty is not feasible. Thus, the traditional probability is employed for some parameters, and interval analysis is used for the rest (Ferson & Ginzburg, 1996).
	Imprecise Probability Analysis	A lower and upper probability when available knowledge is weak (Aven et al., 2014). Based on this generalization of probability theory, uncertainty about event A is indicated by a lower probability $\underline{P}(A)$ and an upper probability $\overline{P}(A)$ so that $0 \leq \underline{P}(A) \leq \overline{P}(A) \leq 1$. The definition of imprecision is as the following (Coolen, 2004).

Technique type	Technique name	Technique description
		$$\Delta P(A) = \overline{P}(A) - \underline{P}(A).$$ The interval can be an elicitation by direct discussion or an indirect construction by assigned possibility functions or evidence mass functions (Flage et al., 2014).
Non-probabilistic Analysis	Fuzzy set	A subset of X, as a space of objects (points) i.e. X ={ x}, denoted by A is distinguished as a fuzzy set (class) through a membership function f_A or μ_A which maps every point in A, x, to a real number in the interval [0,1] as $f_A(x)$ ($\mu_A(x)$) representing the grade of membership of x in A. Moving toward 1 shows a higher grade of membership of an object, x, in A (Zadeh, 1965). According to (Lee, 2005), the membership function can be indicated as: $\mu_A : X \to [0,1]$ So, $A = \{(x, \mu_A(x))\}$ Or $\sum_{i=1}^{n} \mu_A(x_i)/x_i$ And if A has continuous points $A = \int \mu_A(x)/x$ Where μ_A, represents a possibility of element x of X on set A that can be defined as a possibility distribution function. A fuzzy set has totally, nonstatistical characteristics (Zadeh, 1965). Based on Lee (2005) for an event A: $\mu(A) \geq P(A)$
	Fuzzy Probability	Let event A be a fuzzy event or a fuzzy set considered in the space $\mathbb{R}^n$ (Lee, 2005). $A = \{(x, \mu_A(x)) \mid x \in \mathbb{R}^n\}$ then Crisp probability of a fuzzy event is: $P(A)=\int \mu_A dP$, or $P(A) = \sum \mu_A(x) P(x)$ And fuzzy probability of a fuzzy event is: $P(A)= \{(P(A_\alpha), \alpha) \mid \alpha \in [0,1]\}$ Where $A_\alpha = \{x \mid \mu_A(x) \geq \alpha\}$, and $P(A_\alpha) = \sum_{x \in A_\alpha} P(x)$

Technique type	Technique name	Technique description
Non-probabilistic Analysis	Possibility Theory	An uncertainty characterization, by double set functions, namely possibility and necessity measures when information is not complete. For each x of set S, possibility function π represents a degree of possibility of x. $\pi(x) = 0$ means that the outcome x is impossible (Aven et al., 2014), expressing that known information completely rebuts the "*occurrence*" or "*appropriateness*" of x (Helton, 2011). While $\pi(x) = 1$ means that the outcome x is possible, normal, and unsurprising (Aven et al., 2014), indicating that there is a complete lack of knowledge about the "*occurrence*" or "*appropriateness*" of x in S (Helton, 2011). Based on (Aven et al., 2014), for an event A of S: Possibility function: $\prod(A) = sup_{x\in A}\pi(x)$ Necessity function: $N(A) = 1 - \prod(\bar{A}) = inf_{x\notin A}(1 - \pi(x))$, $\bar{A}\ is\ complete\ of\ A$ and it is interpreted that: $N(A) \leq P(A) \leq \prod(A)$
	Evidence Theory	Evidence theory, Dampster-Shafer theory, or belief theory in situations with uncertain, imprecise, and incomplete information (Smets, 1994) specifies two degrees of likelihood, belief (Ble) and plausibility (Plu). For an event A, $Ble(A)$ measures the degree of belief, of an event A occurrence, and $Plu(A)$ measures the amount of information based on evidence about happening $\bar{A}$. $Ble(A) = \sum_{U\subseteq 2^S} m(U)$ and $Plu(A) = \sum_{U\cap A\neq\emptyset} m(U)$ where sample space $S = \{y_1, y_2, y_3 \dots, y_n\}$ is a set of n possible outcomes, and 2^S as power set is a collection of all subsets of S.

Technique type	Technique name	Technique description
		$m(U) \in [0,1]$ reflects basic belief assignment for each U of 2^S, $m(0) = 0 \quad and \quad \sum_{U \in 2^S} m(U) = 1$ For an event A, there is an interpretation of belief function, that is, $Ble(A) \leq P(A) \leq Plu(A)$ (Aven et al., 2014).
Hybrid Models	Depends on the combination, for instance, probability-possibility analysis	A combination of different methods of representing uncertainty (depending on different situations), such as probability, possibility, and evidence theory. Probability bound analysis exemplifies a hybrid model that combines probabilistic and interval analysis (Aven et al., 2014).
Semi-quantitative approach	Semi-quantitative approach	A hybrid model and a combination of a quantitative representation (probability analysis) and qualitative methods such as the strength of background knowledge assessment, the sensitivity analysis, and assumption deviation risk (Flage et al., 2014) such as Semi-quantitative Risk Assessment (SQRA) or Extended Semi-quantitative Risk Assessment (EQRA)

4. Characteristics of Uncertainty in Innovation Projects

Innovations, represented in chapter 2, are characterized by some features. In the following, uncertainty as one of the most prominent innovation attributes is described and specified by some aspects. Considering uncertainty description and dimensions in innovation, also types of uncertainty in risk assessment, a discussion is presented on which innovation uncertainty is selected for treatment.

4.1 Innovation descriptive factors suggested by the author

As seen, innovations have been defined and classified from different perspectives. Nevertheless, the author thinks these views express common features for innovations. According to innovation definitions, a novelty aims at improving existing products or (and) processes defined as incremental innovation. It can also be introducing completely new ideas represented as radical innovation. It seems that a novel notion leads to a final product, fully or partially new for customers or (and) a process(es) and fully or partially new for firms. It means that innovations represent a degree of novelty in their description. In addition, open innovation definitions explain that innovation success depends on how organizations utilize and manage internal and external sources and knowledge. The extent to which enterprises use external sources and out-house knowledge differs from one to another. In fact, innovations express a degree of openness towards external knowledge utilization. Therefore, the innovative projects have a degree of openness towards external resources and knowledge flow and represent a quality of novelty to customers, competitors, or the business environment.

The effect of innovation openness can be studied in conducted surveys. As Fagerberg (2017) reports from 1991 onwards, the European Union has carried out surveys of organizations' innovative practices and their influential factors on members of the Community Innovation Survey, CIS. The results show high consistency among different surveys at different times. Figure 5 and Figure 6, derived from Fagerberg (2017), represent the results of the CIS survey. In Figure 5, European companies were asked to determine the most important sources of information in their innovation. According to the diagram, the firm itself is the most significant source of information.

After internal sources exist external sources, among which the highest importance are customers and suppliers. Other organizations in the same industry follow the customer and suppliers (Fagerberg, 2017). This illustration shows that although the main source of information is within the firm, they use other external information in their innovative projects. Figure 6 depicts the most important external parties of firms in their innovations. Similar to the previous diagram, the most significant business partners of organizations in European member countries are suppliers and customers, followed by other firms in the group (Fagerberg, 2017). Therefore, companies exchange knowledge and cooperate in innovations to accomplish their objectives, and the level of this information exchange, their openness, differs from one organization or innovation to another.

Considering two inherent qualities of innovations: degree of novelty and openness, a frame is recommended in Figure 7, which can be used to describe innovation. Based on this suggestion, each creative idea can be explained by a degree of novelty (defined in section 2.2.6), how radical is a new notion, and an openness quality, the extent to which it is open to out-house knowledge and external source. For instance, quality improvement and adaptive innovations described in chapter 2 are incremental innovations with a degree of openness that can be different for each. Similarly, disruptive and fundamental innovations (typical of radical novelties) can be open to an external source and knowledge with different levels.

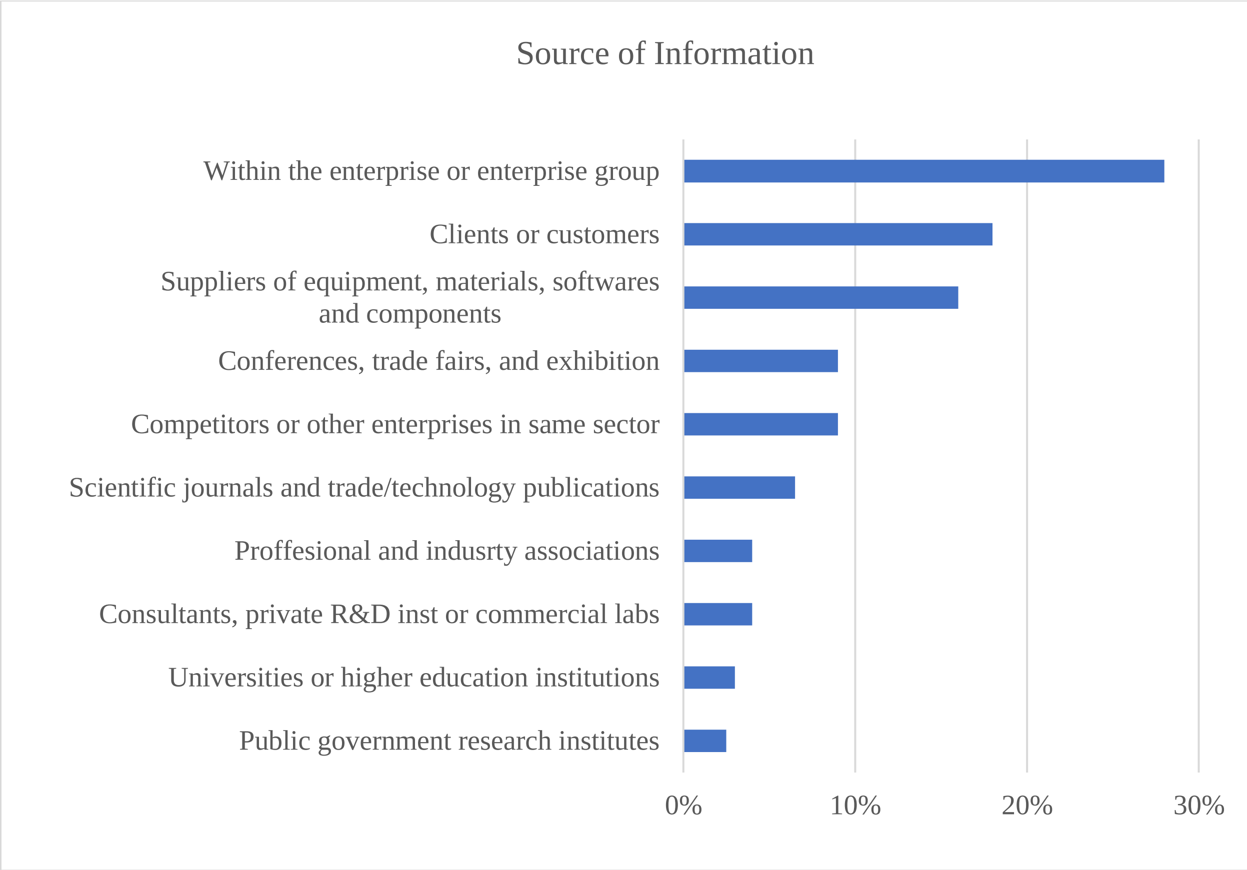


Figure 5, Important Sources of Information in Innovations, derived from Fagerberg (2017)

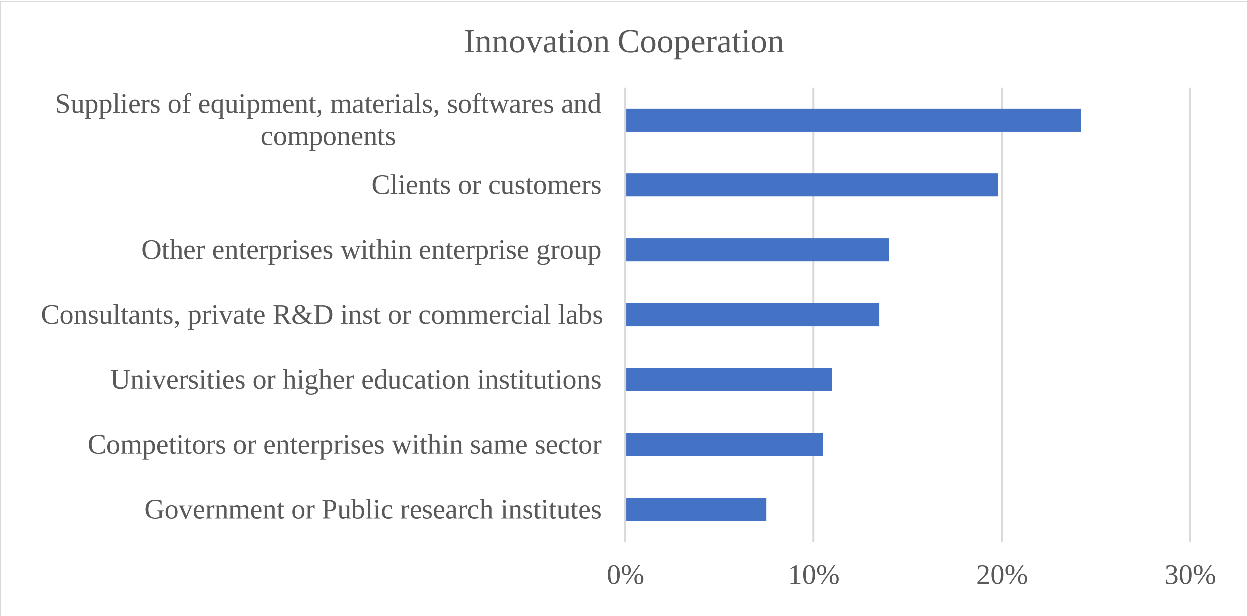


Figure 6, Innovation Cooperation, sourced from Fagerberg (2017)

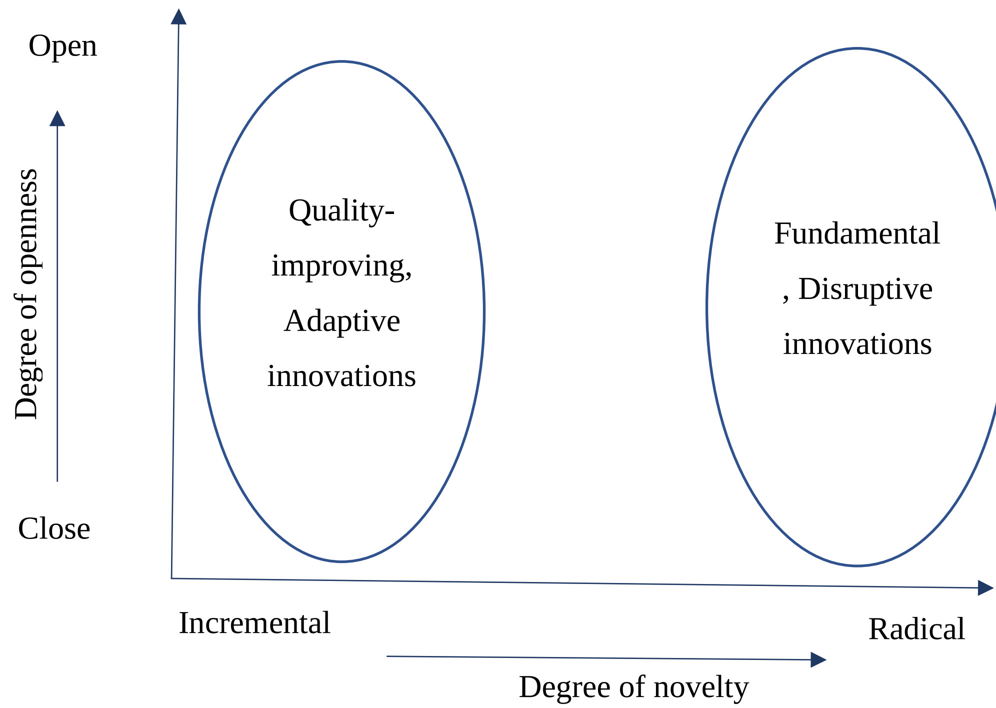


Figure 7, Recommended Frame for Innovations Description

4.2 **Characteristics of innovations**

Innovation is inherently about the unknown, about 'possibilities' and 'opportunities' related to developing a new thing from which gaining a benefit in the future is doubtful (Afuah, 2003). Innovative creators will participate in 'non-linear' and repetitive development practices that eventually lead to more organized behavior, yielding a new product or service (Cheng & Van de Ven, 1996; Van de Ven, 1999, 2017). Usually, innovation projects are distinguished with different common features such as complexity associated with involved activities and kind of needed knowledge and resources, as well as uncertainty related to technologies and what customers prefer (Cassiman et al., 2010; Du et al., 2014; Felin & Zenger, 2014). Complexity refers to *"the non-linear interactions between parts of a system"* (Cisnetto & Barlow, 2020), which is logically followed from their openness quality (Diamond, 2005). Uncertainty, according to Galbraith (1973), is defined as "*deference between the amount of information required to perform the task and the amount of information already possessed by the organization*". Uncertainty and complexity, among other innovation features, have been determined as the most important characteristics of them, from scholars' points of view (Almirall & Casadesus-Masanell, 2010; Brunswicker et al., 2016; Nickerson & Zenger, 2004).

4.3 **Uncertainty nature of innovations**

"Innovation is an hypothesis, whose truth cannot be established with certainty" (Hurst, 1982).

It is strongly believed that decisions in organizations are made under uncertain conditions. This decision-making with uncertainty occurs when information is incomplete or imperfect, the firm's set of values are not thorough, consistent, ambiguous, and stable, and "*historicity*" places constraints (Hurst, 1982). Likewise, innovation processes encompass and necessitate taking action in a state of uncertainty (Jalonen, 2011). In other words, innovation is a process of "*muddling through*" (Rehn & Lindahl, 2012) so that one moves towards the 'unknown' (Hurst, 1982). The reason is that future events do not follow a pattern of past events; moreover, there is a lack of comprehensive knowledge about the future (Jalonen, 2011). Afuah (2003) believes that innovation management practice is, in fact, coping with uncertainty because uncertainty will always be the bane of the project process. In innovation management, the attempt is to "*convert uncertainty to a calculated risk*" based on the significant important part of this conversion, knowledge (Tidd & Bessant, 2009).

Both aspects of uncertainty, known and unknown (described in chapter 3), cause dissatisfaction within companies. This happens due to a lack of satisfaction perceived by organizations and their people if they continue acting and making decisions under uncertain conditions. Individuals intend to act under certainty and deny uncertainty. Because of real or presumed negative consequences of uncertain events, people select uncertainty avoidance strategies in the face of such situations (Jalonen, 2011). For instance, from Hofstede's (1984, 2001) point of view, avoiding uncertainty forms one of the fundamental cultural features of a nation (see also Kaasa & Vadi, 2010; Kalliny & Hausman, 2007). Change in organizations also implies uncertainty avoidance. New and puzzling situations of an organizational change make individuals consider it as a threat to their status in the company and resist the change when they feel dissatisfaction about it (e.g. Agboola & Salawu, 2011; Kooter & Schlesinger, 1979). Uncertainty avoidance leading to change resistance may produce apathy across the organization (Hannan & Freeman, 1984; Wong-MingJi & Milletter, 2002)

However, innovation uncertainty can bear positive meaning or at least be without detrimental effects, despite its harmful consequences (Jalonen, 2011). To make a connection between uncertainty and entrepreneurship Johnson (2001) represents uncertainty and ambiguity toleration as essential conditions of making events occur. In the same way, some other authors have shaped the concept of innovation selection and implementation as processes of dealing with uncertainty (Gerwin & Tarondeau, 1982; Souder & Moenaert, 1992; van Riel et al., 2004). They introduce innovation as a way of reducing uncertainty through processing the information. Hanft & Korper (1981) and Rogers (2003) stepped further into offering an optimistic opinion about uncertainty. According to Hanft & Korper (1981), uncertainty can improve decisions since when differences between "*fact*" and values might cause stubborn attitude among experts uncertainty plays a contributor role to reach an agreement. Rogers (2003) also believed that technological innovation, as an influential structure, declines uncertainty in causal relationships involved in achieving a predetermined result. Finally, some scholars like Foster (2010), by describing uncertainty as a foundation of innovation, have adopted an evolutionary approach towards uncertainty. In uncertain events, people's beliefs differ and often conflict, resulting in mistakes and errors. Nonetheless, these mistakes and errors are valued because in a competitive process of selecting the best option, they can be removed or replaced by better views. Therefore, mistakes and errors are crucial as they constitute a basis in the process of economic growth generation (Foster, 2010).

Regarding this thesis research questions in chapter 1, the study tries to describe innovation uncertainties and discuss how they can be treated in the risk assessment context. Therefore, the thesis aims at analysing treatment approaches for innovation uncertainties to reduce their negative consequences that can lead them to success.

4.4 **Dimensions of uncertainty in innovations**

Study about types, sources, and aspects of uncertainty that are interchangeable terms has been carried out for more than 40 years. Environmental uncertainty is one of the factors which has received specific attention from organization analysts. Environmental uncertainty has a significant role to play in reviewing the link between the environment and organization particularly, when organizational design theories are discussed (Burns & Stalker, 1961; Duncan, 1972; Thompson, 1967). Milliken (1987) recommended three different external categories of uncertainty namely: state, effect, and response. He differentiated the real environment from its unforeseen features, which may have an impact on the organization and its functions that cannot be always controlled by the firm. Other theorists describe innovation as a process by which the information gaps between customers' requirements and technological advantages can be closed (Goldhar et al., 1976; Rothwell & Robertson, 1973; Souder & Moenaert, 1992). In another view, the dependency of market, competition, and technology uncertainties is emphasized (Duncan, 1972). Jalonen (2011) took a systematic approach to review more than 100 scientific articles and identified 18 different aspects of uncertainty in innovation processes. Figure 8 illustrates how these factors can be classified into three main groups which are market, technology, and organizational uncertainty.

This clustering is also according to other research in the uncertainty area. Souder & Moenaert (1992) suggest "*user needs, competitive environment, technological environment, and organizational resources*" as four primary sources of uncertainty. The market uncertainty is often caused by the first two dimensions. In the internal source of uncertainty, organization resource, the knowledge uncertainty (knowledge gap) can be reduced by improving or adapting a way of organizing a company. In the continue, each factor of the illustration is described.

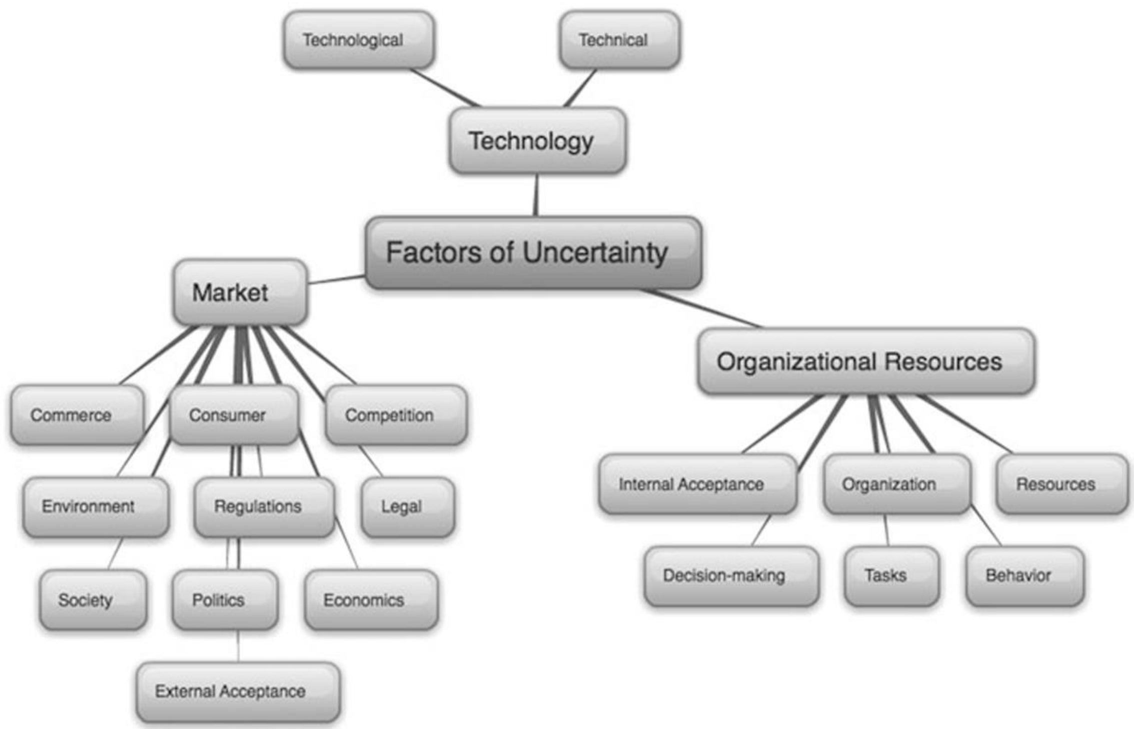


Figure 8, Dimensions of Uncertainty in Innovation, derived from Gaubinger et al. (2015)

4.4.1 Technology uncertainty

An innovation creator encounters double technology uncertainty to specify a product and process a production (Harris & Woolley, 2009). This high level of uncertainty is for supplement information about "*components and techniques*" required for a new product or service creation based on a specification that a firm needs to determine (Afuah, 2003). The uncertainty involved in specifying a product relies on the novelty of the technology, causing uncertainty relevant to capabilities and knowledge needed to apply new technology successfully (Tatikonda & Montoya-Weiss, 2001). This aspect of uncertainty is distinguished by factors like new material, new components, new technologies, a new technique of production, etc. (Gaubinger et al., 2015). To summarize, the technology uncertainty in innovation processes is caused when the detailed knowledge about new technology lacks or the knowledge needed for new technology application is incomplete, or both (Jalonen, 2011).

4.4.2 Market uncertainty

Market uncertainties refer to concerns about the characteristics and abilities of a specific market in the successful creation of a new product. They consist of problems relevant to customers' expectations and needs which can be present or hidden in interactions between users and designed products also ways of selling and distributing the goods (Leifer et al., 2001). Unclear user requirements, unknown behavior of customers, and concerns about determining price and demand for innovation are major sources of uncertainty imposed by customers (Souder & Moenaert, 1992; Tatikonda & Montoya-Weiss, 2001).

Further, market uncertainty is distinguished as knowledge shortage associated with competitors' actions. An organization encounters this type of uncertainty in the face of worldwide and "*liberalized*" markets (Ortt & Smits, 2006). To exemplify some influential factors in market uncertainty, new customer needs, new user categories, new marketing mix, new distribution channels, new competitors, new sources of supply, and new business models can be mentioned (Gaubinger et al., 2015). Overall, market uncertainty in innovation projects is generated, on the one side, when a company relationships with its users experience unplanned changes and, on the other side, when firm relationships with its competitors face unexpected changes followed by probable new markets opened by competitors (Jalonen, 2011). Many schools of thoughts consider the environmental aspect of innovation in the market dimension (Lynn & Akgün, 1998; van der Panne et al., 2003).

4.4.3 Organizational uncertainty

This class of uncertainties is affected by resource uncertainty, decision-making uncertainty, and acceptance uncertainty, that the last two aspects are part of task uncertainty. Task uncertainty is created by out-of-ordinary R&D activities and a high degree of organizational and technical interrelationship necessary for their implementation. In order to benefit from a successful innovation, sources of uncertainty should be reduced. But to achieve uncertainty reduction, resource allocation must be bone, which causes resource uncertainty. In fact, uncertainty about the technology and market can make organizations more uncertain about required resources considering their kind and amount (Milliken, 1987).

Figure 9 shows an uncertainty model extended by Gaubinger et al. (2015) in which organizational uncertainty is the third dimension. Based on this model, as incremental innovations utilize present knowledge, have a low degree of technology and market uncertainty. In market innovations, developing new markets using existing knowledge based on a market-based strategy is the target. This development causes uncertainty because the firm needs to know about a new market, its expectations, requirements, and competitors. Technology innovations perform in the well-defined market and offer new technologies. Known market segments are set as a market goal by the

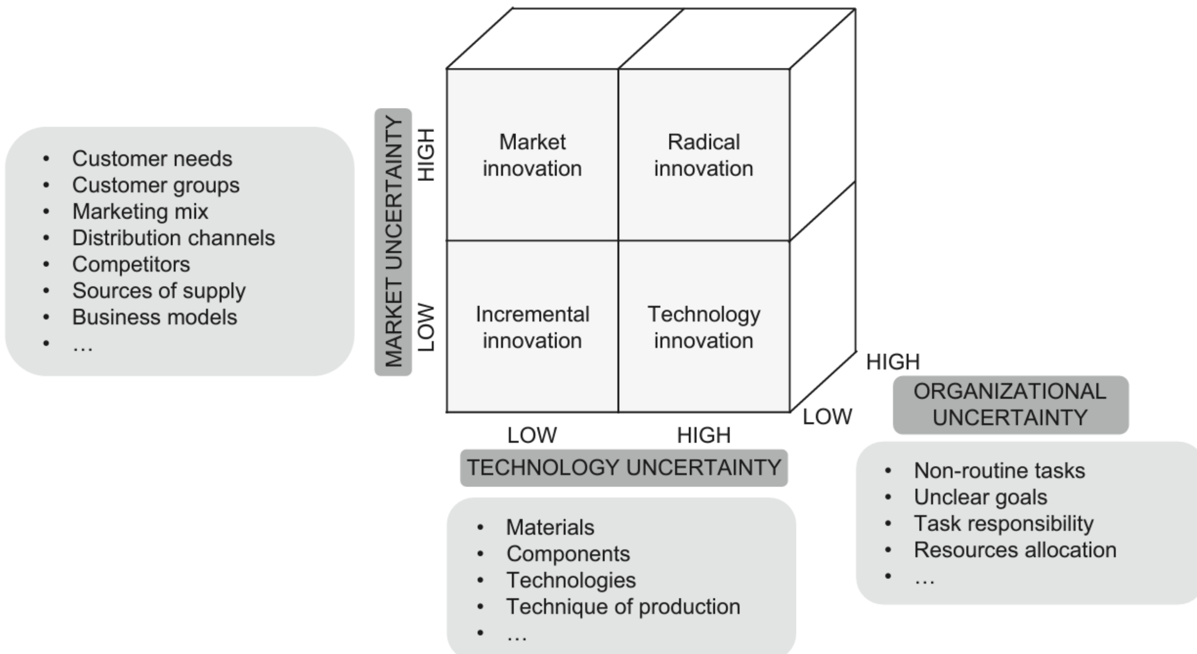


Figure 9, Uncertainty Matrix, taken from Gaubinger et al. (2015)

products; however, introduced technology is new for customers and imposes high uncertainty. Radical innovations are a source of many uncertain phenomena. Not only the market and technological requirements are unknown, but technical viability is not also known from the beginning of the innovation process. The reason behind this lack of knowledge is that the product is developing in and dependent on a market that has not been understood well. The third dimension of the uncertainty matrix depicts that the structure and resources of a company affect the total uncertainty of all innovation types (Gaubinger et al., 2015).

4.5 **A discussion about innovation uncertainties from the risk perspective**

Innovation definitions and descriptions imply that these processes face a formidable challenge in treating epistemic uncertainty, although both epistemic and aleatory uncertainty is involved in innovation risk management. Their definitions express introducing something new that can be a minor change in an improvement called incremental innovation or a novel idea in an organization or (and) to the market called radical innovation. Innovations bring the concept of and can be recognized by a degree of novelty as explained in section 4.1. Generally, novelty or newness always comes with 'unknowns' (lack of knowledge) and in some situations with true ambiguity, as described in level 4 of uncertainty in section 3.2. Innovations are distinguished with 'unknowns' about the technological, market, and organizational aspects of implementing a new idea. For instance, introducing a new product to a market creates technological uncertainties such as, what can be the technical specifications of the new product? Which of these specifications will have expected usefulness and feasibility? Technological concerns about the production processes of a new product, are skills and knowledge needed to produce it, which may be unknown.

Moreover, in analyzing the market, one source of uncertainty is customers and their requirements. What are the users' expectations of this novelty? When and how these requirements should be provided? The customers' needs can be categorized based on, for example, age group or demographic of the population, so what criteria should be defined to classify the users? What can be the customers' behavior towards a new product? Which model is useful for demand prediction of the new product and what are this model's parameters? What factors should be included in customers' support budget analysis? Another aspect of market uncertainty is the price of the new product. Price prediction depends on many factors such as the demand for the product, competitors' behavior, raw material procurement, most or all of which may be unknown. One concern about the competitors is that if they open a new market at the early stage of introducing the product to the market? Also, organizational uncertainties are sources of risk. It is unknown for firms whether their facilities contribute to innovation dissemination or block it. The regulatory environment may be unknown for an organization in deciding on an innovation. For example, is the new product technology completely compatible with the current regulations about its application? Also, allocating human resources in what way can serve the project progress? These uncertainty dimensions of innovations express lack of knowledge in different areas and are sources of epistemic uncertainty and risk for these projects' success. Therefore, in innovation risk management, assessing and treating these uncertainties over these projects' lifecycle can contribute significantly to warrant their triumph.

Novel ideas in incremental innovations may benefit from existing knowledge, 'knowns', but their true values are unknown, and variation in their future quantities might affect the purpose of new 'thing' creation. Therefore, both epistemic and aleatory uncertainties are involved in innovations. Nevertheless, as much as the innovation's degree of novelty increases, the market, technological, and organizational unknowns will also increase, resulting in more epistemic uncertainty. The newness quality (lack of knowledge) of innovations in many areas (innovation uncertainty dimensions and dependent on the innovation's degree of novelty) and its negative consequences and risks discussed in section 4.3 highlight the significant role of epistemic uncertainty in innovation risk assessment and management. So, in this thesis treating epistemic uncertainty of novel projects is studied.

Moreover, in this thesis, the epistemic uncertainty of assessment inputs is regarded for treatment. Based on section 3.1, to conduct an uncertainty analysis in the risk assessment context, a model g(X) is defined to describe a relevant system. This model produces Z as the quality of interest. In innovation uncertainty analysis, there are input X uncertainty, uncertainty propagation across the model g(X), and error uncertainty Z-g(X). In this work, the epistemic uncertainty treatment of the model input X is concerned, and other uncertainty analyses are not considered.

5. Adopting Approach to Treat Epistemic Uncertainty in Innovation Projects

The purpose of this chapter lies in analyzing epistemic uncertainty representations due to proposing an appropriate approach for treating this type of uncertainty in innovations. According to the previous chapter, treating the epistemic uncertainty of innovations is aimed to meet their consequent challenges in these projects. To find a proper approach(es) towards epistemic uncertainty treatment in the innovations, presented views about the practical application of epistemic uncertainty representations, introduced in 3.3, were analyzed. The analysis shows that the semi-quantitative approach can provide innovation managers with a comprehensible and practical quantitative risk assessment (QRA) technique to treat innovation epistemic uncertainty. Therefore, a hybrid model containing two semi-quantitative approaches with a knowledge dimension method is recommended and sounds appropriate to deal with the epistemic uncertainty of these processes.

The model constitutes three techniques. The first approach, the semi-quantitative risk assessment SQRA presents a framework to assess innovation epistemic uncertainty. In the second technique, the knowledge used in risk and uncertainty calculation of the first approach is evaluated and communicated. The third method extended semi-quantitative risk assessment EQRA, describes how to treat innovation epistemic uncertainty. In the following sections, the application and interpretation of epistemic uncertainty assessment techniques discussed by Flage et al. (2014) are explained. Then regarding the discussion, the suggested hybrid model in more detail and possible reasons why this model seems effective to treat innovation epistemic uncertainty will follow.

5.1 Views about epistemic uncertainty representations

In this section, views about practical applications of epistemic uncertainty representations, introduced in Table 2, are explained. Analyzing these uncertainty representations shed light on the finding semi-quantitative approach proper for the assessment and treatment of innovations epistemic uncertainty.

As mentioned in section 3.3, probability analysis causes major issues in the assessment. Epistemic uncertainty representation of probability has met with some criticism. Several opponents of applying probability in practical settings acknowledge that a problem (about subjective probability) in assigning imprecise probabilities exists, which is related to probability elicitation, not the concept of probability itself. One possible problem is that (subjective) probability is the only appropriate uncertainty measure in the risk assessment and management if the analysis and decision-making are carried out by one analyst (assessor). However, in practice, the analysis output is used by decision-makers and stakeholders, people other than the assessor. In other words, there is a separation between analysts and decision-makers whose judgments and preferences affect the decisions made. Also, there is intersubjectivity in the assignment. It means that due to increasing the involvement of more professional expertise, more than one assessor may participate in the assessment (Flage et al., 2014).

Obviously, in these circumstances, the background knowledge of analysts used in probability calculation has some effects on decision-making. There is a direct link between the strength of assessors' knowledge about the processes or (and) events studied and the strength of the analysis. The strength of background knowledge also affects the decision-makers. The assigned probability, $P(A)$, is conditional on the analyst(s)' knowledge, K, indicated as $P(A|K)$. In a subjective or intersubjective assessment, it is possible to have $P(A|K_1) = P(A|K_2)$ based on thoroughly different background knowledge, K_1 and K_2 of two analysts that K_1 relies on relevant and available data, reliable models, almost complete agreement among analysts, and weak assumptions derived from a strong background knowledge about the considered system and events, while K_2 consists of less reliable models, scarce and unavailable data, disagreement among experts, and strong assumptions because of poor knowledge about the system and phenomena involved. It indicates the importance of adding the strength of background knowledge K as the second component to the assessment output, quantitative analysis (Flage et al., 2014).

Fuzzy set theory as another quantitative epistemic uncertainty representation is employed by some scholars to deal with aleatory and epistemic uncertainty by fuzziness, ambiguity, and vagueness concepts (Blockley, 2013; Ross et al., 2002). But some others believe that uncertainty should be differentiated from ambiguity which must be reduced before taking on meaning in uncertainty analysis (Bedford & Cooke, 2001). In addition, from Flage et al.'s (2014) point of view, fuzzy set theory and its relevant representations (such as fuzzy probability) cannot explain epistemic uncertainty about unknown true numbers but can produce uncertainty descriptions about vague or ambiguous statements such as few explosion.

Furthermore, two-valued probability analysis, possibility and evidence theory, also hybrid models as quantitative risk assessment (QRA) approaches provide epistemic uncertainty analysis, most using lower and upper limits. These techniques have not received approval from the risk analysts. Despite putting considerable effort into introducing and assessing uncertainty representations, the bases of these methods and their applications in both interpretation and risk-informed-decision making are open to many questions (see e.g., Aven, 2011; Aven et al., 2014; Bernardo & Smith, 1994; R. Cooke, 2004; Lindley, 2000; Smets, 1994; Walley, 1996). Many risk scholars are doubtful about using these choices for representing and treating uncertainty in risk analysis used in decision making, and some present serious arguments against them (see e.g., North, 2010, p. 280). Cooke (2014) believes that "*an explosion of alternative uncertainty representations through the 1980s*" is derived from "*expert systems*" in the 1970s and these techniques are reducing over the last 20 years or so in the artificial intelligence area. It appears that the experts in the origin field of emerging alternative representations are lately and dominantly developing Bayesian framework over the first introduced ones, though they are re-emerging in new areas (R. M. Cooke, 2014; Flage et al., 2014). One main issue is that these representations lack "*operational meaning*" or "*interpretations*" (Flage et al., 2014) discussed in the following inspired by Flage et al. (2014).

Theoretically, intervals assignment as a main part of the description in two-valued probability analysis appears to be more suited to a situation of poor knowledge about the system bringing about imprecision in the probabilities assignment. The reason is that the risk expert can express her/his knowledge and relevant uncertainty by lower and upper quantities in the assignment instead of one exact number. Nonetheless, the real challenge is that two numbers are required to be assigned for each uncertain variable, not one, and expresses imprecise assignments when there is a lack of knowledge. To exemplify, consider the likelihood of $x = 3$ is the question that should be tackled. Determining one number in $[0, 1]$ is difficult for the analyst, but how she/he can assign two numbers as lower and upper limits. This can be carried out through direct assignment and assuming that the probability of $x = 3$ belongs to the interval $[0.2, 0.5]$. But this assignment is deemed arbitrary, and with two bounds assignment, she/he generates two arbitrary values. Another issue is to describe what assigned interval really means. Firstly, it indicates the analyst's unwillingness to present a more precise degree of belief about the probability of $x = 3$ than $[0.2, 0.5]$. Besides, the interval can be interpreted as the analyst's degree of belief about the value of $x = 3$ higher than taking a specific ball out of an urn containing five balls and lower than drawing one ball out of an urn having two balls. She/he is not willing to take a further degree of belief than this about the quantity of x. This way of interpreting is not easily perceived and might be difficult for probability assessors to "*absorb*". Experiences have shown that the analysts require to be trained and practiced intensely capable of understanding this meaning.

In addition, grasping what is the benefit of using lower-upper probability assignments instead of one probability has caused a struggle for the uncertainty analysts. Even though a well-described interval probability with a good representation of the assignment imprecision, encounters serious difficulties understanding two-bounds value compared to one value for a quantity. Considering the issues assessors face, they doubt the necessity of broadening uncertainty representation of single-valued perspective out of its borders. This implies a need for identifying, tackling, and taking care of these problems as they have a significant impact on risk assessment; consequently, decision making.

As Table 2 depicts, possibility theory and evidence theory can present two uncertainty interpretations, though they struggle to provide operational definitions. Belief and plausibility measures of evidence theory and necessity and possibility measures of possibility theory can introduce two-bound probabilities. In fact, from a technical perspective, possibility and probability theory are derived from evidence theory under specific conditions. The evidence and possibility theories can also generate belief measure and possibility measure respectively that can be described as "*degree of belief*" and "*degree of possibility*" respectively, other than lower and upper probability limits. Degree of possibility measures "*the amount of likelihood or confidence*" about, and degree of belief measures "*positive evidence supporting*" an event A occurrence (Helton, 2011). According to Shafer (1976), a degree of belief Bel is the central targeted theme of evidence theory. Shafer (1990) describes $Bel(A) = q$ as the analyst's judgment on the evidence strength about the extent to which event A is true that can be compared with having the evidence obtained by a $q \times 100\%$ reliable witness, in other words,

$$Bel(A) = P(\text{"}the\ witness\ claiming\ that\ A\ is\ true\ is\ reliable\text{"}).$$

Therefore, a dual interpretation that exists in the probability about frequentist probability ("*limiting relative frequency*") versus subjective probability ("*degree of belief*") also exists in the possibility theory in term of 'degree of necessity/possibility' against lower and upper probabilities and in the evidence theory for 'degree of necessity/plausibility' versus lower and upper probabilities. Adopting and developing techniques founded on interpretations different from interval representation clearly indicates taking another approach toward uncertainty communication in the risk assessment context. The reason is that degree of possibility and degree of belief phrases in possibility and evidence theory, respectively, cannot provide risk and uncertainty assessment with adequately understandable description.

Moreover, hybrid models combine different uncertainty representations dependent on the situations. But choosing between probability or other uncertainty assessment approaches for each condition lacks available "*authoritative guidelines*" in the risk community. As Flage (2010, p. 33) says, some believe that only if there is an adequate amount of available information for probability assignment, the probability seems proper to represent the uncertainty. Nevertheless, it is not apparent how to put this into practice. For instance, in the case of an adequately large amount of available data for parameters of a frequency probability model, uncertainty representation is not required because there is no epistemic uncertainty. If there exist data but not enough to provide exact true value(s) for uncertain quantities, applying single-valued probability is justified when imprecision cannot affect the analysis, though some level of imprecision is always involved. On the other side, the simple way of using probabilities makes this approach sensible to be employed if the degree of imprecision is trivial. But when using probability is not justifiable, factors for choosing specific uncertainty representation from all alternatives (interval analysis, imprecise probability, possibility theory, etc.) are needed. This requirement necessitates directing the research towards developing the hybrid approach and particular hybrid methods (interval analysis/probability, probability/possibility, etc.).

As seen, all the above QRA approaches provide the risk assessment with quantitative values for risk and uncertainty. The above discussion intends to highlight capturing and communicating uncertainty require widening the perspective beyond the probability or other quantitative approaches. Also, other presented methods are not simply practicable. Epistemic uncertainty representation developments of non-probabilistic and hybrid techniques deal most with technical problems, while less attention is paid to fundamental difficulties, and little is found on rules and guidelines for method selection and implementation in the risk assessment context.

However, the semi-quantitative approach (in Table 1) is founded on this belief that probability or any other quantitative technique cannot transform the whole aspect of uncertainty with only mathematical calculations. There are unknown or uncertain quantities concealed in the subjective probabilities that need to be identified and assessed qualitatively. This approach is a hybrid model and a mixture of quantitative representation and qualitative techniques. The semi-quantitative approach supplements probability analysis (a QRA method) with identification and qualitative description of 'uncertainty factors' (assumptions) hidden in the background knowledge used in subjective probability. The framework was proposed to capture all aspects of risk and uncertainty and deal with the issue probability cannot transform the risk and uncertainty involved thoroughly into a "*quantitative format*". Quantitative approaches (probability-bound analysis, imprecise analysis, and possibility and evidence theories) in Table 2 lack a qualitative perspective capable of fully describing risk and uncertainties. Nonetheless, the semi-quantitative technique presents an approach to serving the risk assessment: to reveal involved risk and uncertainty.

The qualitative methods of this approach determine the criticality or importance of assumptions providing the risk analysis with some improvement. These qualitative techniques are the strength of knowledge (SoK) assessment, sensitivity analysis, and assumption deviation risk.

The SoK assessment is carried out, according to Flage & Aven (2009). The background knowledge is categorized as strong if all of the below conditions holds true:

- The assumption made are seen very reasonable
- Much reliable data is available
- There is broad agreement/consensus among analysts/experts
- The phenomena involved are well understood: the model applied are known to provide predictions with the required accuracy

On the other hand, if one or more of these conditions are true the background knowledge is assessed as weak:

- The assumptions made represent a strong simplification
- Data is not reliable or available

- There is a lack of agreement among the analysts/experts
- The phenomena involved are not understood very well: models do not exist or are believed to give poor predictions

All cases between strong and weak strength of knowledge are classified as moderate strength of knowledge.

In the sensitivity analysis, the change of risk metric derived from deviation in uncertain factors or uncertain assumptions is analyzed to determine the criticality of these assumptions. If a minor assumption deviation increases the risk measure in the risk analysis significantly and the strength of knowledge supporting the assessment is weak, the assumption is critical. In assumption deviation risk, the magnitude and impacts of assumption deviation are considered to assign a risk score. This number quantifies the importance of the assumption. Finally, the strength of knowledge applied for these judgments is evaluated. The main intention is to guide analysts towards improving the critical assumptions by some methods, such as the law of total probability.

Semi-quantitative risk assessment SQRA (Berner & Flage, 2016) and extended semi-quantitative risk assessment EQRA (Berner & Flage, 2017) are two techniques established on the semi-quantitative approach to treat risk and uncertainty.

5.2 Adopted approach to innovation epistemic uncertainty representation

The above discussion appears that the semi-quantitative approach can substantially contribute to reducing epistemic uncertainty in innovations. Risk analysis is an inevitable part of the planning process. Regardless of the planning subject, we need to imagine all situations resulting in damage, loss, or any detrimental consequences. Data, information, and all available evidence are used to develop a model representing the system and its environment. The risk is described in this model in conceptual and (or) mathematical format (Covello & Mumpower, 1985). However, the model tries to approximate the reality. It is established on assumptions and simplifications of the processes controlling and affecting the system behavior. Therefore, a risk description is intrinsically conditional on the model assumptions reflecting the knowledge involved (Beard, 2004).

Assumptions or uncertain factors hidden in the background knowledge are a certain part of a quantitative risk assessment (QRA). They are made because of scarce or no knowledge about a phenomenon to simplify a complex uncertainty assessment (Flage & Berner, 2017). Shortage or lack of knowledge in innovations brings about generating assumptions to simplify the situations with approximately many (dependent on the innovation degree of novelty) technological, market, and organizational unknowns. The semi-quantitative approach highlights and assesses the criticality also deviation risks of subjective and non-subjective assumptions hidden in the background knowledge used in innovation risk management. Moreover, the strength of knowledge used for the assessments is evaluated and communicated to the innovation decision-makers. It addresses the subjective assignments problem discussed in section 5.1 (intersubjectivity, separation, and influence of the SoK on decision-making) by expressing the SoK applied for assumptions criticality assessment. Overall, the semi-quantitative approach can serve innovation managers to assess, treat, and decline the epistemic uncertainty involved in these projects.

5.3 Proposed model for epistemic uncertainty treatment in innovation projects

Considering the broad areas of innovations, the importance of the epistemic nature of innovation uncertainty, and the previous section, a hybrid model is suggested to treat epistemic uncertainty of innovations. The model consists of SQRA and EQRA approaches focusing on the uncertain assumptions of risk analysis and a background knowledge assessment method inspired by Flage & Aven (2009). The model tries to express and deal with innovation analysts' concerns about epistemic uncertainty in innovation projects through the semi-quantitative risk assessment SQRA approach, which assesses uncertainty systematically and applies probabilistic analysis. Addressing the problem described in section 5.1 about (subjective) probability is another concern which the model tries to deal with by assessing and expressing the strength of knowledge involved in the SQRA risk calculation. The model also tries to tackle innovation manager's concerns about epistemic uncertainty by treating these uncertainties through the extended semi-quantitative risk assessment EQRA scheme, which guides managers towards uncertainty treatment strategies. The model seems to throw light on epistemic uncertainty treatment in innovation projects with high uncertainty.

The SQRA and EQRA affect the innovation project management by addressing the epistemic uncertainty derived from shortage or lack of knowledge in these projects, dependent on their novel quality. These approaches can provide innovation managers with critical assumptions highlighted, assumptions risk assessment and treatment approached, and innovation epistemic uncertainty and risk reduction scheme.

Semi-quantitative risk assessment SQRA concentrates on the assumptions as inputs for QRA and assesses uncertain assumptions through a qualitative screening scheme (QSS). QSS involves the sensitivity analysis of risk indices to assumptions deviations and assessing the belief in assumptions deviations from their base case values also the strength of knowledge supporting these evaluations (the belief in deviations and sensitivity). SQRA approach then presents eight settings that a risk analyst may encounter when carrying out a risk assessment. These settings made by classified uncertain assumptions represent how to assess these assumptions risks (Flage & Berner, 2017).

EQRA approach as an uncertainty treatment approach tries to manage assumption deviation risks when assumptions are one component of the knowledge used in the uncertainty assessment. The background knowledge consists of assumptions, models, data, understanding phenomena, and expert judgments. It is crucial to evaluate and communicate the strength of the background knowledge to the decision-makers. In long-term processes, following up assumption deviations from the initial values might also affect the projects' success since predicting the future with negligible imprecision is complicated, and assessed risks may deviate from acceptable levels. The uncertainty treatment approach in EQRA focuses on assumptions as part of background knowledge and establishes management strategies to control the negative deviations of assumptions. The qualitative screening scheme QSS identifies assumptions uncertainties followed by eight settings based on assumptions-based planning, ABP. The main target lies in communicating and providing guidance on assumptions made by the analysts, particularly critical ones to those engaged in risk management that can decide appropriate strategies and deal with uncertain assumptions (Berner & Flage, 2017).

Similar to SQRA, EQRA applies QSS to identify uncertain assumptions regarding the belief in assumption deviation from their first values, the sensitivity analysis, and evaluating the strength of knowledge SoK, supporting these assessments. For uncertain assumptions classified by QSS, settings present treatments based on the assumption-based planning approach proposing how to monitor these assumptions during the innovation execution. This strategy development guideline on assumption uncertainties seems a proper uncertainty treatment approach for innovations and can contribute substantially to these projects reaching their set goals.

According to Flage & Berner (2017), in both techniques, the qualitative screening scheme QSS is employed to identify the criticality of uncertain assumptions. As the QSS is the same to a large extent for both SQRA and EQRA, it is described first. Then, presented eight settings for each approach, their contribution to assess and treat epistemic uncertainty in innovations, and the role of knowledge dimension in the model will follow, separately in continued sub-chapters.

5.3.1 Qualitative screening scheme QSS

The qualitative screening scheme (QSS) is founded on assessing the belief in assumptions deviation from the base case and the sensitivity of risk index to changes of assumptions also the SoK assessment. The QSS general format, regardless of settings' content for SQRA and EQRA, is illustrated in Table 3. In this table, $R(x_0)$ is an expected value-based risk metric, and x_0 refers to a specific assumption quantity. The low and moderate/high categorization of the sensitivity analysis and the belief in assumption deviation as well as the strong and moderate/weak classification of the SoK, introduce eight settings (Flage & Berner, 2017).

Table 3, Qualitative Screening Scheme, source: Flage & Berner (2017)

Belief in deviation from x_0	**Sensitivity of $R(x_0)$ wrt x_0**	**Strength of knowledge**	
		Strong	**Moderate/weak**
Low	Low	Setting I	Setting II
	Moderate/high	Setting IIIa	Setting IVa
Moderate/High	Low	Setting IIIb	Setting IVb
	Moderate/high	Setting V	Setting VI

Specifying the low or moderate/high classification of the belief in deviation can be conducted through a probability or expected value calculation. That is, the belief in deviation of an assumption $X = x_0$ is low, if for some value, d the probability $P(X - x_0 > d)$ is lower than a threshold, or if expected value $E[X - x_0]$ is above or lower than some a threshold (Flage & Berner, 2017).

In the sensitivity analysis, the sensitivity of the risk index to assumptions deviation (uncertain factors) from what has been assumed, is classified into low, moderate, and high. Berner & Flage (2016) define assumption as "*condition/inputs that are fixed in the assessment but which are acknowledged or known to possibly deviate to a greater or lesser extent in reality*". Regarding the potential deviation of the assumptions, they are called 'uncertain assumptions'. When the actual values of assumption deviate from their base case, the assessed risk index may change dependent on the magnitude of the deviation and the sensitivity of the risk index to the assumption deviation. (Flage & Berner, 2017). Therefore, the sensitivity can be categorized as below (Flage & Aven, 2009):

- High: Relatively small changes in the initial assumptions require to cause changes in the results
- Moderate: Relatively large changes in initial assumptions require to cause changes in the results
- Low: Unrealistically large changes in initial assumptions require to cause changes in the results

The sensitivity analysis determines the criticality or importance of an assumption. An assumption is critical/non-critical or has high/low sensitivity if the sensitivity of the related risk metric is recognized as high/low to changes in the original assumption, and the strength of knowledge supporting these assessments is weak/strong. Based on Flage & Berner (2017), the criticality of assumptions in Table 3 increases by moving from setting I to VI, also in both vertical (e.g., I, IIIa, IIIb, V) and horizontal (e.g., V, VI) directions. They also believe that to classify the sensitivity as low or moderate/high, specific quantitative criteria are not required. It can be an analyst's crude judgment on some selected importance measures compared to a threshold. In other words, the sensitivity is low when the importance measure is lower than the threshold.

In QSS, the strength of background knowledge assessment follows the method explained in section 5.1. In EQRA, Berner & Flage (2017) represented this SoK assessment by a pedigree matrix illustrated in Table 4, which is the only difference between QSS of SQRA and QSS of EQRA.

This matrix is applied in NUSAP national scheme for uncertainty and quality for policy to evaluate provided information qualitatively (Funtowicz & Ravetz, 1990). In the pedigree matrix, each column indicates one dimension of the background knowledge and is required to be assessed and scored from 1 to 3. The overall strength of knowledge is strong if all judged knowledge aspect is 3. In some situations, some dimensions of the knowledge (assumption, data, models/phenomena, expert) may be irrelevant that can be written as, for example, (2, 3, NA, 1) (Berner & Flage, 2017). Then, based on the pedigree matrix, (3, 3, 3, 3) shows a strong knowledge, and (2, 3, 2, 2), for instance, represents a moderate knowledge strength.

Moreover, when the criteria are applied for assessing the strength of knowledge relevant to an assumption $X = x_0$, the data, expert judgment, and models/phenomena criteria must be related to X and phenomenon producing an outcome of X. While, the first criterion, assumptions, must be related to supplementary assumptions that follow from x_0, the assumption being assessed (Flage & Berner, 2017).

Since QSS in both SQRA and EQRA uses the same method to evaluate the SoK and the result of SQRA will be employed in EQRA, the pedigree matrix is suggested for SQRA. This visualization of knowledge strength shows and clarifies the weak aspects in the background knowledge on which the assessment based. Accordingly, stakeholders and decision-makers can consider knowledge weaknesses in their decision-making and define improvement actions to strengthen the background knowledge.

Table 4, Pedigree Matrix, taken from Berner & Flage (2017)

Score	SoK label	Phenomena/model	Data	Expert agreement	Realism of assumption
3	Strong	The phenomena involved are well understood; the models used are known to give predictions with the required accuracy.	Much reliable data is available.	There is broad agreement among experts.	The assumption made is seen as very reasonable.
2	Moderate	Conditions in between strong and weak: say the phenomena involved are well understood, but the models used are considered simple/crude.	Conditions in between strong and weak; say some reliable data are available.	Conditions in between strong and weak.	Conditions in between strong and weak.
1	Weak	The phenomena involved are not well understood; models are nonexistent or known/believed to give poor predictions.	Data are not available or are unreliable.	There is lack of agreement/ consensus among experts.	The assumption made represent a strong simplification.

5.3.2 Semi-quantitative risk assessment, as an uncertainty assessment approach for innovations

The SQRA approach proposes a method capable of assessing innovation uncertainty. How this approach serves innovation managers is explained after describing the technique.

Before describing SQRA according to Flage & Berner (2017), it is required to highlight that the risk in this section is conceptualized by the triplet (s_i, p_i, c_i) and described by the triplet (C', Q, K). In risk concept, s_i is the ith scenario, p_i is the probability of that scenario, and c_i is the consequence of the ith scenario, i =1, 2, ... N. In the risk description, C' refers to the determined consequences, Q a probability measure of uncertainty related to C', and K the background knowledge that supports C' and Q (which includes SoK assessment) (SRA, 2015). If Y indicates the quantity describing the consequences, that is Y = C', $R(x_0)$ is expected value-based risk metric and defined as (Berner & Flage, 2016):

$$R(x_0) = cE(Y|X = x_0\,, K)$$

Where c is normalizing constant and X as part of K is an uncertainty number with fixed value x_0.

Also, the law of total expectation is used in SQRA to calculate the risk index unconditional on X, but conditional on K, as follows (Berner & Flage, 2016):

$$R = E\left[R(X) \,\middle|\, K\right] = \int R(X) dF(x|K),$$

Where $F(x|K) = P(X \leq x|K)$.

Eight presented settings for assessing uncertain assumptions in SQRA are depicted in Table 5 and explained according to (Flage & Berner, 2017) as follows.

Setting I, identifies assumptions with a low degree of belief in deviation and low criticality (low degree of the sensitivity of associated risk metric to changes in assumed values of the assumptions), and the knowledge supporting the belief in deviation and the sensitivity analysis is strong. In this case, $X = x_0$ is documented as non-critical, and reporting $R(x_0)$ is strongly justifiable.

Assumptions in setting II are distinguished by low belief in deviation and low sensitivity, although the knowledge basis for this judgment is not strong. As $X = x_0$ sounds the best assumption and other risk measures than $R(x_0)$ are not available, decision-makers should be informed about the weak knowledge used in this evaluation.

In setting V, assumptions are critical since the belief in deviation and sensitivity are assessed moderate/high supported by strong knowledge. Besides, the strong knowledge can lead to establishing a probability distribution $F(x|z_0,\ K) = P(X\ \leq x|Z = z_0,\ K)$ that can calculate unconditional risk index $E[R(X)]$ using the law of total expectation. $Z = z_0$ as additional assumptions are applied to establish the distribution F and because of the strong knowledge, introducing them is strongly justifiable and can be documented as non-critical.

Setting VI similar to setting V identifies assumptions with moderate/high belief in deviation and sensitivity, but knowledge used for this assessment is weak/moderate. Consequently, establishing probability distribution with strong justified assumptions $Z = z_0$ is difficult. Two alternative approaches were introduced in SQRA, that is,

1- Establishing interval/imprecision probability distribution on X, then determining the risk index over an interval. In other words, for a strongly justified conditional distribution

$F(x|Z,K)$ and a strongly justified interval $[z_{min}, z_{max}]$ certainly containing the Z, integration with regard to $F(x|Z = z_{min}, K)$ and $F(x|Z = z_{max}, K)$ can be used for specifying an interval for unconditional risk index $E\left[R(X) \middle| K\right]$.

2- Considering $Z = z_0$ as a best-assigned assumption, conditional risk index $E\left[R(X) \middle| z_0, K\right]$ can be calculated by integration with respect to $F(x|Z = z_0, K)$ using the law of total expectation. Then highlighting an assumption deviation risk for $Z = z_0$ based on interval/imprecise probability is required.

Table 5, Guideline for Uncertain Assumption Treatment in SQRA, derived from Flage & Berner (2017)

Belief in deviation from x_0	**Sensitivity of $R(x_0)$ to x_0**	**Strength of knowledge**	
		Strong	**Moderate/weak**
Low	Low	Setting I: Report $R(x_0)$ List the assumption $X = x_0$ as noncritical	Setting II: Report $R(x_0)$ Highlight qualitative strength of knowledge assessment of assumption $X = x_0$
Low	Moderate/high	Setting III: Report $R(x_0)$ Highlight assumption deviation risk assessment for assumption $X = x_0$, based on probability *or* As for Setting V	Setting IV: Report $R(x_0)$ Highlight assumption deviation risk assessment for assumption $X = x_0$, based on probability or interval/imprecise probability. *or* As for Setting VI
Moderate/high	Low	(as Setting III)	(as Setting IV)
Moderate/high	Moderate/high	Setting V: Assign $F(x\|z_0,K)$ and determine $E[R(X)\|z_0,K]$ wrt F using law of total expectation. List assumption $Z = z_0$ as noncritical	Setting VI: Assign $F(x\|z_0,K)$ and determine $E[R(X)\|z_0,K]$ wrt F using law of total expectation. Highlight assumption deviation risk assessment for assumption $Z = z_0$, based on probability or interval/imprecise probability *or* Assign interval/imprecise probability distribution on X and determine resulting interval for $E[R(X)\|K]$

The deviation between the initial assumed case and the actual value of an assumption can pose a risk termed as assumption deviation risk coined by Aven (2013). The aspects of assessing assumption deviation risk assessment are (Aven, 2013, p. 139):

- The magnitude of deviation with related consequences
- A measure of uncertainty of this deviation (such as probability) and consequences
- The knowledge supporting these

To assess this risk, for deviation $D = X - x_0$with different potential values $d = (d_1, \dots, d_n)$, relevant probabilities $p = (p_1, \dots, p_n)$ and consequences $s = (s_1, \dots, s_n)$ where $p_i = P(D = d_i|K)$ and $s_i = R(x_0) + R(x_0 + d_i)$ should be assessed. The SoK assessment of the triplet (d, p, s) needs to be supplemented that can be qualitative as low, moderate, and high (Aven, 2013).

Assumptions in settings III and IV have the same characteristics in the belief in deviations and sensitivity; nevertheless, the SoK in the former is strong and in the latter is moderate or weak. Both settings have alternative approaches for the assessment (settings V and VI respectively), however assessing assumption deviation risk should be reported in both settings, when in setting IV it is possibly based on interval/imprecise probability due to weak knowledge compared with setting III, which applies probability because of strong knowledge.

SQRA contribution to innovation epistemic uncertainty treatment

SQRA approach provides the innovation managers with a solution to deal with involved epistemic uncertainty by presenting a technique to assess and reduce the risk and uncertainty involved in innovations. This approach employs single-valued probabilistic analysis for quantitative risk assessment, which is much easier to understand and has clear operational interpretation rather than two bound probabilistic or non-probabilistic representations. The technique also addresses innovations epistemic uncertainty stemmed from scarce or lack of knowledge. These innovative processes lack data and information about a new idea represented by their degree of novelty. And the more innovations' degree of novelty, the higher degree of uncertainty encounters these projects. In order to assess the risks and uncertainty of innovations and due to weak knowledge derived from the innovations' novelty, subjective assignments come on the scene to simplify a complex situation for the assessment through making some assigned assumptions.

For example, in analyzing the technological risk of new product development (NDP), its technical functionality is a source of uncertainty (and risk) and unknown. Technical functionality may refer to whether the product functions based on its technical expectations or not and what the product system reliability is. In assessing the product reliability considering expert judgments, the exponential distribution may be assigned (subjective probability) for the product lifetime to express related uncertainty about the product failure times. This assignment creates a new assumption for the risk assessment as it is assumed that the product failures can be estimated by the exponential distribution. Or in incremental innovation, for assessing market risk and uncertainty of adding new suppliers to existing distribution channels, some assumptions are assigned. For instance, a specific value for a new supplier's lead time (average time from ordering to receiving an order) is assigned and entered the assessment as a new assumption. In other words, assignments that stemmed from a lack of knowledge add new assumptions to the risk and uncertainty assessment. SQRA technique assesses the criticality and consequent risk of subjective and non-subjective assumptions dealing with innovations epistemic uncertainty.

Furthermore, the strength of present and assigned knowledge (subjective assignments) are assessed and communicated in the SQRA that can lead to innovations triumph. The SoK assessment not only addresses the problem detailed in 5.1 about subjective probability by adding the strength of knowledge assessment into QRA, but it also informs the innovations' managers about the strength of (assigned) knowledge used in QSS. Especially, when the pedigree matrix gives a format by which weak class(es) of knowledge dimensions, i.e., models/phenomena, data, experts, and assumptions in the (assigned) knowledge, are specified with numbers for each assumption, for example (2, 3, 1, 1). Such information can be used in decision-making and managerial review, as their purpose is to make risk-informed decisions based on the results of the risk assessment. In addition, the innovation managers can define some improvement for weak knowledge dimension(s) (dimensions three and four with value 1 in the above example) during the project execution, to strengthen the knowledge, reassess the criticality of subjective assumptions (e.g., new supplier's lead time), reduce the risk, and increase the project success.

5.3.3 Knowledge dimension in innovation risk and uncertainty calculation

As described in section 5.1, the strength of background knowledge assessment needs to be reflected and added to a quantitative risk assessment. In semi-quantitative risk assessment, the strength of knowledge used for judgment on the belief in assumption deviation and the sensitivity of risk index to the assumption deviation is evaluated and communicated by the pedigree matrix. Nonetheless, the knowledge assessment applied to calculate the risk in SQRA, with the below formula, is not considered and expressed.

$$R(X) = cE(Y|X, K)$$

Where Y indicates a quantity describing consequences and X is an assumption as part of the K.

In other words, data used for calculating risk, models/phenomena involved to describe Y, expert judgments, and all assumptions used in calculating $R(X)$ should be considered capturing the whole uncertainty involved in innovation risk assessment. In SQRA, nevertheless, data, model, and expert judgment related to each assumption $X = x_0$, as well as all assumptions followed from the assumption being assessed, are taken into account to assess the belief in deviation and sensitivity analysis of that assumption. For example, in the market risk assessment of introducing a new product to the market, customer behavior is analyzed. One may assume 15% of the users react adversely to the product. In SQRA, data, models, and expert judgments are taken into consideration to assess the extent to which this percentage may deviate and what the sensitivity of the market risk index to such deviation will be. But due to calculating risk and uncertainty, data, models, and expert judgments are used to calculate the consequences of the customers' behavior (adverse reaction) that can be economic loss and damage to the organization popularity caused by, for instance, these users negative promotions on the social networking sites.

Therefore, the knowledge classifications evaluation needs to be carried based on the described method in section 5.1. In order to communicate the SoK assessment, similar to SQRA and EQRA approaches, the pedigree matrix, Table 4, is suggested. That is, the strength of this knowledge assessment can be represented as, for instance, (2,3,2,1).

Supplementing the whole knowledge assessment to the quantitative risk assessment benefits the innovation processes in two ways. It informs decision-makers with the SoK supported the risk assessment and addresses the issue explained in section 5.1 about the subjective probability. In addition, it can substantially contribute to providing a clear picture about knowledge dimensions employed in the risk calculation for innovation managers, particularly when all subjective assignments cannot be transformed into a quantitative format. They may be established on a qualitative basis, for example, to describe (part of) scenarios or models. Communicating the knowledge dimensions of each risk index in each innovation uncertainty dimension by pedigree matrix would help the project managers distinguish the weak part of the knowledge and take actions before or during the process implementation to widen the knowledge. For instance, consider a situation that the action of an improperly selected human resource causes risk and damage in an innovation. But if the strength of knowledge in assessing human resource risk (a component of organizational uncertainty aspect) shows weak knowledge about human resource behavior, some measures could have been defined to collect required information about human resources during the project implementation reducing relevant risk. Improved knowledge can be used as new data to update subjective assignments, for example applying the Bayesian approach for updating models' parameters and reassess risk. Broaden knowledge can mitigate the risk and epistemic uncertainty over the project life period.

5.3.4 Extended quantitative risk assessment, as an uncertainty treatment approach for innovations

In EQRA, the main intention lies in identifying and following up critical assumptions ensuring that their deviation or "*failure*" does not invalidate the results of the risk assessment also judgments made and decisions informed by the risk assessment results. Presented eight settings in EQRA, are defined based on "*assumptionbased planning*" ABP framework (JA. Dewar, 2002), which Berner & Flage (2017) believe provides a valuable foundation for managing uncertain assumptions in the risk assessment. In EQRA, the ABP framework includes some main strategies to deal with uncertain assumptions with the following definitions (Flage & Berner, 2017).

- Signpost is an event or threshold expressing a significant change in the belief in assumption deviation from what has been assumed, or the sensitivity of this deviation to the related risk index
- Shaping indicates taking action that prevents critical and unwanted assumption deviation from their base case, used in the risk assessment
- Hedging indicates taking action before the plan execution that well-prepares the organization/system for situations in which one of its critical assumptions may fail

- Contingency expresses taking action during the plan execution if and when deviations happen

Figure 10 illustrates the link between the ABP and risk management approaches. This figure shows how signpost, shaping, hedging, and contingency strategies of ABP act like leading indicators, preventive barriers, and consequence-reducing barriers of the Bow-tie diagram in risk management. Based on this figure, ABP emphasizes assumption deviation as a hazard and introduces the above responding strategies as systematical outputs of the risk assessment to the risk management (Berner & Flage, 2017).

Suggested strategies by Berner & Flage (2017) in the EQRA approach for different settings can be seen in Table 6. In continue, the explanations of settings come from Flage & Berner (2017).

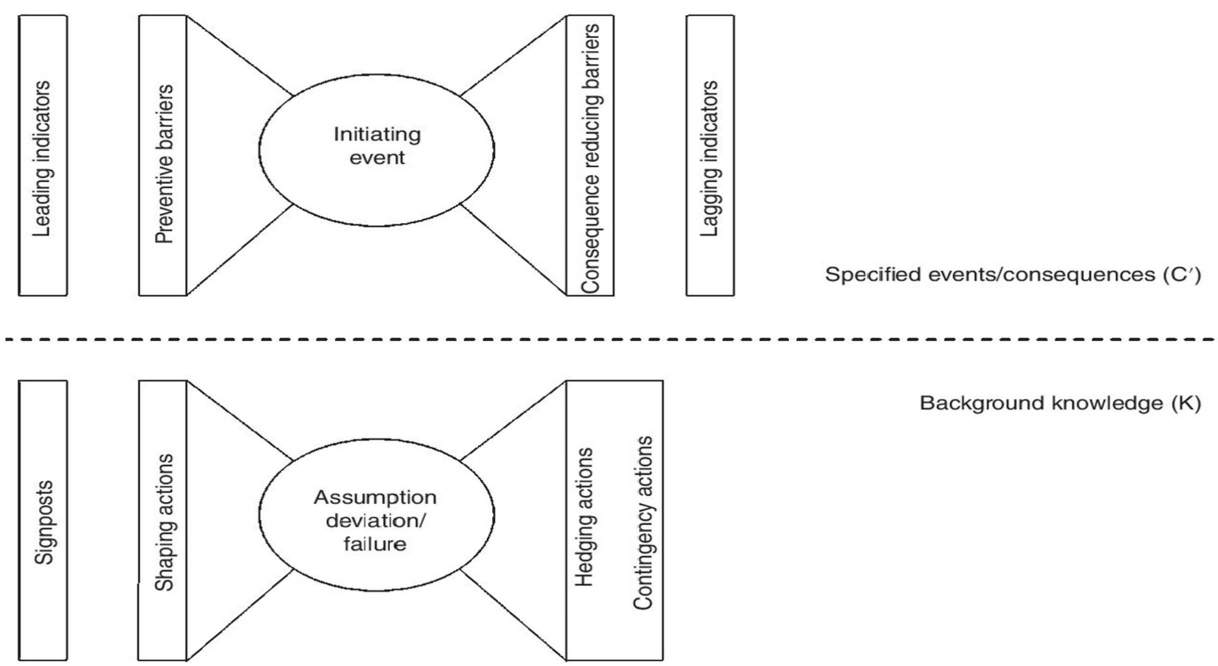


Figure 10, The Bow-tie Model to Depict the Parallel between ABP and Risk Management, source: Berner & Flage (2017)

Table 6, Uncertain Assumption Management Strategies, source: Flage & Berne (2017)

Belief in deviation from x_0	Sensitivity of $R(x_0)$ to x_0	Strength of knowledge	
		Strong	Moderate/weak
Low	Low	Setting I: Verify SoK	Setting II: Signpost
	Moderate/high	Setting IIIa: Verify SoK (Singpost) (Hedging) (Contingency)	Setting IVa: Signpost (Shaping) (Hedging) (Contingency)
Moderate/high	Low	Setting IIIb: Verify SoK (Shaping)	Setting IVb: Shaping (Hedging) (Contingency)
	Moderate/high	Setting V: Shaping Hedging Contingency	Setting VI: Shaping Hedging Contingency (Signpost)

Settings I and II show that assumptions in these settings deviate and create sensitivity to a low degree. The knowledge used for classification in setting I is assessed as strong, and knowledge verification reinforces the decision that assumptions in this setting are not required to be followed up. On the other hand, in setting II, the knowledge used for assessing the belief in deviation and sensitivity analysis is evaluated as moderate/weak. As knowledge is not strong, a surprise may happen. Therefore, due to monitor the assumption deviation establishing one or more signposts is recommended. Based on deviation factors of a signpost, actual or possible deviations will be dealt with.

Assumptions in settings IIIa and IVa are characterized by a low degree of belief in deviation and a moderate/high sensitivity. The knowledge supporting these categorizations in setting IIIa is judged strong. Verifying this assessment with the particular emphasis on the belief in deviation can be used to alert decision-makers to a possible change in the deviation belief. Moderate or high sensitivity leads to take a cautionary approach towards assumption in setting IIIa and choosing hedging and contingency as the secondary strategy. Nevertheless, in setting IVa the knowledge applied for classifying the sensitivity and belief in deviation is assessed as moderate or weak. As surprises may occur and assumptions in setting IVa may deviate, cautionary thinking justifies developing signpost as a primary and possibly shaping as a secondary strategy. Similarly, moderate or high sensitivity can justify taking hedging and contingency actions (as secondary actions).

There is moderate or high belief in deviation and low sensitivity for assumptions in settings IIIb and IVb. In setting IIIb, the knowledge supporting this judgment is strong. The classification verification, particularly for the sensitivity analysis, is recommended. Since assumption deviation may cause more than a small effect, shaping actions can be taken as a secondary strategy. On the other side, the strength of background knowledge used for assessing the belief in deviation and sensitivity is not strong in setting IVb. As the low sensitivity is questioned, following shaping actions (main strategy) about the happening of an assumption create more efficiency than hedging and contingency actions (as secondary strategies) related to the impact of assumptions.

Settings V and VI represent assumptions with a moderate or high degree of belief in deviation and sensitivity. As the knowledge supporting this classification in setting V is judged strong, shaping also hedging and contingency actions are required to be taken. Signposts also sound essential. But in setting VI, the knowledge for classification is assessed as moderate or weak. Recommended actions for this setting are as setting V, although signposts in setting VI as a secondary approach collect data about the occurrence of assumption deviation that strengthens the knowledge used for the belief in deviation categorization.

EQRA contribution to innovation epistemic uncertainty treatment

EQRA approach draws a guideline for innovation managers on proper treatments during the project lifecycle leading to thriving innovations. As ISO 31000 (The British Standards Institution, 2018, p. 13) describes, the first step in addressing the risk is to formulate and select risk treatment alternatives. Presented settings in SQRA assess risks and uncertainties in innovation projects, and in EQRA provides innovation managers with guidance about how to formulate treatment options for assessed risks and uncertainties by introducing ABP strategies (signpost, shaping, hedging, and contingency). Proposed secondary actions also present other treatment alternatives. Moreover, the EQRA approach directs innovation managers towards optimized treatment choice(s) and asks them to select the secondary strategies based on their cautionary thinking and resource management strategies. They can plan and maintain a balance between the costs and benefits of implementing the second actions regarding the project degree of novelty (and related uncertainty), their limited resources, and the firm's objectives. These features of the EQRA technique can support innovation managers in effective risk and project management.

Also, adding the knowledge dimensions and the SoK to the assessment can play a valuable role in innovative process success and address the issues detailed in section 05.1. Similar to what was explained in section 5.3.2 about the background knowledge, expressing the SoK by pedigree matrix used in EQRA not only addresses the problem mentioned in section 5.1, but also the pedigree matrix gives a vivid picture of knowledge dimensions used in the assessment to innovation managers. They can strengthen the knowledge over the project lifetime and reassess the strategy selection or improving actions considering new information reducing the uncertainty and increasing the process success.

Furthermore, EQRA represents influential factors in innovation accomplishment and defines some levels of control over these factors from the management perspective. Based on Berner & Flage (2017), the main objective of assumption-based planning is the process's success by creating a reliable and robust system. But traditional risk assessment and management provides support for planning this system through a failure avoidance approach. The innovations triumph, considering a high level of uncertainty is vital for its managers. Uncertain assumptions, in particular subjective assumptions, form influential factors in innovations' success. Defining different levels for controlling these factors guides innovation managers into building a reliable and robust system. It means that following up the influential factors and implementing the control levels: signpost, shaping, hedging, and contingency as the threshold, monitoring deviations, and taking actions in case of assumptions' deviations can warrant the innovation victory by developing a reliable and robust innovation system.

6. Discussion

In this chapter, the proposed model in section 5.3 is discussed. The first part explains some reflections on the approaches in the model. The last part recommends future research to improve and develop a framework for innovation epistemic uncertainty treatment.

6.1 Reflections on the suggested model

By applying the described model, epistemic uncertainty in implementing new ideas can be assessed, communicated, controlled, and treated. The model includes two semi-quantitative approaches SQRA and EQRA, but as the QSS framework of both methods is the same, the results of SQRA are used in EQRA defining following-up strategies to control uncertain assumptions risk. It means that QSS in EQRA uses the classified uncertain assumptions in SQRA and the QSS re-implementation is not necessary. Also, it is crucial to make a distinction between the SoK assessment for QSS and evaluating the knowledge dimension used for uncertain assumptions risk assessment. Innovation decision-makers are required to distinguish between the strength of knowledge assessment applied to QSS as well as risk and uncertainty calculation.

The suggested model can highlight two criteria resource management and cautionary thinking in innovation objectives achievement. Adopting the cautionary approach in both semi-quantitative techniques (SQRA and EQRA) is a justifiable reason for using them for innovation uncertainty reduction, particularly in radical innovation with a high degree of novelty and epistemic uncertainty. Based on Berner & Flage (2017) in QSS, a more cautious scheme is used to classify the belief in deviation and sensitivity analysis also SoK. In the latter, medium and low strength of knowledge are merged versus strong knowledge, while for the other high and medium classifications are merged versus low. If medium and high strength of knowledge is grouped, also low and medium categorizations in the belief in deviation and sensitivity are joined, the approaches will be less cautious. Also, as mentioned in section 5.3.4 in EQRA, the secondary strategies are according to cautionary thinking. Firms' managers can balance these strategies with available resources considering the organization's objectives providing the opportunity to implement them if applicable. The cost and burden of secondary actions implementation are evaluated in innovation managerial review and judgment discussing whether implement them or not. But being cautious in innovation processes can contribute to better management of innovation risk and uncertainty over the project lifecycle especially if the improved background knowledge opens new windows for reducing existing epistemic uncertainty.

Moreover, both SQRA and EQRA approaches manage resources required for epistemic uncertainty assessment and treatment by identifying critical assumptions and presenting assessment and treatment settings accordingly (Flage & Berner, 2017). It helps innovation managers put more justified effort into risk management of uncertain assumptions with a higher level of criticality; consequently, controlling the cost of the project execution.

However, the model faces some limitations in execution. SQRA and EQRA lack a quantitative format to calculate the threshold defining when to classify the belief in deviation and sensitivity analysis into high, moderate, or low independent of context. It can be addressed by adopting a pragmatic view and qualitative framework to carry out the classification without a specified quantitative threshold. Another problem is that uncertainty assessment and treatment approaches do not consider simultaneous assumption deviations of different subjects or phenomena and interdependences between them (Flage & Berner, 2017).

Unfortunately, due to time restrictions and lack of data, the model was not studied by a real case examining its expected positive features. It prevented the work from the practical knowledge of the model application in innovations.

6.2 The need for future research

Some research can improve the model and innovation uncertainty treatment in the risk assessment context. The model applicability for a real case needs to be conducted, obtaining feedback that would throw light on its practical benefit and obstacles. In addition, research about the model implementation for specific innovation industries or contexts would contribute to better defining uncertain assumptions associated with innovation scope. Also, these research results can be used to define some guidance on or standards of assessment and treatment of uncertain assumptions for each innovation industry or context.

The semi-quantitative approach applies probabilistic analysis and a qualitative method to capture all aspects of epistemic uncertainty. Developing a similar framework for other quantitative uncertainty representations (probability-bound analysis, interval analysis, possibility theory, and evidence theory) with operational meaning is needed. These uncertainty representations are two-valued uncertainty measures when available information is weak. Therefore, the results of such research might develop uncertainty treatment frameworks for innovation managers in projects suffering from scant or lack of data.

7. Conclusion

Uncertainty poses a threat to innovations' success. Reducing innovation uncertainty can significantly contribute these novelties to objectives accomplishment. This thesis analyzes how to treat innovation uncertainties. The idea is to reduce risk and uncertainty in innovations with a (high) degree of uncertainty. The thesis aims to distinguish innovation uncertainty and propose an approach to treat this uncertainty from a risk perspective. Innovations scarce or lack of knowledge in implementing a novel idea highlight the importance of epistemic uncertainty in their progress and victory. To assess and treat innovation epistemic uncertainty the hybrid model is proposed. The model consists of semi-quantitative risk assessment SQRA technique, knowledge dimension method, and extended semi-quantitative risk assessment EQRA approaches. The model can play a significant role in innovation risk and uncertainty treatment and reduction affecting these projects triumph.

In order to deal with the thesis topic, 'on the treatment of innovation uncertainty', it was divided into five research questions clarifying the work path. In the first question, the innovations descriptions are investigated, explaining what innovation means. A novelty can be implementing a new improvement in a product or process known as incremental innovation or a radical idea known as radical innovation.

In the second question, the general and risk concept of uncertainty, also ways of representing uncertainty in the risk assessment context, are explained. Known and unknown uncertainties respectively represent aleatory and epistemic uncertainty communicated by different techniques in risk engineering. Characterizing innovation uncertainty was addressed in the third and fourth questions. Innovations degree of novelty imposes uncertainty on these processes. Novel quality of innovations causes technological, market, and organizational uncertainties and implies that epistemic uncertainty can hinder innovations. In addition, the level of epistemic uncertainty rises when the innovation degree of novelty increases. Therefore, reducing and treating this type of uncertainty in innovations can substantially affect their target achievement.

To addressing the last question, the representations of epistemic uncertainty were analyzed, resulting in proposing a hybrid model to assess and treat innovation epistemic uncertainty. The adopted framework includes SQRA and EQRA based on the semi-quantitative approach, also the knowledge dimension method. The purpose of the model is to highlight, assess, and treat uncertain factors (assumptions) hidden in the background knowledge involved in innovation risk and uncertainty assessment. Due to a lack of knowledge in these projects, subjective assignments add new assumptions to simplify the risk assessment models. Subjective assumptions supplemented with other assumptions used for the innovation risk assessment constitute uncertain assumptions as one aspect of the background knowledge. The model establishes a practical framework for innovation management to determine the criticality of uncertain assumptions present in innovation risk analysis and assess their related risk. Also, the model guides innovation decision-makers on proper actions for dealing with uncertain assumptions according to their criticality. Applying the knowledge dimension technique serves the innovations to evaluate and communicate the strength of background knowledge involved in the innovation assumption risk calculation capturing all aspects of knowledge (data, models, expert judgment, and assumptions) uncertainty.

Overall, the thesis presents that innovation projects encounter a (high) degree of epistemic uncertainty. The recommended model can help innovation managers assess and treat uncertain assumption risks and follow up critical assumptions over the process lifecycle boosting the project success.

8. References

Afuah, A. (2003). *Innovation Management: Strategies, Implementation and Profits* (2nd ed). Oxford University Press.

Agboola, A. A., & Salawu, R. O. (2011). Managaing Deviant Behavior and Resistance to Change. *International Journal of Business and Management*, *6*(1), 235–242.

Almirall, E., & Casadesus-Masanell, R. (2010). Open Versus Closed Innovation: A Model of Discovery and Divergence. *Academy of Management Review*, *35*(1), 27–47. https://doi.org/10.5465/amr.35.1.zok27

Altshuler, A., & Zegans, M. D. (1997). Innovation and Public Management: Notes from the State Houseand City Hall. In *Innovation in American Government: Challenges, Opportunities, and Dilemmas*. Brooking Institution Press.

Apostolakis, G. (1990). The Concept of Probability in Safety Assessments of Technological Systems. *Science*, *250*(4986), 1359–1364. https://doi.org/10.1126/science.2255906

Arrighi, P. A., Le Masson, P., & Weil, B. (2015). Managing Radical Innovation as an Innovative Design Process: Generative Constraints and Cumulative Sets of Rules: Managing Radical Innovation as an Innovative Design Process. *Creativity and Innovation Management*, *24*(3), 373–390. https://doi.org/10.1111/caim.12135

Atuahene-Gima, K. (2005). Resolving the Capability–Rigidity Paradox in New Product Innovation. *Journal of Marketing*, *69*(4), 61–83. https://doi.org/10.1509/jmkg.2005.69.4.61

Aven, T. (2010). Some Reflections on Uncertainty Analysis and Management. *Reliability Engineering & System Safety*, *95*(3), 195–201. https://doi.org/10.1016/j.ress.2009.09.010

Aven, T. (2011). On the Interpretations of Alternative Uncertainty Representations in a Reliability and Risk Analysis Context. *Reliability Engineering & System Safety*, *96*(3), 353–360. https://doi.org/10.1016/j.ress.2010.11.004

Aven, T. (2013). Practical Implications of the New Risk Perspectives. *Reliability Engineering & System Safety*, *115*, 136–145. https://doi.org/10.1016/j.ress.2013.02.020

Aven, T., Baraldi, P., Flage, R., & Zio, E. (2014). *Uncertainty in Risk Assessment: The Representation and Treatment of Uncertainties by Probabilistic and Non-probabilistic Methods*. Wiley.

Badke-Schaub, P., Goldschmidt, G., & Meijer, M. (2010). How Does Cognitive Conflict in Design Teams Support the Development of Creative Ideas?: Cognitive Conflict in Design Teams. *Creativity and Innovation Management*, *19*(2), 119–133. https://doi.org/10.1111/j.1467-8691.2010.00553.x

Baraldi, P., & Zio, E. (2010). A Comparison Between Probabilistic and Dempster-Shafer Theory Approaches to Model Uncertainty Analysis in the Performance Assessment of Radioactive Waste Repositories: Model Uncertainty Analysis in the Performance Assessment of Radioactive Waste Repositories. *Risk Analysis*, *30*(7), 1139–1156. https://doi.org/10.1111/j.1539-6924.2010.01416.x

Barczak, G., & Wileman, D. (1991). Communications Patterns of New Product Development Team Leaders. *IEEE Transactions on Engineering Management*, *38*(2), 101–109. https://doi.org/10.1109/17.78406

Baudrit, C., Dubois, D., & Guyonnet, D. (2006). Joint Propagation and Exploitation of Probabilistic and Possibilistic Information in Risk Assessment. *IEEE Transactions on Fuzzy Systems*, *14*(5), 593–608. https://doi.org/10.1109/TFUZZ.2006.876720

Beard, A. N. (2004). Risk Assessment Assumptions. *Civil Engineering and Environmental Systems*, *21*(1), 19–31. https://doi.org/10.1080/10286600310001605489

Bedford, T., & Cooke, R. M. (2001). *Probabilistic Risk Analysis: Foundations and Methods*. Cambridge University Press.

Bernardo, J. M., & Smith, A. F. M. (1994). *Bayesian Theory*. Wiley.

Berner, C., & Flage, R. (2016). Strengthening Quantitative Risk Assessments by Systematic Treatment of Uncertain Assumptions. *Reliability Engineering & System Safety*, *151*, 46–59. https://doi.org/10.1016/j.ress.2015.10.009

Berner, C., & Flage, R. (2017). Creating Risk Management Strategies Based on Uncertain Assumptions and Aspects from Assumption-based Planning. *Reliability Engineering & System Safety*, *167*, 10–19. https://doi.org/10.1016/j.ress.2017.05.009

Bessant, J., Öberg, C., & Trifilova, A. (2014). Framing Problems in Radical Innovation. *Industrial Marketing Management*, *43*(8), 1284–1292. https://doi.org/10.1016/j.indmarman.2014.09.003

Blockley, D. (2013). Analysing Uncertainties: Towards Comparing Bayesian and Interval Probabilities'. *Mechanical Systems and Signal Processing*, *37*(1–2), 30–42. https://doi.org/10.1016/j.ymssp.2012.05.007

Brashers, D. E. (2001). Communication and Uncertainty Management. *Journal of Communication*, *51*(3), 477–497. https://doi.org/10.1111/j.1460-2466.2001.tb02892.x

Brunswicker, S., Bagherzadeh, M., Lamb, A., Narsalay, R., & Jing, Y. (2016). Managing Open Innovation Projects with Impact. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2821203

Bullen, E., Fahey, J., & Kenway, J. (2006). The Knowledge Economy and Innovation: Certain Uncertainty and the Risk Economy. *Discourse: Studies in the Cultural Politics of Education*, *27*(1), 53–68. https://doi.org/10.1080/01596300500510286

Burgelman, R. A., Christensen, C. M., & Wheelwright, S. C. (2009). *Strategic Management of Technology and Innovation* (5. ed., internat. ed). McGraw-Hill.

Burns, T., & Stalker, G. M. (1961). *The Management of Innovation*. Tavistock.

Cassiman, B., Di Guardo, M. C., & Valentini, G. (2010). Organizing Links with Science: Cooperate or Contract? *Research Policy*, *39*(7), 882–892. https://doi.org/10.1016/j.respol.2010.04.009

Chandler, A. D., & Hikino, T. (1990). *Scale and Scope: The Dynamics of Industrial Capitalism*. Belknap Press.

Chandra, Y., & Yang, S. S. (2011). Managing Disruptive Innovation: Entrepreneurial strategies and tournaments for corporate longevity. *Journal of General Management*, *37*(2), 23–50. https://doi.org/10.1177/030630701103700202

Cheng, Y. T., & Van de Ven, A. H. (1996). Learning the Innovation Journey: Order out of Chaos? *Organization Science*, *7*(6), 593–614. https://doi.org/10.1287/orsc.7.6.593

Chesbrough, H. W. (2003). *Open Innovation: The New Imperative for Creating and Profiting from Technology* (Nachdr.). Harvard Business School Press.

Chesbrough, H. W. (2006). *Open Business Models: How to Thrive in the New Innovation Landscape*. Harvard Business School Press.

Chesbrough, H. W., & Bogers, M. (2014). Explicating Open Innovation: Clarifying an Emerging Paradigm for Understanding Innovation. In *New Frontiers in Open Innovation* (pp. 3–28). Oxford University Press.

Christensen, C. M. (1997). *The Innovator's Dilemma*. Harvard Business School Press.

Christiansen, J. K., Hansen, A., Varnes, C. J., & Mikkola, J. H. (2005). Competence Strategies in Organizing Product Development. *Creativity and Innovation Management*, *14*(4), 384–392. https://doi.org/10.1111/j.1467-8691.2005.00358.x

Cisnetto, V., & Barlow, J. (2020). The Development of Complex and Controversial Innovations. Genetically Modified Mosquitoes for Malaria Eradication. *Research Policy*, *49*(3), 103917. https://doi.org/10.1016/j.respol.2019.103917

Cooke, R. (2004). The Anatomy of the Squizzel: The Role of Operational Definitions in Representing Uncertainty. *Reliability Engineering & System Safety*, *85*(1–3), 313–319. https://doi.org/10.1016/j.ress.2004.03.019

Cooke, R. M. (2014). Deep and Shallow Uncertainty in Messaging Climate Change. In S. RDJM, van G. PHAJM, M. S, & V. ACWM (Eds.), *Safety, Reliability, and Risk Analysis: Beyond the Horizon. Proceedings of the European Safety and Reliability Conference, Esrel 2013, Amsterdam, The Netherlands, 29 September-2 October 2013 (ESREL 2013)* (pp. 13–25). CRC Press/Balkema.

Coolen, F. P. A. (2004). On the Use of Imprecise Probabilities in Reliability. *Quality and Reiliablity Engineering International*, *20*, 193–202.

Courtney, H. (2003). Decision-driven Scenarios for Assessing four Levels of Uncertainty. *Strategy & Leadership*, *31*(1), 14–22. https://doi.org/10.1108/10878570310455015

Courtney, H., Kirkland, J., & Viguerie, P. (1997). Strategy Under Uncertainty. *Hrvard Business Review*, *75*(6), 66–79.

Covello, V. T., & Mumpower, J. (1985). Risk Analysis and Risk Management: An Historical Perspective. *Risk Analysis*, *5*(2), 103–120. https://doi.org/10.1111/j.1539-6924.1985.tb00159.x

Daft, R. L., & Lengel, R. H. (1986). Organizational Information Requirements, Media Richness and Structural Design. *Management Science*, *32*(5), 554–571. https://doi.org/10.1287/mnsc.32.5.554

Dahlander, L., & Gann, D. M. (2010). How Open Is Innovation? *Research Policy*, *39*(6), 699–709. https://doi.org/10.1016/j.respol.2010.01.013

Darroch, J., & McNaughton, R. (2002). Examining the Link Between Knowledge Management Practices and Types of Innovation. *Journal of Intellectual Capital*, *3*(3), 210–222. https://doi.org/10.1108/14691930210435570

Devooght, J. (1998). Model Uncertainty and Model Inaccuracy. *Reliability Engineering & System Safety*, *59*(2), 171–185. https://doi.org/10.1016/S0951-8320(97)00137-3

Dewar, JA. (2002). *Assumption-based Planning: A Tool for Reducing Avoidable Surprises*. Cambridge University Press.

Dewar, R. D., & Dutton, J. E. (1986). The Adoption of Radical and Incremental Innovations: An Empirical Analysis. *Management Science*, *32*(11), 1422–1433. https://doi.org/10.1287/mnsc.32.11.1422

Diamond, J. M. (2005). *Guns, Germs and Steel. A Short History of Everybody in the Last 13,000 Years*. Vintage.

Dosi, G. (1988). Sources, Procedures, and Microeconomic Effects of Innovation. *Journal of Economic Literature*, *26*, 1120–1171.

Drucker, P. F., & Noel, J. L. (1986). Innovation and Entrepreneurship: Practices and Principles. *The Journal of Continuing Higher Education*, *34*(1), 22–23. https://doi.org/10.1080/07377366.1986.10401060

Du, J., Leten, B., & Vanhaverbeke, W. (2014). Managing Open Innovation Projects with Science-based and Market-based Partners. *Research Policy*, *43*(5), 828–840. https://doi.org/10.1016/j.respol.2013.12.008

Duncan, R. B. (1972). Characteristics of Organizational Environments and Perceived Environmental Uncertainty. *Administrative Science Quarterly*, *17*(3), 313. https://doi.org/10.2307/2392145

Durmusoglu, S. S. (2004). Open Innovation: The New Imperative for Creating and Profiting from Technology. *European Journal of Innovation Management*, *7*(4), 325–326. https://doi.org/10.1108/14601060410565074

Edquist, C., Hommen, L., & McKelvey, M. D. (2001). *Innovation and Employment: Process versus Product Innovation*. Edward Elgar.

Ellsberg, D. (1961). Risk, Ambiguity, and the Savage Axioms. *The Quarterly Journal of Economics*, *75*(4), 643. https://doi.org/10.2307/1884324

Ettlie, J. E. (1997). Integrated Design and New Product Success. *Journal of Operations Management*, *15*(1), 33–55. https://doi.org/10.1016/S0272-6963(96)00095-2

Ettlie, J. E., Bridges, W. P., & O’Keefe, R. D. (1984). Organization Strategy and Structural Differences for Radical Versus Incremental Innovation. *Management Science*, *30*(6), 682–695. https://doi.org/10.1287/mnsc.30.6.682

Ettlie, J., & Rubenstein, A. H. (1987). Firm Size and Product Innovation. *Journal of Product Innovation Management*, *4*(2), 89–108. https://doi.org/10.1016/0737-6782(87)90055-5

Fagerberg, J. (2017). Innovation Policy: Rationales, Lessons and Challenges. In *Innovation, Economic Development and Policy (Selected Essays)* (Vol. 31, pp. 497–512). Journal of Economic Surveys. http://doi.wiley.com/10.1111/joes.12164

Fagerberg, J. (2018). *Innovation, Economic Development and Policy: Selected Essays*. Edward Elgar Publishing.

Felin, T., & Zenger, T. R. (2014). Closed or Open Innovation? Problem Solving and the Governance Choice. *Research Policy*, *43*(5), 914–925. https://doi.org/10.1016/j.respol.2013.09.006

Ferson, S., & Ginzburg, L. R. (1996). Different Methods Are Needed to Propagate Ignorance and Variability. *Reliability Engineering & System Safety*, *54*(2–3), 133–144. https://doi.org/10.1016/S0951-8320(96)00071-3

Flage, R. (2010). *Contributions to the Treatment of Uncertainty in Risk Assessment and Management* [PhD thesis NO 100, University of Stavanger]. NO 100.

Flage, R., & Aven, T. (2009). Expressing and Communicating Uncertainty in Relation to Quantitative Risk Analysis. *Reliab Risk Anal*, *2*(13), 9–18.

Flage, R., Aven, T., Zio, E., & Baraldi, P. (2014). Concerns, Challenges, and Directions of Development for the Issue of Representing Uncertainty in Risk Assessment: Perspective. *Risk Analysis*, *34*(7), 1196–1207. https://doi.org/10.1111/risa.12247

Flage, R., & Berner, C. (2017). Treatment and Communication of Uncertain Assumptions in (Semi-)quantitative Risk Assessments. In T. Aven & E. Zio (Eds.), *Knowledge in Risk Assessment and Management* (pp. 49–79). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119317906.ch3

Foster, J. (2010). Productivity, Creative Destruction and Innovation Policy: Some Implications from the Australian Experience. *Innovation*, *12*(3), 355–368. https://doi.org/10.5172/impp.12.3.355

Freeman, C. (1974). *The Economics of Industrial Innovation* (The first). Penguin Books.

Freeman, C., & Soete, L. (1997). *The Economics of Industrial Innovation* (3rd ed). MIT Press.

Funtowicz, S. O., & Ravetz, J. R. (1990). *Uncertainty and Quality in Science for Policy*. Kluwer Academic Publishers.

Galbraith, J. R. (1973). *Designing Complex Organizations*. Addison-Wesley Pub. Co.

Galbraith, J. R. (1977). *Organization Design*. Addison-Wesley Pub. Co.

Gales, L., & Mansour-Cole, D. (1995). User Involvement in Innovation Projects: Toward an Information Processing Model. *Journal of Engineering and Technology Management*, *12*(1–2), 77–109. https://doi.org/10.1016/0923-4748(95)00005-7

Garcia, R., & 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. https://doi.org/10.1111/1540-5885.1920110

Gaubinger, K., Rabl, M., Swan, S., & Werani, T. (2015). *Innovation and Product Management: A Holistic and Practical Approach to Uncertainty Reduction* (1st ed. 2015). Springer Berlin Heidelberg : Imprint: Springer. https://doi.org/10.1007/978-3-642-54376-0

Geels, F. W. (2004). From Sectoral Systems of Innovation to Socio-technical Systems. *Research Policy*, *33*(6–7), 897–920. https://doi.org/10.1016/j.respol.2004.01.015

Gerwin, D., & Tarondeau, J. C. (1982). Case Studies of Computer Integrated Manufacturing Systems: A View of Uncertainty and Innovation Processes. *Journal of Operations Management*, *2*(2), 87–99. https://doi.org/10.1016/0272-6963(82)90025-0

Goedhuys, M., & Veugelers, R. (2012). Innovation Strategies, Process and Product Innovations and Growth: Firm-Level Evidence from Brazil. *Structural Change and Economic Dynamics*, *23*(4), 516–529. https://doi.org/10.1016/j.strueco.2011.01.004

Goldhar, J. D., Bragaw, L. K., & Schwartz, J. J. (1976). Information Flows, Management Styles, and Technological Innovation. *IEEE Transactions on Engineering Management*, *EM-23*(1), 51–62. https://doi.org/10.1109/TEM.1976.6447150

Green, S. G., Gavin, M. B., & Aiman-Smith, L. (1995). Assessing a Multidimensional Measure of Radical Technological Innovation. *IEEE Transactions on Engineering Management*, *42*(3), 203–214. https://doi.org/10.1109/17.403738

Grin, J., & van Staveren, A. (2007). *Werken aan Systeeminnovaties. Lessen uit de Praktijk van Innovatie Netwerk [Working on system innovations. Lessons from practice of the Innovation Network]*. Van Gorccum.

Groen, A. D., & Linton, J. D. (2010). Is Open Innovation a Field of Study or a Communication Barrier to Theory Development? *Technovation*, *30*(11–12), 554. https://doi.org/10.1016/j.technovation.2010.09.002

Hallén, L., Johanson, J., & Seyed-Mohamed, N. (1991). Interfirm Adaptation in Business Relationships. *Journal of Marketing*, *55*(2), 29–37. https://doi.org/10.1177/002224299105500204

Hanft, R. S., & Korper, S. P. (1981). Some Notes on Uncertainty; Federal Policy and Innovation. *Computers in Biology and Medicine*, *11*(1), 1–7. https://doi.org/10.1016/0010-4825(81)90010-X

Hannan, M. T., & Freeman, J. (1984). Structural Inertia and Organizational Change. *American Sociological Review*, *49*(2), 149–164. https://doi.org/10.2307/2095567

Harris, E., & Woolley, R. (2009). Facilitating Innovation Through Cognitive Mapping of Uncertainty. *International Studies of Management & Organization*, *39*(1), 70–100. https://doi.org/10.2753/IMO0020-8825390104

Hauschildt, J. (2004). *Innovationsmanagement*. Vahlen.

Helto, J. C., & Burmaster, D. E. (1996). Guest Editorial: Treatment of Aleatory and Epistemic Uncertainty in Performance Assessment for Complex System. *Reliability Engineering & System Safety*, *54*, 91–94.

Helton, J. C. (2011). Quantification of Margins and Uncertainties: Conceptual and Computational Basis. *Reliability Engineering & System Safety*, *96*(9), 976–1013. https://doi.org/10.1016/j.ress.2011.03.017

Helton, J. C., Johnson, J. D., Sallaberry, C. J., & Storlie, C. B. (2006). Survey of Sampling-based Methods for Uncertainty and Sensitivity Analysis. *Reliability Engineering & System Safety*, *91*(10–11), 1175–1209. https://doi.org/10.1016/j.ress.2005.11.017

Henderson, R. M., & Clark, K. B. (1990). Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms. *Administrative Science Quarterly*, *35*(1), 9. https://doi.org/10.2307/2393549

Henkel, J. (2006). Selective Revealing in Open Innovation Processes: The Case of Embedded Linux. *Research Policy*, *35*(7), 953–969. https://doi.org/10.1016/j.respol.2006.04.010

Hofstede, G. H. (1984). *Culture's Consequences: International Differences in Work-related Values* (Abridged ed). Sage Publications.

Hofstede, G. H. (2001). *Culture's Consequences: Comparing Values, Behaviors, Institutions, and Organizations Across Nations* (2nd ed). Sage Publications.

Hurst, P. (1982). Ideas into Action Development and the Acceptance of Innovations. *International Journal of Educational Development*, *1*(3), 79–102. https://doi.org/10.1016/0738-0593(82)90046-3

Jalonen, H. (2011). The Uncertainty of Innovation: A Systematic Review of the Literature. *Journal of Management Research*, *4*(1). https://doi.org/10.5296/jmr.v4i1.1039

Johnson, D. (2001). What Is Innovation and Entrepreneurship? Lessons for Larger Organizations. *Industrial and Commercial Training*, *33*(4), 135–140. https://doi.org/10.1108/00197850110395245

Kaasa, A., & Vadi, M. (2010). How Does Culture Contribute to Innovation? Evidence from European Countries. *Economics of Innovation and New Technology*, *19*(7), 583–604. https://doi.org/10.1080/10438590902987222

Kalliny, M., & Hausman, A. (2007). The Impact of Cultural and Religious Values on Consumer's Adoption of Innovation. *Academy of Marketing Studies Journal*, *11*(1), 125–137.

Keeley, L., Pikkel, R., Quinn, B., & Walters, H. (Eds.). (2013). *Ten Types of Innovation: The Discipline of Building Breakthroughs*. Wiley.

Kiureghian, A. D., & Ditlevsen, O. (2009). Aleatory or Epistemic? Does it Matter? *Structural Safety*, *31*(2), 105–112. https://doi.org/10.1016/j.strusafe.2008.06.020

Knight, F. H. (1921). *Risk, Uncertainty, and Profit (Reprinted ed.)*. Beard Books Incorporation.

Kohli, A. K., & Jaworski, B. J. (1990). Market Orientation: The Construct, Research Propositions, and Managerial Implications. *Journal of Marketing*, *54*(2), 1–18. https://doi.org/10.1177/002224299005400201

Kooter, J. P., & Schlesinger, L. A. (1979). Choosing Startegies for Change. *Harvard Business Review*, *57*(2), 106–114.

Laursen, K., & Salter, A. (2006). Open for Innovation: The Role of Openness in Explaining Innovation Performance among U.K. Manufacturing Firms. *Strategic Management Journal*, *27*(2), 131–150. https://doi.org/10.1002/smj.507

Lee, K. H. (2005). *First Course on Fuzzy Theory and Applications*. Springer-Verlag.

Leifer, R., McDermott, C. M., O'Connor, G. C., Peters, L. S., & Veryzer, R. W. (2006). *Radical innovation: How Mature Companies Can Outsmart Upstarts* (Nachdr.). Harvard Business School Press.

Leifer, R., O'Connor, G. C., & Rice, M. (2001). Implementing Radical Innovation in Mature Firms: The Role of Hubs. *Academy of Management Perspectives*, *15*(3), 102–113. https://doi.org/10.5465/ame.2001.5229646

Lindley, D. V. (2000). The Philosophy of Statistics. *Journal of the Royal Statistical Society: Series D (The Statistician)*, *49*(3), 293–337. https://doi.org/10.1111/1467-9884.00238

Lundvall, B.-Å. (2010). *National Systems of Innovation: Toward a Theory of Innovation and Interactive Learning* (This ed. 1. publ). Anthem Press.

Lynn, G. S., & Akgün, A. E. (1998). Innovation Strategies Under Uncertainty: A Contingency Approach for New Product Development. *Engineering Management Journal*, *10*(3), 11–18. https://doi.org/10.1080/10429247.1998.11414991

March, J. G. (1991). Exploration and Exploitation in Organizational Learning. *Organization Science*, *2*(1), 71–87. https://doi.org/10.1287/orsc.2.1.71

Milliken, F. J. (1987). Three Types of Perceived Uncertainty about the Environment: State, Effect, and Response Uncertainty. *The Academy of Management Review*, *12*(1), 133. https://doi.org/10.2307/257999

Morgan, M. G., Henrion, M., & Small, M. J. (1990). *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge University Press.

Motet, G., & Bieder, C. (Eds.). (2017). *The Illusion of Risk Control: What Does it Take to Live With Uncertainty?* (1st ed. 2017). Springer International Publishing : Imprint: Springer. https://doi.org/10.1007/978-3-319-32939-0

Mowery, D. C. (2008). Plus Ca Change: Industrial R&D in the "Third Industrial Revolution." *Industrial and Corporate Change*, *18*(1), 1–50. https://doi.org/10.1093/icc/dtn049

Nickerson, J. A., & Zenger, T. R. (2004). A Knowledge-Based Theory of the Firm—The Problem-Solving Perspective. *Organization Science*, *15*(6), 617–632. https://doi.org/10.1287/orsc.1040.0093

North, W. (2010). Probability Theory and Consistent Reasoning. *Risk Analysis*, *30*(3), 377–380. https://doi.org/10.1111/j.1539-6924.2010.01362.x

Oakey, R. P. (2013). Open Innovation and its Relevance to Industrial Research and Development: The Case of High-technology Small Firms. *International Small Business Journal: Researching Entrepreneurship*, *31*(3), 319–336. https://doi.org/10.1177/0266242612458942

O'Connor, G., C. (1998). Market Learning and Radical Innovation: A Cross Case Comparison of Eight Radical Innovation Projects. *Journal of Product Innovation Management*, *15*(2), 151–166. https://doi.org/10.1111/1540-5885.1520151

O'Connor, G. C., & Veryzer, R. W. (2001). Th Nature of Market Visioning for Technology-Based Radical Innovation. *Journal of Product Innovation Management*, *18*(4), 231–246. https://doi.org/10.1111/1540-5885.1840231

OECD (Ed.). (2010). *Measuring Innovation: A New Perspective*. OECD.

Ortt, J. R., & Smits, R. (2006). Innovation Management: Different Approaches to Cope with the Same Trends. *International Journal of Technology Management*, *34*(3/4), 296. https://doi.org/10.1504/IJTM.2006.009461

Pavitt, K. (1984). Sectoral Patterns of Technical Change: Towards a Taxonomy and a Theory. *Research Policy*, *13*(6), 343–373. https://doi.org/10.1016/0048-7333(84)90018-0

Pleschak, F., & Sabisch, H. (1996). *Innovationsmanagement* (Vol. 4). Schäffer-Poeschel.

Polder, M., Leeuwen, G. van, Mohnen, P., & Raymond, W. (2010). *Product, Process and Organizational Innovation: Drivers, Complementarity and Productivity Effects*. UNU-MERIT, Working Papers Series. The Netherlands.

Prigogine, I., & Stengers, I. (1990). *Orde Uit Chaos: Een Nieuwe Dialoog Tussen de Mens en de Natuur [From chaos to order: A new dialogue between mankind and nature]*. Uitgeverij Bert Bakker.

Reddy, S. G. (1996). Claims to Expert Knowledge and the Subversion of Democracy: The Triumph of Risk over Uncertainty. *Economy and Society*, *25*(2), 222–254. https://doi.org/10.1080/03085149600000011

Rehn, A., & Lindahl, M. (2012). Muddling Through in Innovation—On Incremental Failure in Developing an Engine. *Journal of Business Research*, *65*(6), 807–813. https://doi.org/10.1016/j.jbusres.2010.12.020

Remneland-Wikhamn, B. (2013). Two Different Perspectives on Open Innovation—Libre versus Control. *Creativity and Innovation Management*, *22*(4), 375–389. https://doi.org/10.1111/caim.12035

Rice, M. P., O'Connor, G. C., Peters, L. S., & Morone, J. G. (1998). Managing Discontinuous Innovation. *Research-Technology Management*, *41*(3), 52–58. https://doi.org/10.1080/08956308.1998.11671210

Rip, A., & Kemp, R. (1998). Technological Change. In S. Rayner & E. L. Malcolm (Eds.), *Human Choice and Climate Change. An International Assessment* (Vol. 2, pp. 327–399). Batell Press.

Rogers, E. M. (1995). *Diffusion of Innovations* (4th ed). Free Press.

Rogers, E. M. (2003). *Diffusion of Innovations* (5th ed). Free Press.

Rosenbusch, N., Brinckmann, J., & Bausch, A. (2011). Is Innovation Always Beneficial? A Meta-Analysis of the Relationship Between Innovation and Performance in SMEs. *Journal of Business Venturing*, *26*(4), 441–457. https://doi.org/10.1016/j.jbusvent.2009.12.002

Ross, T. J., Booker, J. M., & Parkinson, W. J. (Eds.). (2002). *Fuzzy Logic and Probability Applications: Bridging the Gap*. Society for Industrial and Applied Mathematics ; American Statistical Assoxciation.

Rothwell, R., & Robertson, A. B. (1973). The Role of Communications in Technological Innovation. *Research Policy*, *2*(3), 204–225. https://doi.org/10.1016/0048-7333(73)90003-6

Rotmans, J., Loorbach, D., & van de Brugge, R. (2005). Transitiemanagement en Duurzame Ontwikkeling; Coevolutionaire Sturing in Het Licht Van Complexiteit [Transition Management and Sustainable Development; Co-evolutionary Steering in the Light of Complexity]. *Beleidswetenschap*, *19*, 3–23.

Salomo, S., Gemünden, H. G., & Billing, F. (2007). Dynamisches Schnittstellenmanagement Radikaler Innovationsvorhaben. In C. Herstatt & B. Verworn (Eds.), *Management der* *frühen Innovationsphasen* (pp. 215–248). Gabler. https://doi.org/10.1007/978-3-8349-9293-2_11

Sartorius, C. (2006). Second-Order Sustainability—Conditions for the Development of Sustainable Innovations in a Dynamic Environment. *Ecological Economics*, *58*(2), 268–286. https://doi.org/10.1016/j.ecolecon.2005.07.010

Schmookler, J. (1966). *Invention and Economic Growth* (2. print). Harvard University Press.

Schumpeter, J. A. (1911). *The Theory of Economic Development*. Oxford University.

Schumpeter, J. A. (1934). *The Theory of Economic Development*. Harvard University Press.

Schumpeter, J. A. (1942). *Capitalism, Socialism and Democracy*. Georg Allen & Unwin.

Shafer, G. (1976). *A Mathematical Theory of Evidence*. Princeton Univ. Press.

Shafer, G. (1990). Perspectives on the Theory and Practice of Belief Functions. *International Journal of Approximate Reasoning*, *4*(5–6), 323–362. https://doi.org/10.1016/0888-613X(90)90012-Q

Smets, P. (1994). What Is Dempster-Shafer's Model? In *Advances in the Dempster-Shafer Theory of Evidence* (pp. 5–34). John Wiley & Sons Inc.

Smits, R. (2002). Innovation Studies in the 21st Century: Questions from a User's Perspective. *Technological Forecasting and Social Change*, *69*(9), 861–883. https://doi.org/10.1016/S0040-1625(01)00181-0

Sommer, S. C., & Loch, C. H. (2004). Selectionism and Learning in Projects with Complexity and Unforeseeable Uncertainty. *Management Science*, *50*(10), 1334–1347. https://doi.org/10.1287/mnsc.1040.0274

Souder, W. E., & Moenaert, R. K. (1992). Integrating Marketing and R&D Projet Personnel Within Innovation Projects: An Information Uncertainty Model. *Journal of Management Studies*, *29*(4), 485–512. https://doi.org/10.1111/j.1467-6486.1992.tb00675.x

Spash, C. L. (2002). *Greenhouse Economics: Value and Ethics*. Routledge. http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=95225

SRA. (2015). *SRA Glassory*. https://www.sra.org/wp-content/uploads/2020/04/SRA-Glossary-FINAL.pdf.

Tatikonda, M. V., & Montoya-Weiss, M. M. (2001). Integrating Operations and Marketing Perspectives of Product Innovation: The Influence of Organizational Process Factors and Capabilities on Development Performance. *Management Science*, *47*(1), 151–172. https://doi.org/10.1287/mnsc.47.1.151.10669

Tavassoli, S., & Karlsson, C. (2016). Innovation Strategies and Firm Performance: Simple or Complex Strategies? *Economics of Innovation and New Technology*, *25*(7), 631–650. https://doi.org/10.1080/10438599.2015.1108109

Teubal, M. (2002). What Is the Systems Perspective to Innovation and Technology Policy (ITP) and How Can We Apply it to Developing and Newly Industrialized Economies? *Journal of Evolutionary Economics*, *12*(1–2), 233–257. https://doi.org/10.1007/s00191-002-0113-0

The British Standards Institution. (2018). *BS ISO 31000* [Risk Management-Guidelines]. BSI Standards Limited 2018.

Thompson, J. D. (1967). *Organizations in Action: Social Science Bases of Administrative Theory*. McGraw-Hill.

Tidd, J., & Bessant, J. R. (2009). *Managing Innovation*. Wiley.

Trott, P., & Hartmann, D. (2009). Why “Open Innovation” Is Old Wine In New Bottles. *International Journal of Innovation Management*, *13*(04), 715–736. https://doi.org/10.1142/S1363919609002509

Tushman, M. L., & Anderson, Ph. (1986). Technological Discontinuities and Organizational Environments. *Administrative Science Quarterly*, *31*(3), 439. https://doi.org/10.2307/2392832

Tushman, M. L., & O’Reilly, C. A. (1996). Ambidextrous Organizations: Managing Evolutionary and Revolutionary Change. *California Management Review*, *38*(4), 8–29. https://doi.org/10.2307/41165852

Utterbak, J. M., & Linsu, K. (1985). The Invasion of a Stable Business by Radical Innovation. In *The Management of Productivity and Technology in Manufacturing* (pp. 113–151). Plenum Press.

Vahs, D., & Brem, A. (2013a). *Innovationsmanagement: Von der Idee zur erfolgreichen Vermarktung* (Vol. 64). Schäffer-Poeschel.

Vahs, D., & Brem, A. (2013b). *Innovationsmanagement: Von der Idee zur erfolgreichen Vermarktung* (Vol. 65). Schäffer-Poeschel.

Van de Ven, A. H. (Ed.). (1999). *The Innovation Journey*. Oxford University Press.

Van de Ven, A. H. (2017). The Innovation Journey: You Can’t Control it, but You Can Learn to Maneuver it. *Innovation*, *19*(1), 39–42. https://doi.org/10.1080/14479338.2016.1256780

van der Panne, G., van Beers, C., & Kleinknecht, A. (2003). Success and Failure of Innovation: A Literature Review. *International Journal of Innovation Management*, *07*(03), 309–338. https://doi.org/10.1142/S1363919603000830 van Riel, A. C. R., Lemmink, J., & Ouwersloot, H. (2004). High-Technology Service Innovation Success: A Decision-Making Perspective. *Journal of Product Innovation Management*, *21*(5), 348–359. https://doi.org/10.1111/j.0737-6782.2004.00087.x

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

von Hippel, E. (1986). Lead Users: A Source of Novel Product Concepts. *Management Science*, *32*(7), 791–805. https://doi.org/10.1287/mnsc.32.7.791

Vrande, V. van de, Vanhaverbeke, W., & Gassmann, O. (2010). Broadening the Scope of Open Innovation: Past Research, Current State and Future Directions. *International Journal of Technology Management*, *52*(3/4), 221. https://doi.org/10.1504/IJTM.2010.035974

Walley, P. (1996). Inferences from Multinomial Data: Learning About a Bag of Marbles. *Journal of the Royal Statistical Society: Series B (Methodological)*, *58*(1), 3–34. https://doi.org/10.1111/j.2517-6161.1996.tb02065.x

West, J., & Gallagher, S. (2006). Challenges of Open Innovation: The Paradox of Firm Investment in Open-source Software. *R and D Management*, *36*(3), 319–331. https://doi.org/10.1111/j.1467-9310.2006.00436.x

Wong-MingJi, D. J., & Milletter, W. R. (2002). Dealing with the Dynamic Duo of Innovation and Inertia: The “in-” Theory of Organization Change. *Organization Development Journal*, *20*(1), 36–55.

Workman, J. P. (1993). Marketing’s Limited Role in New Product Development in One Computer Systems Firm. *Journal of Marketing Research*, *30*(4), 405–421. https://doi.org/10.1177/002224379303000402

York, J. G., & Venkataraman, S. (2010). The Entrepreneur–Environment Nexus: Uncertainty, Innovation, and Allocation. *Journal of Business Venturing*, *25*(5), 449–463. https://doi.org/10.1016/j.jbusvent.2009.07.007

Zadeh, L. A. (1965). Fuzzy sets. *Information and Control*, *8*(3), 338–353. https://doi.org/10.1016/S0019-9958(65)90241-X

Zio, E., & Apostolakis, G. E. (1996). Two Methods for the Structured Assessment of Model Uncertainty by Experts in Performance Assessments of Radioactive Waste Repositories. *Reliability Engineering & System Safety*, *54*(2–3), 225–241. https://doi.org/10.1016/S0951-8320(96)00078-6