Centre for Technology Management working paper series
ISSN 2058-8887

No. 6

January 2019

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https://doi:10.17863/CAM.35692

Leonidas Aristodemou (CTM-IIPM, University of Cambridge) *
Frank Tietze (CTM, University of Cambridge)
Elizabeth O'Leary (University of Cambridge)
Matt Shaw (University of Cambridge)

* Please contact the corresponding author for feedback:
la324@cam.ac.uk

A Literature Review on Technology Development Process (TDP) Models

Leonidas Aristodemou (la324@cam.ac.uk)
Dr. Frank Tietze (frank.tietze@eng.cam.ac.uk)
Elizabeth O'Leary (eo288@cam.ac.uk)
Matt Shaw (ms2247@cam.ac.uk)

Research Background

Innovation is a hybrid concept that has evolved over time and adapts itself to changing conditions (Fagerberg et al., 2006). It plays a major role in the growth and economic competitiveness of companies, industries and countries (Gardiner, 2010). The definition of innovation varies depending on the context but one can define it as the introduction of new things, ideas or ways of doing something (Venuvinod, 2010). Over time the understanding of innovation has evolved and was recognized by Austrian economist Joseph Schumpeter, who considered innovations as the introduction of a good product, methods of production which are new to a particular branch of industry, the opening of new markets, the use of new sources of supply, or the new form of competition (Schumpeter, 1934, 1939). Innovation can also be defined as improvements in technology and better methods or ways of doing things, or the application of new ideas to firms, regardless of whether the new ideas are embodied in products, processes or services (Grant, 2012). Fagerberg et al. (2006) argues that the function of innovation is to introduce novelty into the economic sphere and is crucial for long-term economic growth.

Innovation management is a discipline, which involves building knowledge and searching for unique opportunities, that fit the organization's strategic direction. Knowledge is considered as an economic driver and a knowledge-based economy is defined as an economy directly based on the production, distribution and use of knowledge (European Commission, 2004). In addition, this knowledge-driven economy is at the heart of the technological era, which affects the innovation process as it strengthens the growth of all economies and sustainability paths (OECD, 2016). The increasing importance of knowledge as an economic driver has major implications for innovation management, which is a key determinant of competitiveness in the global knowledge-driven economy.

Consequently, companies invest in innovation to build knowledge and thus increase competitive advantage. Front-end innovation (FEI) projects, and in particular technology development projects, are therefore a fundamental component of innovation and a crucial factor in developing new competitive advantages. *Technology Development Process*, is a directed process at developing new knowledge, skills and artefacts that in turn facilitates platform development (Halman et al., 2003), which leads in product/ process development (Cooper, 2007; Högman and Johannesson, 2013). The technological outcomes from such process are by definition new, different and unpredictable (Ajamian and Koen, 2002; Eldred and Mcgrath, 1997). It is often located at the front-end of innovation, within the innovation management processes (Fig.1). Opportunity-driven and idea-driven processes are the origin of all innovations, and contribute greatly to the potential (Ford et al., 2016; Goffin and Mitchell, 2016); however, not all innovations can be realised and structured technology development processes are usually required to identify the best of them and next course of action (Cooper, 1999; Cooper et al., 2001, 2002; Cooper and Mills, 2005).

In this paper, we contribute to the growing literature on technology development processes by producing a narrative and descriptive literature review on technology development process (TDP) models.

Methodology

The paper aims to summarise the existing work on TDP models. To carry out the literature review, the narrative literature review approach has been adopted (Cronin et al., 2008), and a research search strategy has been developed (Creswell, 2013; Robson, 2011). The articles on TDP models were identified from the Scopus database to find the most relevant published articles or in press articles. Also, published articles and working articles were identified using a snowball effect, with relevant literature We search within the tittle, abstract and key words for various terms such as "front end innovation", "front end idea screen", "Fuzzy front innovation", "Innovation management", "Idea screening", and "fuzzy front end". The search is then narrowed to documents that also contain either in the tittle or the abstract or in the key words, the terms "technology development", "technology development process", and "technology stage gate". In order to focus on recent literature, the search is limited publications after the year 1990, and which refer to frameworks or processes. The reference lists of the published research on the FEI are scanned, and then put into categories (Table 1), to establish the baseline leading to technology development process models. The purpose of presenting the research on TDP models is to provide the readers with the latest research on the features of each TDP model.

Table 1 Literature terms relative to Front End of Innovation, adapted from Teza et al. (2015)

Term	Literature
Fuzzy front end	Cao et al. (2011); Christiansen and Gasparin (2016); Cooper (2006b); Danguleva (2014); De Brentani and Reid (2012); Dornberger and Suvelza (2012); Eling et al. (2014); Galbraith et al. (2006); Högman (2011a); Husig and Kohn (2003,?); Khurana and Rosenthal (1998); Koen et al. (2001); Kurkkio (2011); Martinsuo and Poskela (2011); Mendes and Toledo (2011); Montoya-Weiss and Calantone (1994); Riel et al. (2013); Schulz et al. (2000); Sommer et al. (2015); Takey and Carvalho (2016); Teza et al. (2015); Wowak et al. (2016)
Front End of Innovation	Chen and Katilla (2008); Cooper (2006b, 2014); Cooper and Edgett (2010); De Brentani and Reid (2012); de Oliveira et al. (2015); Dornberger and Suvelza (2012); Galbraith et al. (2006); Högman (2011b); Högman and Johannesson (2010); Hultgren and Tantawi (2014); Ilevbare (2013); Koen (2004); Koen et al. (2001, 2014b); Markham (2013); Riel et al. (2013); Takey and Carvalho (2016); Teza et al. (2015)
Front End process	Cooper et al. (2002); Cooper and Mills (2005); Dang et al. (2012); Danguleva (2014); Martinsuo and Poskela (2011); Nobelius (2002); Teza et al. (2016, 2015)
Front End of New Product Development /Pre-development	Ajamian and Koen (2002); Chen and Katilla (2008); Cooper (2009, 1990, 1999, 2006b, 2007, 2008b, 2014); Cooper and Edgett (2008a,b, 2012, 2014a); Cooper and Kleinschmidt (1986); Danguleva (2014); Dewulf (2013); Florén and Frishammar (2012); Hultgren and Tantawi (2014); Ismail et al. (2012); Jugend et al. (2015); Khurana and Rosenthal (1998); Kobe (2001); Koen (2004); Koen et al. (2014b); Kurkkio (2011); Kurkkio et al. (2011); Martinsuo and Poskela (2011); Mendes and Toledo (2011); Schulz et al. (2000); Sommer et al. (2015); Takey and Carvalho (2016); Teza et al. (2015); Warren (2004)
Early Phases of Innovation	Dewulf (2013); Koppinen et al. (2010); Neumann (2006); Nobelius (2002); Teza et al. (2015)

Technology Development Process Models

Innovation management, and in particular, the FEI sometimes defined as technology development (Cooper, 2007), or referred to as the fuzzy-front end (Koen et al., 2014b), have received substantial research attention over the last decade. Fig.1 shows the location of the TDP, within the innovation management funnel (Chesborough, 2007; Chesbrough, 2003, 2012), which is similar to the proposition put forward by Ajamian and Koen (2002); Cooper (2007); Koen et al. (2014b). In addition, these can be further enhanced by the industrial emergence framework by Phaal et al. (2011), where we argue that the TDP can be found between the science-technology transition and the technology-application transition, where the project has moved past research and is within the technology dominated (embryonic) phase (Fig.2).

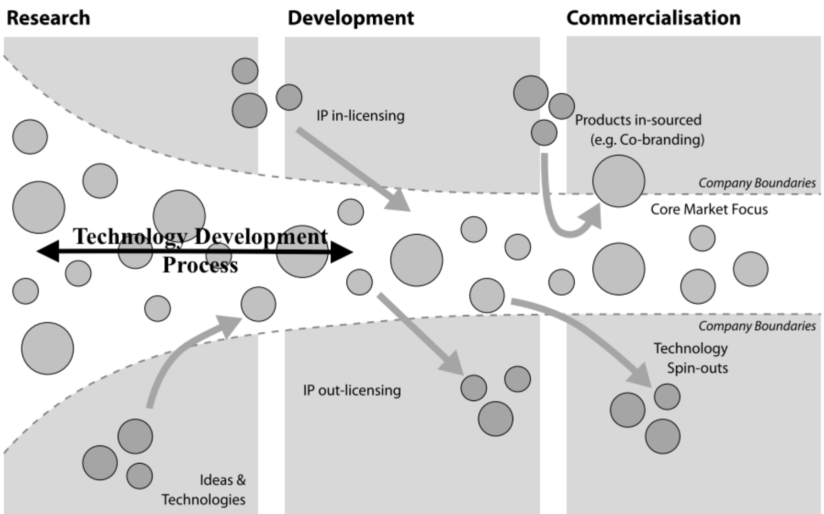


Fig. 1 Innovation management funnel and TDP, source: Mortara et al. (2009b,c)

The FEI covers the period from the idea generation to its approval for development (Dewulf, 2013), and commences when an opportunity is first considered worthy of further ideation, exploration and assessment (Khurana and Rosenthal, 1998). We define the front end phase as all the innovation activities up to and including the application stage gate decision point (Fig.12) (Cooper, 2007; Dewulf, 2013).

Technology in relation to innovation is considered as an enabler, consisting of theoretical and practical knowledge that can be used to develop products and services (Burgelman et al., 2009; Nieto, 2003, 2004; Nieto and Quevedo, 2005). Burgelman et al. (2009) argues that technologies are usually the outcome of development activities to put inventions and discoveries to practical use, and in industry there is rarely the separation between technology development processes and product development processes. Technology development aims to develop and mature new

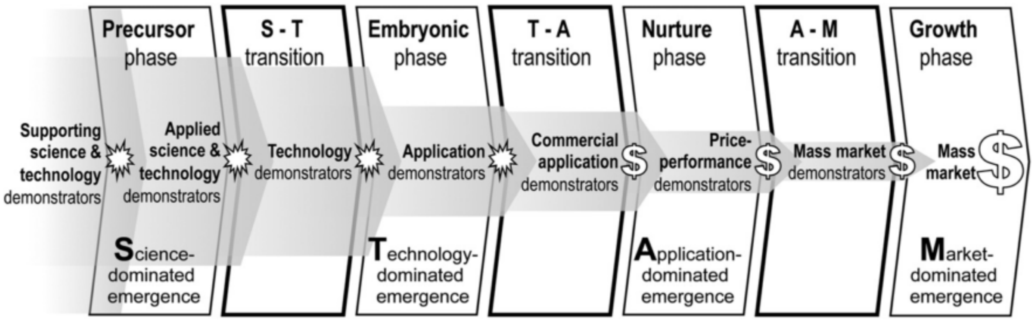


Fig. 2 Industrial Emergence Transitions, source: Phaal et al. (2011)

technologies in directed efforts prior to their introduction in the development of a particular application, product, process, license activity (Cooper, 2006b, 2007).

Technology development is defined as a directed effort at developing new knowledge, skills and artefacts that in turn will facilitate platform development (Halman et al., 2003), which leads in product/ process development (Högman and Johannesson, 2013; Kim and Kogut, 1996; McGrath, 1995; Prahalad and Hamel, 1990). It can be embodied in people, materials, cognitive and physical processes, plant, equipment and tools (Burgelman et al., 2009). It is by definition new, different and unpredictable (Ajamian and Koen, 2002; Eldred and Mcgrath, 1997), and it is often located at the FEI (Koen, 2004). Technology development is different compared to product development in a number of dimensions (Nobelius, 2002), and the literature argues that these should be studied differently (Cooper, 2006b; Martinsuo and Poskela, 2011).

Traditional product development processes are usually focused on the development of incremental ideas. These ideas or projects are relatively low risk, and thus risk management decisions are mainly based on market analysis and financial returns. However, these selection criteria are insufficient to be used for high risk and high uncertainty projects (Martinsuo and Poskela, 2011), like technology projects (Cooper, 2006b).

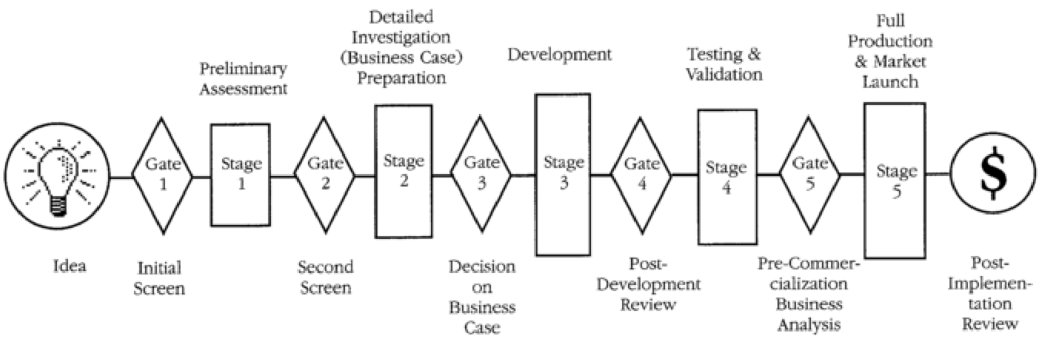


Fig. 3 New product development process, source: Cooper (1990)

There is a substantial amount of literature on the nature of the New Product Development (NPD) process. Cooper and Kleinschmidt (1986) look into the activities of the process when a product moves from idea to launch, and explore the effectiveness and impact of these on project outcomes (Cooper and Mills, 2005). They argue that a higher proficiency in the initial screening stage is needed, which is strongly correlated with all measures of project performance. The most common industry model to conduct product development is the stage-gate model (Cooper, 1990). Cooper (1990) identifies the need for a better new product management process, where value is defined as the long term investment and the company's degree of innovativeness, and proposes the stage-gate model (Fig.3). Using this models, Cooper (2014) argues that better project evaluation can be achieved (Cooper, 2006a,c; Cooper and Edgett, 2006a,b; Cooper and Mills, 2005).

Over the years, literature concerning the distinction between technology development and product development has grown. Eldred and Mcgrath (1997) argue for making such a separation in order to accommodate the differences in characteristics of technology and product development. Cooper (2006b) proposes the stage-gate model for technology development, stressing that the process has to be adapted to the special characteristics inherent in exploratory work, where the outcome is new knowledge rather than a product (Cooper, 2007). He goes one step further to describe the invisible success factors in innovation for doing the right projects and doing the projects right (Cooper, 1999; Cooper et al., 2001, 2002). Table 2 shows the difference between TDP and NPD from a variety of dimensions (Dewulf, 2013; Högman and Johannesson, 2013; Nobelius, 2002).

Table 2 Differences between technology development and product development (synthesized from Dewulf (2013); Högman and Johannesson (2010); Nobelius (2002)

Dimension	Technology Development	Product Development
Nature	Problem focused	Solution focused
Method	Exploration oriented	Exploitation oriented
Degree of formalization	Low	High
State of an idea	Probable, fuzzy	Determined, clear
Technical Maturity	Technology evaluation	System integration
Time commitments	Long-term	Short-term
Competence required	Unclear	Clear and predictable
Uncertainty	High	Low
Risk	High	Low
Process repeatability	Low	Higher
Completion point	Unclear	Sharp
Development result	Knowledge, capability	Marketable product, service etc.
Damage if abandoned	Relatively small	Substantial

Despite the large amount of literature on the NPD process and methods, and the differences between NPD and TDP, there is limited literature on the TDP, its models and how they are used. Table 3 shows the TDP models in the literature. These models share many similarities, with both advantages and disadvantages. The most important similarity is the purpose they are used, and specifically for managing the TDP and facilitating rational decision making in evaluating technology projects. All the models from Table 3 attempt to consider the uncertain and risky nature of technology development, its benefits in the long term strategic landscape of the firm, and its differences from traditional NPD processes (Table 2). The most widely known model is the Technology Stage Gate model, proposed by Cooper (2006b, 2007), which many firms make use today due to its simplicity. In the rest of the section, we review the models found in Table 3.

Table 3 Technology development models in the literature in order of publication year

Model	Origin	Author
Technology Realisation and Commercialisation (TRAC)	Industry (PRTM)	Eldred and Mcgrath (1997)
Holistic Front-End	Academia	Khurana and Rosenthal (1998)
Exxon Research and Engineering (ERE) technology advancement	Industry (Exxon)	Cohen et al. (1998)
Technology development knowledge building	Industry (Rohm and Haas)	Sheasley (1999, 2000)
Total technology development	Academia	Schulz et al. (2000)
New Concept Development (NCD)	Academia	Koen et al. (2001)
TechSG	Academia	Ajamian and Koen (2002)
Global Enterprise Technology System (GETS)	Industry (Boeing)	Lind (2006)
Technology Stage Gate (TSG)	Academia	Cooper (2006b)
Technology acquisition stage gate	Industry	Cáñez et al. (2007)
Theoretical model of TDP	Academia	Caetano et al. (2011)
BIG picture	Industry	Lercher (2016a)

Technology Realization and Commercialisation (TRAC) model

The TRAC model is an integrated methodological approach for managing technology development (Eldred and Mcgrath, 1997), which efficiently evaluate the suitability of a given technology for commercialization. It consists of four elements: a review process, a team, a senior review committee and a structured methodology. This is shown in Fig. 4). The review process provides an overall framework, which consists of a series of pre-agreed technical reviews at the end of each development stage, with the senior review committee. In addition, the team leads the effort to plan, execute and evaluate the various stages.

Eldred and Mcgrath (1997) argue that the TDP of a company should implement a company's strategy and transfer technology to the NPD process. They argue that using this review process should improve decision making; however, they note that there are high risks and uncertainty involved with these kind of projects and thus there should be no guarantee that a technology project will succeed.

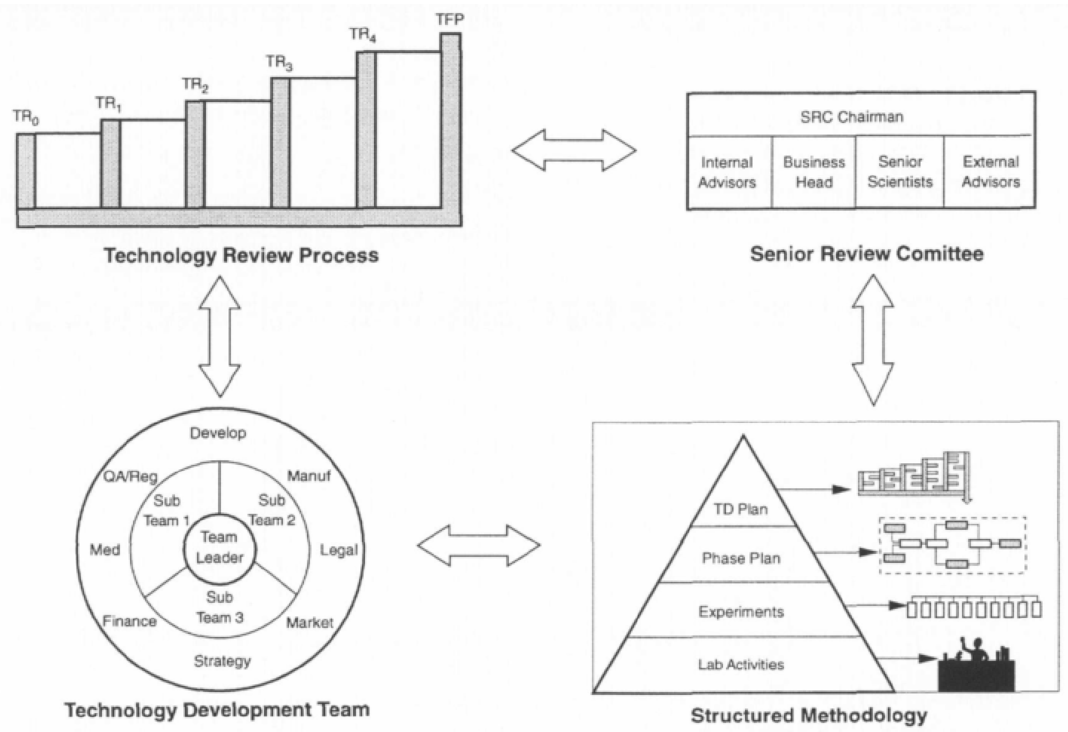


Fig. 4 Technology realization and commercialization model, source: Eldred and Mcgrath (1997)

Holistic Front-End model

The holistic front end model is a 3-phase process view that manages the activities taking place at the front end, just before the NPD process (Khurana and Rosenthal, 1998). Its purpose is to understand and manage the interrelationships between product and strategy with the focus being on foundation technology developments in the first phase. In this phase, the TDP activities, such as ideation , market analysis, opportunity identification, technology analysis are taking place, followed by conceptualization and feasibility, similar to the TSG (Cooper, 2006b).

Khurana and Rosenthal (1998) argue that this model effectively links the strategic, operational, informational and organizational perspective of the development process (Fig.5), similar to Eldred and Mcgrath (1997). They also argue that there is no successful universal system to structure the fuzzy front end.

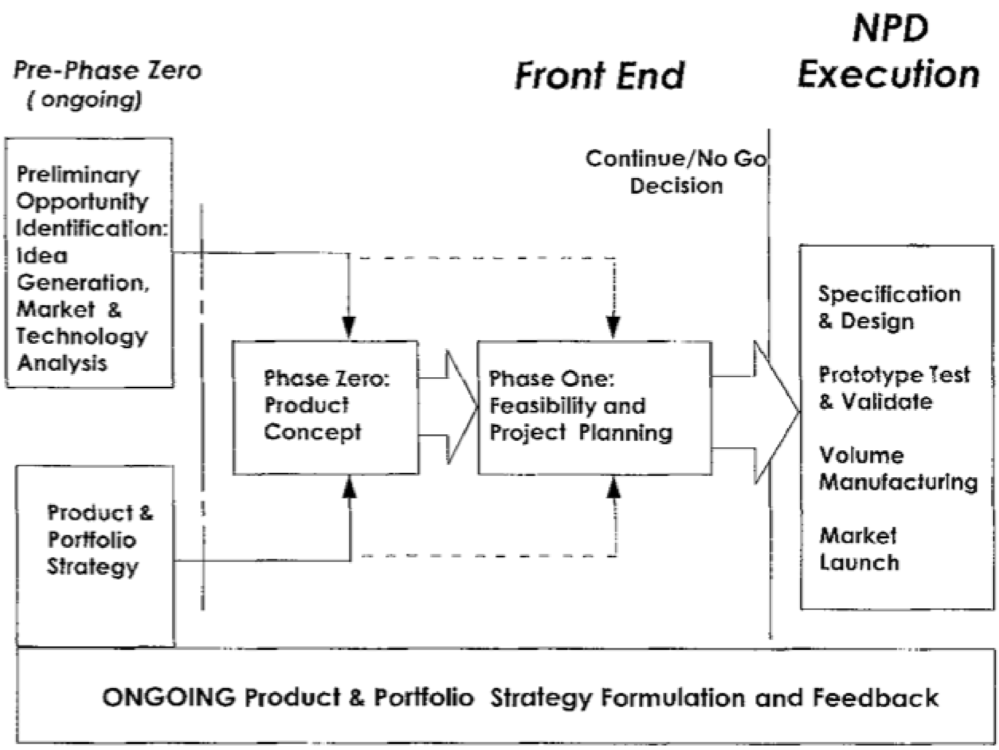


Fig. 5 Holistic front end model, source: Khurana and Rosenthal (1998)

Exxon Research and Engineering (ERE) technology advancement Model

This model builds on the product development gating system, recognizing that research of a fundamental nature is often required to generate science-based technologies (Cohen et al., 1998). It adds early stage gates for the basic research phases of technology development (Fig. 6), to provide direction for the success of science-based technologies (Phaal et al., 2012).

Cohen et al. (1998) identify the need to provide direction for the success of science-based technology developments, tracking progress and research aims, and integrating it with applied exploratory research and development components, similar to the TSG (Cooper, 2007).

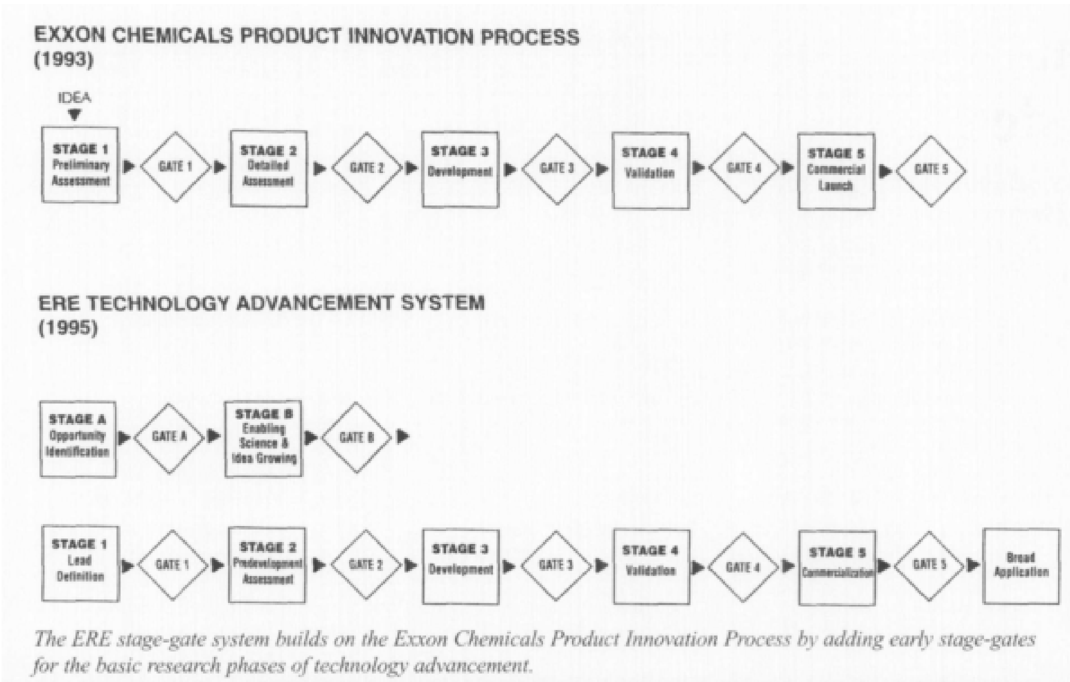


Fig. 6 ERE technology advancement model, source: Cohen et al. (1998)

Technology development knowledge building Model

The technology development knowledge building model focuses on the nature of discovery, or the search for new knowledge. Sheasley (1999) argues that it is a process of discovery or exploratory research for acquiring knowledge (Figure 7), which can later be utilized in the design of new products to meet market needs. It is fundamentally different from developing new products Cooper (2006b); Eldred and Mcgrath (1997). The concepts of cycle time management can provide a framework and protocol for managing technology development (Sheasley, 1999).

Effective oversight requires a strategy for assessing progress in such learning-intensive, discovery-oriented research and ensures value alignment with the business (Sheasley, 1999, 2000). The stages of the knowledge building model (Figure **??**) resemble the ones proposed by Cooper (2006b) in the Technology development stage gate model, but Sheasley (1999) emphasizes the iterative learning process as central and does not frame technology development by a sequential process model.

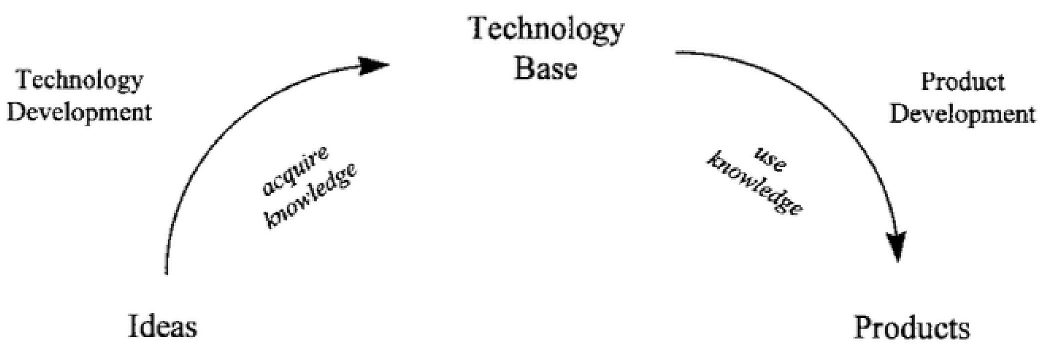


Fig. 7 Technology Development Knowledge Building model; Source: Sheasley (1999)

Total technology development Model

This model has its origins on systems theory, and proposes a separate TDP from NPD process, in a distinct and clearly defined technology steam (Schulz et al., 2000). The model mainly focuses on the deployment, analysis and selection of business strategies, and the transference of technologies to the NPD process.

With challenges such as shortcomings within development systems and use of inappropriate processes, Schulz et al. (2000) propose the separation between TDP and NPD process, and even further to separate between primary and secondary technology development (Fig.8). They define primary technologies as the ones, which directly enhance one or several functions of a system and secondary technologies as the ones, which enable the realization of the primary technologies. The model includes four main phases, very similar to the NCD model by Koen et al. (2002), and the four stage-gate TSG model proposed by Cooper (2007).

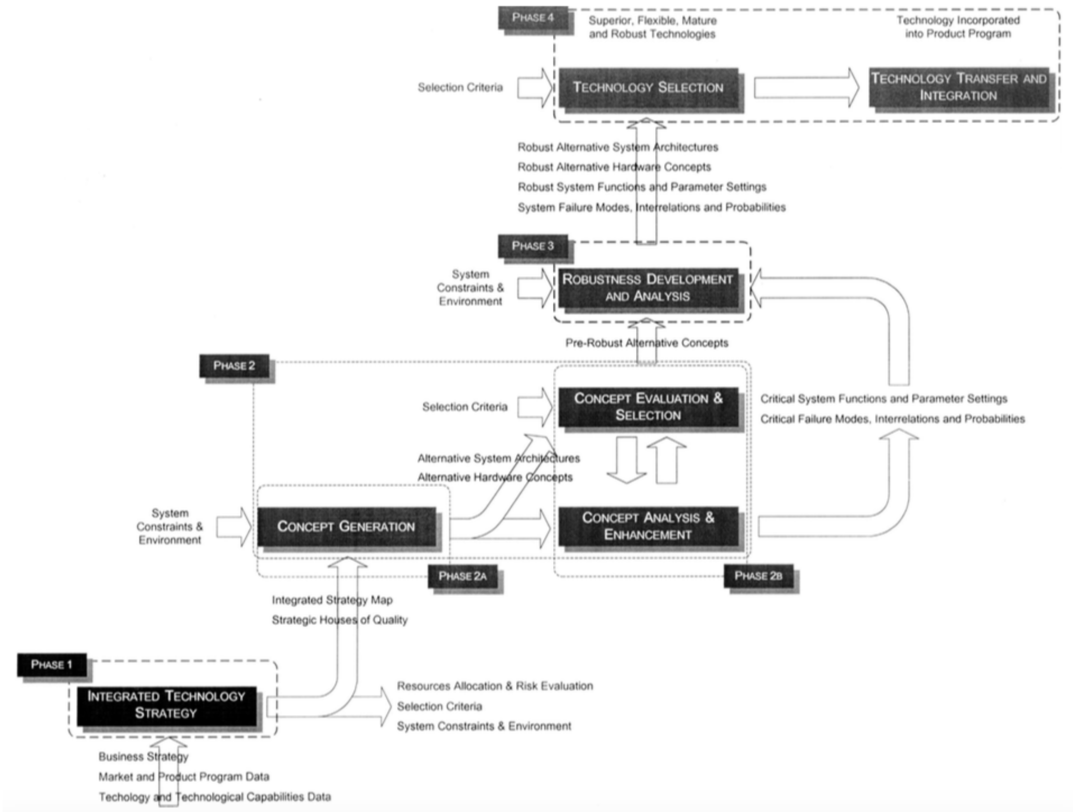


Fig. 8 Total technology development model, source: Schulz et al. (2000)

New Concept Development (NCD) model

The NCD model is focused at the FEI and covers the activities coming prior to formal, structured product and process development Koen et al. (2001). The model is shown in Fig. 9 and consists of three elements: the inner area, which defines the five key elements comprising the FEI (Koen et al., 2001); the engine driving the five FEI elements and fuelled by leadership and organizational culture; and the influencing factors consisting of organizational capabilities, business strategy, and the outside world.

In addition, the NCD fuels both the TDP and NPD process (Koen et al., 2002), and is very similar to the TSG model by Cooper (2006b). Both models make reference to the TDP and the TSG, which is described in three phases, the initial idea genesis/ selection phase, the information gathering phase, and the concept/ technology definition phase. Koen et al. (2014a,b), through two industrial studies, argue that this evolutionary process is essential to build knowledge and understanding of a discovery, and identify the most effective path forward at the FEI.

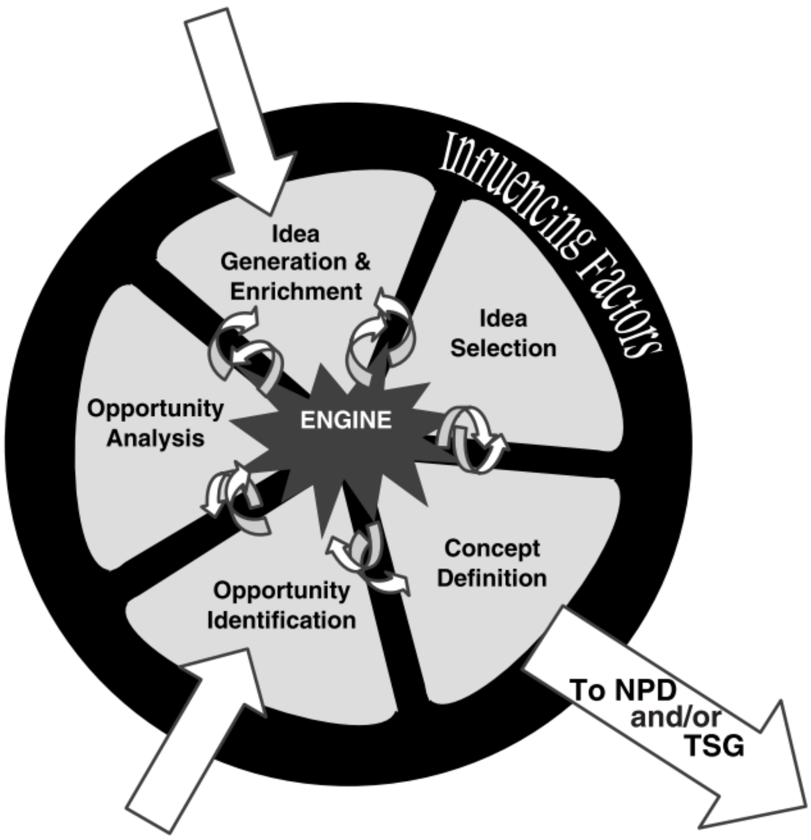


Fig. 9 New concept development; source: Koen et al. (2002)

Technology Stage Gate (TechSG) model

This model manages technology development efforts, and is concentrated at the FEI, where there is high uncertainty and risk. This particular model provides a comprehensive system approach for all elements of the TDP to come together, very similar Schulz et al. (2000). While all the previous models describe processes for TDP, as defined by Shehabuddeen et al. (2000), this particular model describes a system, as defined by Kerr et al. (2006); Shehabuddeen et al. (2000). It was proposed by Ajamian and Koen (2002), extending the TRAC model by Eldred and Mcgrath (1997) to manage technology development, with a long term view towards business strategy.

The purpose of the TechSG system is to bring both scientific and business rigour into the technology discovery process, and it consists of six interlinked elements, which work towards a common technological discovery goal. These elements consist of project charter, technology stage gate, technology development team, technology process owner, technology review committee, and technology structured planning (Fig.10).

Eldred and Mcgrath (1997) argue that the technology development process of a company should implement a company's product strategy and transfer technology to the NPD process. Through this structured review process, the decision-making process should be improved; however, they note that too much structure in the process might hinder the idea generation process. Also, they warn that there are high risks and uncertainty involved with technology projects and there is no guarantee that a project will be successful.

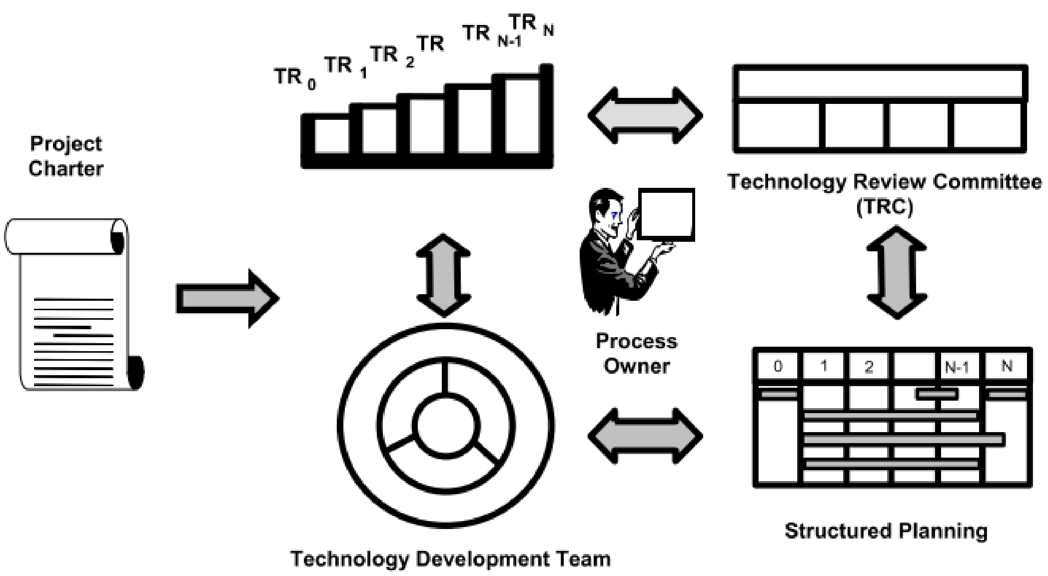
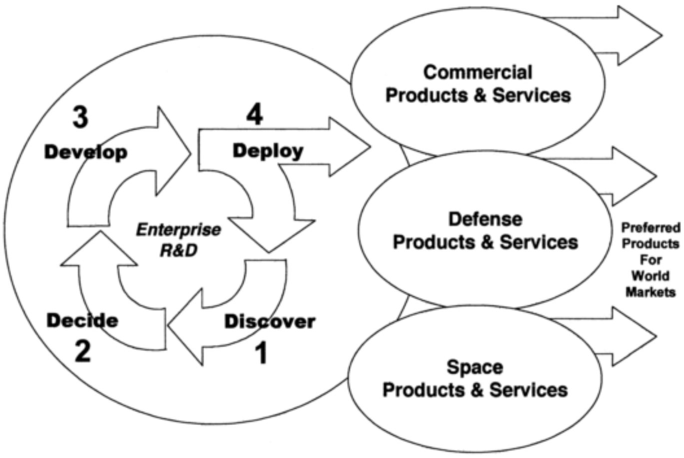


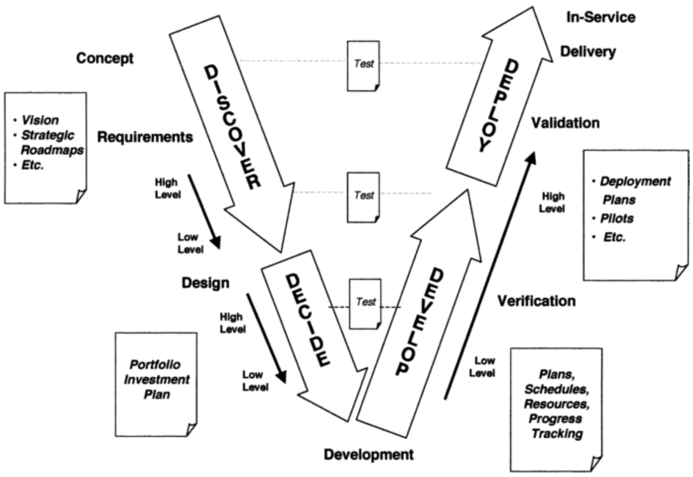
Fig. 10 Technology stage gate (TechSG), source: Ajamian and Koen (2002)

Global Enterprise Technology System (GETS) model

The Global Enterprise Technology System (GETS) provides a strategically-driven and systems-engineering approach to manage innovation (Fig.11a), and in specific technology projects (Lind, 2006). Lind (2006) describes the process implemented in Boeing, closely linked to the systems engineering V-model of **?** (Fig.11b). The model consists of four main stages; the discover stage consists of all the things to explore and understand a technological opportunity; the decide stage screens the ideas to pursue; the develop stage executes the projects; and the deploy stage ensures the effective application and value realization from the innovations.



(a) GETS Approach



(b) GETS portrayal as V model)

Fig. 11 Global enterprise technology system, source: Lind (2006)

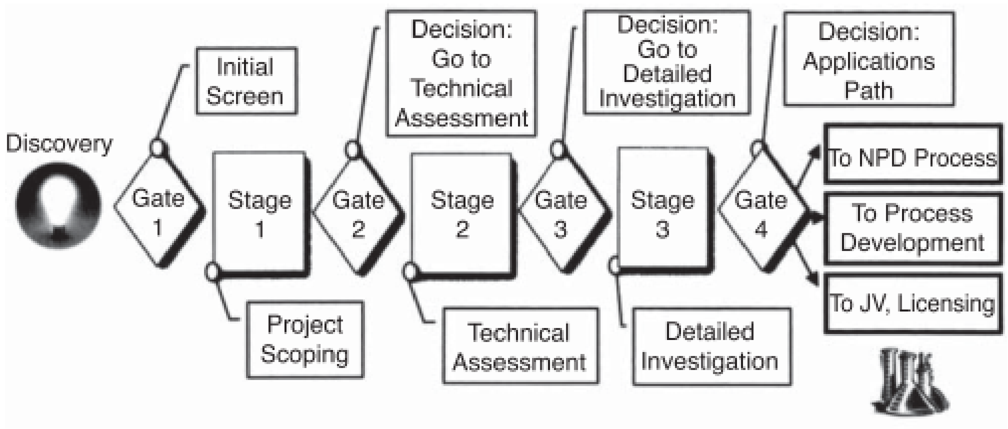
Technology Stage Gate (TSG) model

The process for managing technology development, and a structured review procedure in the form of a technology stage gate, is further supported by the propositions of Cooper (2006b). Cooper (2006b) argues that technology development projects are the foundation platforms for new opportunities and require a separate process to be managed, which he defines as the TDP (Fig.12a). He points that these particular projects, are rare, fragile and unique, identifying the problem that these knowledge-build projects are mismanaged, and proposes the technology stage gate model to manage them (Cooper, 2006b, 2007). He positions this process within the innovation funnel as shown in Fig. 1, similar to the arguments by Ajamian and Koen (2002); Koen et al. (2002).

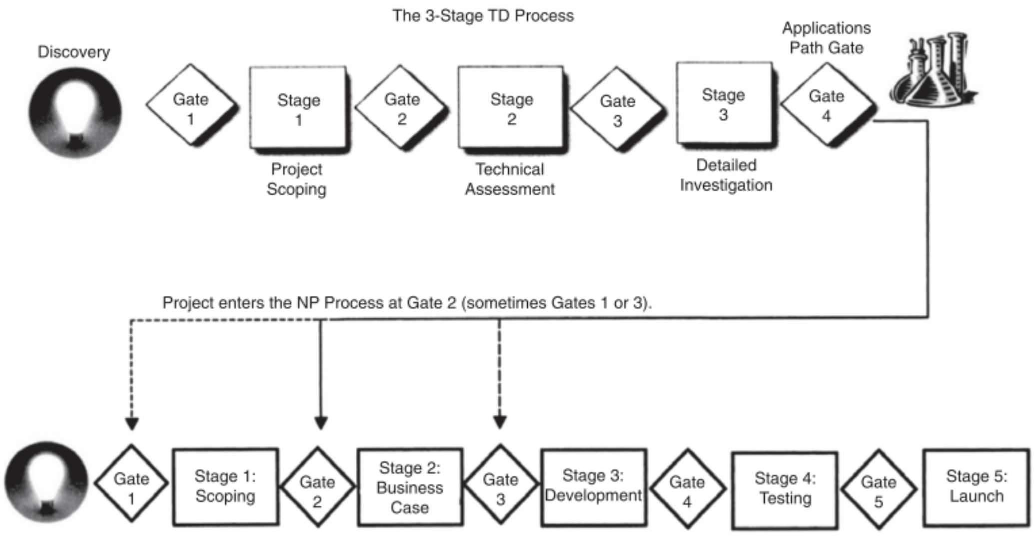
The TSG model consists of three stages and four gates, and fuels the front end of the NPD process (Cooper, 2013, 2014, 2016; Cooper and Edgett, 2014a,b; Cooper and Sommer, 2016). The three stages consist of project scoping, technical assessment and detailed investigation. The four decision gates have different characteristics and consist of initial screening, go to technical assessment, go to detailed investigation, and the applications path (Fig.12). At gate 1, the organization's top leaders verify whether a given idea merits development effort and investment followed by formulation of project and scope. At gate 2, they determine qualitatively the limitations of the project scope, which will enable the technological evaluation. At gate 3, the leadership team analyses the project viability using the information gathered, supporting technological investigation. One of the most crucial gates, is gate 4, the application gate, where the strategic leverage and viable commercialisation strategy of an application of the technology project is identified. This gate integrates the TDP with the NDP process (Fig.12b)

This is similar to the idea proposed by Phaal et al. (2011, 2012) with the transition model of industrial emergence (Fig. 2), that within the innovation funnel there are transitions from discovery to science to technology to product development. In addition, Caetano et al. (2011) propose a theoretical TDP model on similarities from the models described above, which leverages internal competencies to make strategic decisions, based on market and technology trends. From case studies, he identifies a number of open innovation related challenges that firms need to adapt to in order to manage and adopt technology development processes.

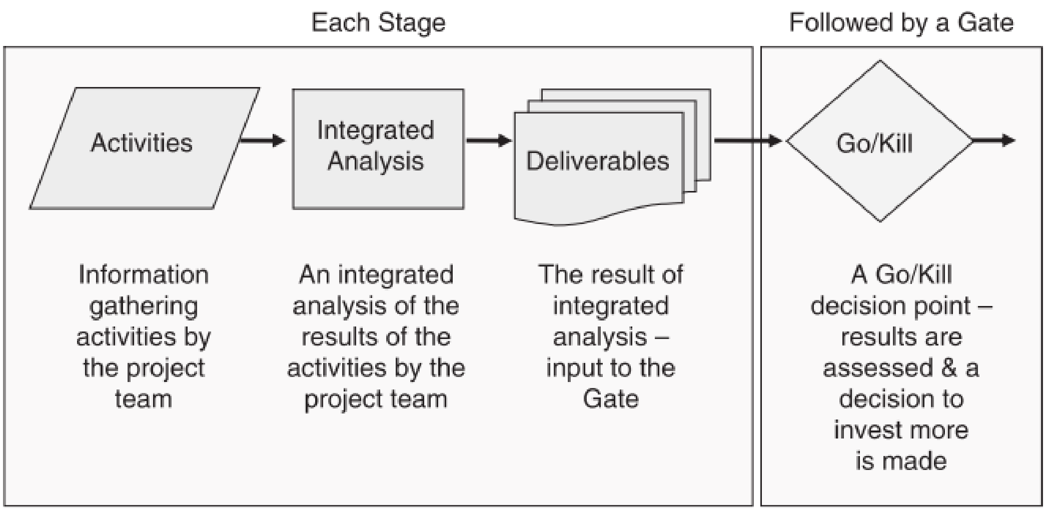
Cooper (2007) also argues that tailored selection criteria should be used to rate and make strategic decisions for these projects at the decision gates. These are guarded by gatekeepers, who ensure the information is collected through a number of scoring qualitative techniques (Cohen et al., 1998; Cooper, 2008a,b,c; Freeman et al., 2016; Mitchell et al., 2014; Mortara et al., 2009a). At each stage, a number of information gathering activities takes place, followed by an integrated analysis, which is used as input to the gate (Fig.12c).



(a) Technology stage gate process, source: Cooper (2006b)



(b) Technology stage gate process feeding the NPD process, source: Cooper (2007)



(c) Technology stage gate procedure, source: Cooper (2008c)

Fig. 12 Technology stage gate model

Technology Acquisition Stage Gate model

Technology acquisition is a three-phase process according to Cáñez et al. (2007). It includes technology scanning (i.e. the identification of potential technologies), technology selection (i.e. the assessment of those technologies based on a set of decision criteria), and technology assimilation (i.e. the capacity to acquire know-how). The technology acquisition stage gate model is used for developing technology based solutions and has three distinct phases: fundamental research, applied research and technology acquisition (Fig.13).

The process has two entry points. F is the entry point for ideas that aim to create "new-to-the-world products," and therefore need to go through a stage of fundamental research before joining the development route. In the D route, one of the key stages is the scoping stage, which refers to defining the technology solution to be developed. At this stage, the organisation looks for an existing technology, and thus route A might be initiated to take into consideration a technology acquisition (Cáñez et al., 2007).

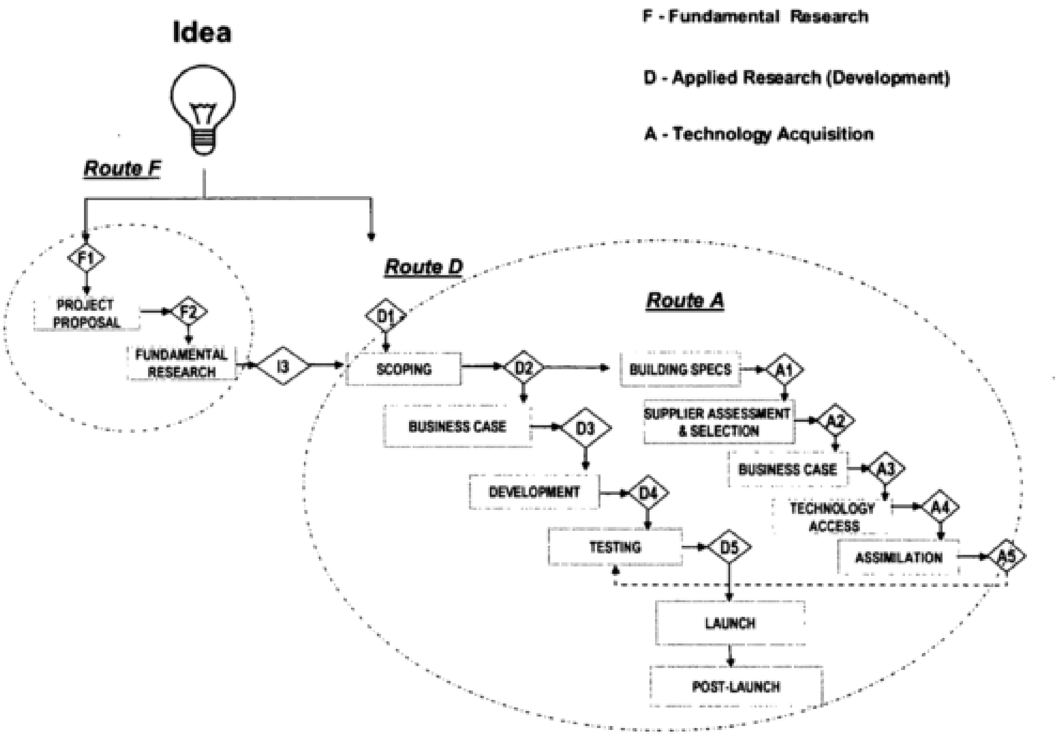


Fig. 13 Technology acquisition model, source: Cáñez et al. (2007)

Theoretical Technology Development Process model

Among other models, the theoretical TDP model is derived from the relevant literature, mainly the TDP model by Cooper (2006b), and consists of stages, which have been grouped together by similarity from the propositions of authors (Caetano et al., 2011). It consists of 5 different stages, which start from an idea and finish at the technology developed and ready to be integrated in a product, service or process development process. These stages can be oriented from the market and technology trends based on internal competencies at the organisation, and are the following: invention, project scope, technology concept development, technology development, technology optimisation, and technology transfer (Fig.14).

This very similar to the TDP model by Cooper (2006b), but including the business integration level from Schulz et al. (2000), and integrating the R& D resources and risks part from Eldred and Mcgrath (1997). Caetano et al. (2011) argues that the development of technology starts from the strategic planning of the organization, along with defining the technology strategies. Idea generation makes the initial invention in the TDP, and in sequence, are conducted the stages of project scope, technology concept development, development and optimization of technology and, finally, the stage of technology transfer.

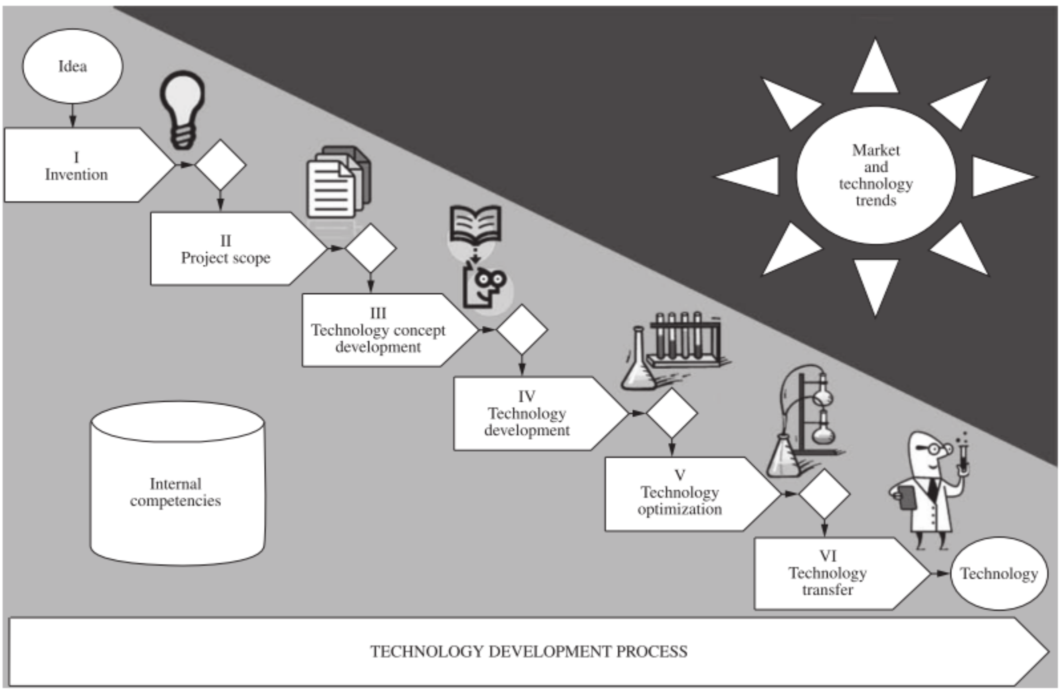


Fig. 14 Theoretical model of technology development process, source: Caetano et al. (2011)

BIG Picture model

The BIG Picture Model (Fig.15 is a holistic integrated cyclic approach for development projects Lercher (2016a). In this model, there are six main paths (Lercher, 2017), with the most relevant to technology high uncertainty and high risk projects being the black, red and blue path (Lercher, 2016b). The black path is information gathering, ideation and initial evaluation, the red path is the radical innovation, and the blue path is the disruptive innovation (Lercher, 2016a).

In contrast to Cooper's model (Fig.12b), BIG Picture does without the fixed sequence of five stages and five gates, and instead uses sequences of work steps and decision steps designed to suit each innovation category. The three typical paths which the innovating company may choose (apart from disruptive innovations), follow Cooper's revised versions of the model (Cooper and Edgett, 2014a).

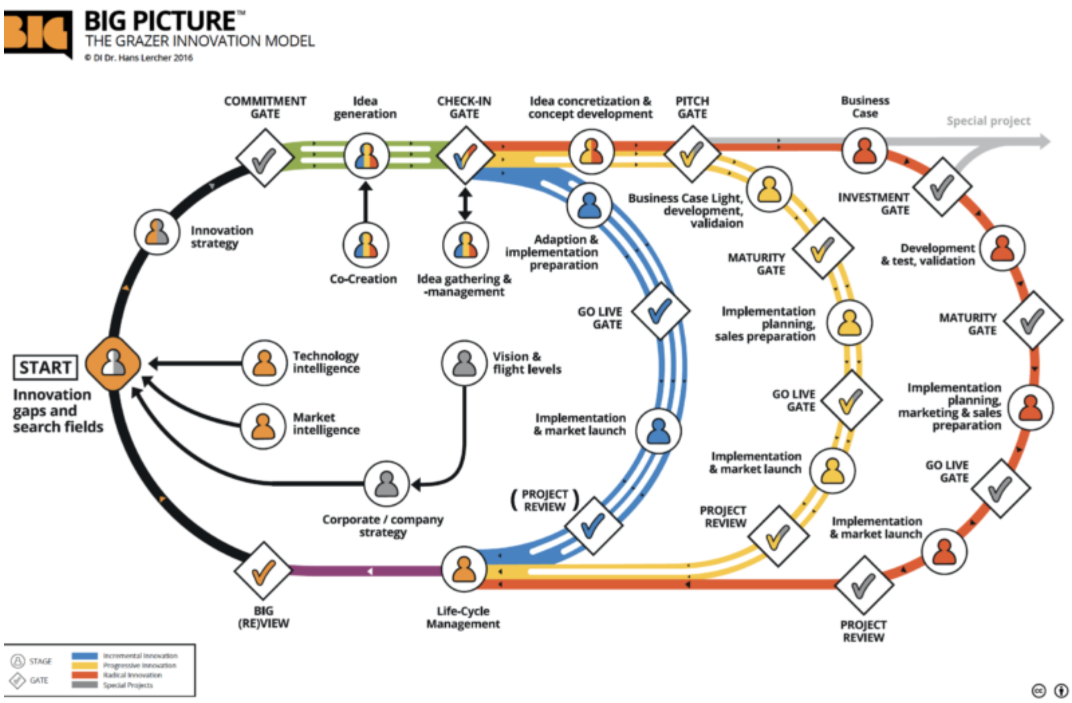


Fig. 15 BIG picture model, source: Lercher (2016a)

Conclusion

While the FEI (Table 1) and NPD processes (Cooper and Kleinschmidt, 1986) have received substantial attention in the literature (Koen et al., 2014b) and their contribution to strategic opportunities, the TDP have lacked behind on their distinction from traditional product development processes and the models and means to support them (Cooper, 2006b).

In this paper, we contribute to the literature on TDP models with a review on the models available in literature (Table 3). All these models share the same purpose of managing the TDP and facilitating rational decision making in evaluating technology projects. However, the true benefit, appropriate design,and the underlying decision support mechanisms of such structured technology development processes is still largely unexploited.

Acknowledgement

The authors would like to acknowledge support of the Engineering and Physical Sciences Research Council (EPSRC). The authors would also like to thank Dr. Robert Phaal, and the Strategic Technology and Innovation Management (STIM) 2018 consortium.

References

Ajamian, G. M. and Koen, P. A. (2002). Technology Stage-Gate: a structured process for managing high-risk new technology projects. In *The PDMA toolbook for new product development*, pages 267–295. John Wiley & Sons, New York.

Burgelman, R. A., Christensen, C. M., and Wheelwright, S. C. (2009). *Strategic management of technology and innovation*, volume 4.

Caetano, M., Araujo, C. S., Amaral, D. C., and Guerrini, F. M. (2011). Open innovation and technology development process: the gap on partnership adoption from a case study perspective. *Product Management & Development*, 9(2):111–120.

Cáñez, L., Puig, L., Quintero, R., and Garfias, M. (2007). Linking technology acquisition to a Gated NPD process. *Research-Technology Management*, 50(4):49–55.

Cao, Y., Zhao, L., and Nagahira, A. (2011). The impact of front end innovation in new product development in Japanese manufacturing companies. *Nankai Business Review International*.

Chen, E. L. and Katilla, R. (2008). Rival Interpretations of Balancing Exploration and Exploitation: Simultaneous or Sequential? *Handbook of Technology and Innovation Management*, pages 197–201.

Chesborough, H. W. (2007). Why companies should have open business models. *MIT Sloan Management Review*, 48(2):22–28.

Chesbrough, H. W. (2003). The era of Open Innovation. *MIT Sloan Management Review*, pages 35–42.

Chesbrough, H. W. (2012). Open Innovation: Where We've Been and Where We're Going. *Research-Technology Management*, 55(August):20–27.

Christiansen, J. K. and Gasparin, M. (2016). Managing Controversies in the Fuzzy Front End. *Creativity and Innovation Management*.

Cohen, L. Y., Kamienski, P. W., and Espino, R. L. (1998). Gate system focuses industrial basic research. *Research-Technology Management*, 41(4):34–37.

Cooper, B. (2009). Conversations on the Cutting Edge. *Journal of Product Development*, (April 2007):1–5.

Cooper, R. G. (1990). Stage-Gate Systems: A New Tool for Managing New Products. *Business Horizons*, 33(3):44–54.

Cooper, R. G. (1999). From Experience: The Invisible Success Factors in Product Innovation. *Journal of Product Innovation Management*, 16(2):115–133.

Cooper, R. G. (2006a). Formula for Success in New Product Development. *Stage-Gate Inc.*, (April).

Cooper, R. G. (2006b). Managing technology development projects. *Research Technology Management*, 49(6):23–31.

Cooper, R. G. (2006c). The seven principles of the latest Stage-Gate ® method add up to a streamlined, new-product idea-to-launch process. *Development*, 15(April):18–24.

Cooper, R. G. (2007). Managing technology development projects. *IEEE engineering management review*, 35(1):67–77.

Cooper, R. G. (2008a). Perspective: The Stage-Gate. pages 213–232.

Cooper, R. G. (2008b). Product Innovation Best Practice Series: Brief Insightful Advice for Busy Innocation Leaders. Technical Report October.

Cooper, R. G. (2008c). What Leading Companies are Doing to Re-invent their NPD Processes. *PDMA Visions Magazine*, (September):6–10.

Cooper, R. G. (2013). Information Technology Development Creativity: A case study of attempted radical change. *Management Information Systems Research Center, University of Minnesota*, 24(2):245–276.

Cooper, R. G. (2014). What's Next?: After Stage-Gate. *Research-Technology Management*, 57(1):20–31.

Cooper, R. G. (2016). Agile-Stage-Gate Hybrids. *Research Technology Management*, 59(1):21–29.

Cooper, R. G. and Edgett, S. (2006a). Ten Ways to Make Better Portfolio and Project Selection Decisions. *PDMA Visions Magazine*, 3(June 2006):11–15.

Cooper, R. G. and Edgett, S. (2008a). Ideation for product innovation : What are the best methods ? *PDMA Visions Magazine*, 1(March 2008):12–17.

Cooper, R. G. and Edgett, S. J. (2006b). Ten ways to make better portfolio and project selection decisions. *Product Development Institute Inc.*, (June):11–15.

Cooper, R. G. and Edgett, S. J. (2008b). Maximizing Productivity Maximizing Productivity. *Research-Technology Management*, 51(2):1–15.

Cooper, R. G. and Edgett, S. J. (2010). Process : What Best Practice Companies are Doing - Part Two Optimizing the Stage-Gate Process. *Technology Management*, 45(5):256–271.

Cooper, R. G. and Edgett, S. J. (2012). Best Practices in the Idea-to-Launch Process and Its Governance. *Research-Technology Management*, 55(2):43–54.

Cooper, R. G. and Edgett, S. J. (2014a). Benchmarking Best Practices Performance Results and the Role of Senior Management.

Cooper, R. G. and Edgett, S. J. (2014b). Portfolio Management for New Products : Picking The Winners Portfolio Management for New Products Picking The Winners.

Cooper, R. G., Edgett, S. J., and Kleinschmidt, E. J. (2001). Portfolio management for new product development : Results of an industry practices study portfolio management for new product development : results of an industry practices study. *R&D Management (Industrial Research Institute, Inc.)*, 13(4):1–39.

Cooper, R. G., Edgett, S. J., and Kleinschmidt, E. J. (2002). New Problems , New Solutions : Making Portfolio Management More Effective. *Research-Technology Management*, pages 1–23.

Cooper, R. G. and Kleinschmidt, E. J. (1986). An investigation into the new product process: steps, deficiences and impact. *Journal of Product Innovation Management*, 3(2):71–85.

Cooper, R. G. and Mills, M. S. (2005). Succeeding at New Product Development the P&G way: A key element is using the "Innovation Diamond". *pdma Visions*, 29(4):8–17.

Cooper, R. G. and Sommer, A. F. (2016). Agile-Stage-Gate: New idea-to-launch method for manufactured new products is faster, more responsive. *Industrial Marketing Management*, 59:167–180.

Creswell, J. W. (2013). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. 4th editio edition.

Cronin, P., Ryan, F., and Coughlan, M. (2008). Undertaking a literature review : a step-by-step approach. 17(1):38–43.

Dang, R. J., Mortara, L., Thomson, R., Minshall, T., Dang, R. J., Mortara, L., Thomson, R., Minshall, T., Dang, R. J., Mortara, L., Thomson, R., and Minshall, T. (2012). Developing technology intelligence strategy to access knowledge of innovation clusters.

Danguleva, A. (2014). *Business Model Development in the Front End of Innovation*. PhD thesis, TU Delft.

De Brentani, U. and Reid, S. E. (2012). The fuzzy front-end of discontinuous innovation: Insights for research and management. *Journal of Product Innovation Management*.

de Oliveira, M. G., Rozenfeld, H., Phaal, R., and Probert, D. (2015). Decision making at the front end of innovation: The hidden influence of knowledge and decision criteria. *R and D Management*, 45(2):161–180.

Dewulf, K. (2013). Sustainable Product Innovation: The importance of the Front End Stage in the Innovation Process. In *Advances in Industrial Design Engineering*, chapter Chapter 7.

Dornberger, U. and Suvelza, A. (2012). *Managing the Fuzzy Front-End of Innovation*.

Eldred, E. W. and Mcgrath, M. E. (1997). Commercializing New Technology I. *Research-Technology Management*, 40(1):41–47.

Eling, K., Griffin, A., and Langerak, F. (2014). Using intuition in fuzzy front-end decision-making: A conceptual framework. *Journal of Product Innovation Management*.

European Commission (2004). Innovation Management and the Knowledge-Driven Economy. *European Commission Directorate-general for Enterprise*, 4(1):164.

Fagerberg, J., Mowery, D., and Nelson, R. (2006). *The Oxford Handbook of Innovation*. Oxford University Press, Oxford, 1st edition.

Florén, H. and Frishammar, J. (2012). From Preliminary Ideas to Corroborated Product Definitions: Managing the Front End of New Product Development. *California Management Review*.

Ford, S., Aubert, C., and Ryckewaert, E. (2016). *Reducing the risk in New Product Development: getting it right at the front end of innovation*.

Freeman, M., Savva, N., Scholtes, S., Freeman, M., and Scholtes, S. (2016). Gatekeepers at Work : An Empirical Analysis of a Maternity Unit. *Management Science*, (Articles in Advance):1–22.

Galbraith, C. S., Ehrlich, S. B., and DeNoble, A. F. (2006). Predicting technology success: Identifying key predictors and assessing expert evaluation for advanced technologies. *Journal of Technology Transfer*, 31(6):673–684.

Gardiner, C. (2010). Evaluation and selection of coagulometers. *International Journal of Laboratory Hematology*, 32(November):1–85.

Goffin, K. and Mitchell, R. (2016). *Innovation Management: Effective Strategy and Implementation*. Palgrave Macmillan.

Grant, R. M. (2012). *Contemporary Strategy Analysis: Text & Cases*, volume 8.

Halman, J. I. M., Hofer, A. P., and Van Vuuren, W. (2003). Platform-driven development of product families: Linking theory with practice. *Journal of Product Innovation Management*, 20(2):149–162.

Högman, U. (2011a). *Processes and platforms aligned with technology development - The perspective of a supplier in the aerospace industry*.

Högman, U. (2011b). *Processes and platforms aligned with technology development - The perspective of a supplier in the aerospace industry*.

Högman, U. and Johannesson, H. (2010). Technology development and normative process models. *11th International Design Conference, DESIGN 2010*, pages 265–274.

Högman, U. and Johannesson, H. (2013). Applying stage-gate processes to technology development - Experience from six hardware-oriented companies. *Journal of Engineering and Technology Management - JET-M*, 30(3):264–287.

Hultgren, A. and Tantawi, A. (2014). Front-End Idea Screening of Potential Radical Innovation in Large Firms. page 112.

Husig, S. and Kohn, S. (2003). Factors influencing the front end of the innovation process: A comprehensive review of selected empirical NPD and explorative FFE. In *European Institute for Advanced Studies in Management, Brussels: 10th International Product Development Management Conference 2003*, pages 1–21.

Ilevbare, I. (2013). *An investigation into the treatment of uncertainty and risk in roadmapping: A framework and a practical process*. PhD thesis, University of Cambridge.

Ismail, K., Leow, Y. R., Yong, C. Y., Abdul-Majid, I., Thwala, W. D., and Ajagbe, M. A. (2012). Critical success factors of new product development in technology based firms: A case study. *African Journal of Business Management*, 6(33):9442–9451.

Jugend, D., da Silva, S. L., Oprime, P. C., and Pimenta, M. L. (2015). Organizational issues for integration of high-technology in new product development: Framework proposal and case studies in Brazilian companies. *Innovation: Management, Policy and Practice*, 17(2):217–231.

Kerr, C. I., Mortara, L., Phaal, R., and Probert, D. R. (2006). A conceptual model for technology intelligence. *International Journal of Technology Intelligence and Planning*, 2(1):73–93.

Khurana, A. and Rosenthal, S. R. (1998). Towards Holistic "Front Ends" In New Product Development.

Kim, D.-J. and Kogut, B. (1996). Technological Platforms and Diversification. *Organization Science*, 7(3):283–301.

Kobe, C. (2001). Technology Intelligence in the Front End of New Product Development. (Kobe).

Koen, P. A. (2004). Understanding the Front End: A Common Language and Structured Picture.

Koen, P. A., Ajamian, G., Burkart, R., Clamen, A., Davidson, J., D 'amore, R., Elkins, C., Herald, K., Incorvia, M., Johnson, A., Karol, R., Seibert, R., Slavejkov, A., and Wagner, K. (2001). Providing Clarity and A Common Language to the Fuzzy Front End. *Research Technology Management*, 44(2):46–55.

Koen, P. A., Ajamian, G. M., Boyce, S., Clamen, A., Fisher, E., Fountoulakis, S., Johnson, A., Puri, P., and Seibert, R. (2002). Fuzzy Front End: Effective Methods, Tools, and Techniques. In *The PDMA toolbook for new product development*, chapter 1, pages 2–35. John Wiley & Sons, New York.

Koen, P. A., Bertels, H. M. J., and Kleinschmidt, E. J. (2014a). Managing the front end of innovation-part II: Results from a three-year study. *Research Technology Management*, 57(3):25–35.

Koen, P. A., Bertels, H. M. J., and Kleinschmidt, E. J. (2014b). Managing the Front End of Innovation — Part I. *Research Technology Management*, 57(3):34–43.

Koppinen, S., Lammasniemi, J., and Kalliokoski, P. (2010). Practical application of a parallel research-business innovation process to accelerate the deployment of research results. *R and D Management*, 40(1):101–106.

Kurkkio, M. (2011). Managing the fuzzy front-end: insights from process firms. *European Journal of Innovation Management*.

Kurkkio, M., Frishammar, J., and Lichtenthaler, U. (2011). Where process development begins: A multiple case study of front end activities in process firms. *Technovation*.

Lercher, H. (2016a). Big Picture Innovation Model Handbook. Technical report.

Lercher, H. (2016b). Das Grazer Innovationsmodell BIG Picture: Ein Template zur Verknüpfung von strategischen und operativen Innovationselementen in einem gesamtheitlichen und geschlossenen Innovationsprozess. In *Forschungsforum Der Osterreichischen Fachhochschulen 2016*, pages 1–8.

Lercher, H. (2017). *Big PictureTM Das Grazer Innovationsmodell.*

Lind, J. (2006). Boeing's Global Enterprise Technology Process. *Research- Technology Management*, 49(5):36–42.

Markham, S. K. (2013). The impact of front-end innovation activities on product performance. *Journal of Product Innovation Management*.

Martinsuo, M. and Poskela, J. (2011). Use of evaluation criteria and innovation performance in the front end of innovation. *Journal of Product Innovation Management*, 28(6):896–914.

McGrath, M. E. (1995). Product Strategy for High-technology Companies. *Research Technology Management*, 38:59–65.

Mendes, G. H. S. and Toledo, J. C. (2011). The Fuzzy Front End of New Product Development for Brazilian Technology-Based Companies in the Medical Device Industry: a Causal Model. *Brazilian Journal of Operations & Production Management*, 8(1):83–102.

Mitchell, R., Phaal, R., and Athanassopoulou, N. (2014). Scoring methods for prioritizing and selecting innovation projects. *PICMET 2014 - Portland International Center for Management of Engineering and Technology, Proceedings: Infrastructure and Service Integration*, (2001):907–920.

Montoya-Weiss, M. M. and Calantone, R. (1994). Determinants of New Product Performance: A Review and Meta-Analysis. *Journal of Product Innovation Management*, 11(5):397–417.

Mortara, L., Kerr, C. I., Phaal, R., and Probert, D. R. (2009a). A toolbox of elements to build Technology Intelligence systems. *International Journal of Technology Management*, 47(4):322.

Mortara, L., Kerr, C. I. V., Phaal, R., and Probert, D. R. (2009b). Technology Intelligence practice in UK technology-based companies. *International Journal of Technology Management*, 48(1):115–135.

Mortara, L., Napp, J. N., Slacik, I., and Minshall, T. (2009c). How to implement open innovation: lessons from studying large multinational companies. Technical report, University of Cambridge Institute for Manufacturing.

Neumann, M. (2006). *Ideation Reference Process Model for the Early Phase of Innovation*. PhD thesis, University de Grenoble.

Nieto, M. (2003). From R&D management to knowledge management: An overview of studies of innovation management. *Technological Forecasting and Social Change*, 70:135–161.

Nieto, M. (2004). Basic propositions for the study of the technological innovation process in the firm. *European Journal of Innovation Management*, 7(4):314–324.

Nieto, M. and Quevedo, P. (2005). Absorptive capacity, technological opportunity, knowledge spillovers, and innovative effort. *Technovation*, 25(10):1141–1157.

Nobelius, D. (2002). *Managing R&D processes - Focusing on technology development, product development, and their interplay*. Number 1842.

OECD (2016). Enabling the Next Production Revolution: the Future of Manufacturing and Services - Interim Report. Technical Report June, OECD.

Phaal, R., O'Sullivan, E., Routley, M., Ford, S., and Probert, D. (2011). A framework for mapping industrial emergence. *Technological Forecasting and Social Change*, 78(2):217–230.

Phaal, R., Routley, M., Athanassopoulou, N., and Probert, D. (2012). Charting Exploitation Strategies for Emerging Technology. *Research-Technology Management*, 55(2):34–42.

Prahalad, C. and Hamel, G. (1990). The Core Competence of the Corporation. *Harvard Business Review*, 68(3):79.

Riel, A., Neumann, M., and Tichkiewitch, S. (2013). Structuring the early fuzzy front-end to manage ideation for new product development. *CIRP Annals - Manufacturing Technology*, 62(1):107–110.

Robson, C. (2011). Real world research. *Edition. Blackwell Publishing. Malden*, pages 1–608.

Schulz, A. P., Clausing, D. P., Fricke, E., and Negele, H. (2000). Development and integration of winning technologies as key to competitive advantage. *Systems Engineering*, 3(4):180–211.

Schumpeter, J. (1934). *The Theory of Economic Development*.

Schumpeter, J. A. (1939). *Business cycles A Theoretical , Historical adn Statistical Analisys of The Capitalist process*, volume 64.

Sheasley, W. D. (1999). Leading the Technology Development Process. *Research Technology Management*, 42(2):130–153.

Sheasley, W. D. (2000). Taking an options approach to new technology development. *Research Technology Management*, 43(6):37–43.

Shehabuddeen, N., Probert, D., Phaal, R., and Platts, K. (2000). Management Representations and Approaches: exploring issues surrounding frameworks. *Bam 2000*, (0):1–29.

Sommer, A. F., Hedegaard, C., Dukovska-Popovska, I., and Steger-Jensen, K. (2015). Improved Product Development Performance through Agile/Stage-Gate Hybrids. *Research Technology Management*, 58(1):34–44.

Takey, S. M. and Carvalho, M. M. (2016). Fuzzy front end of systemic innovations: A conceptual framework based on a systematic literature review. *Technological Forecasting and Social Change*.

Teza, P., Buchele, G. T., de Souza, J. A., and Dandolini, G. A. (2016). Analysis of quantitative empirical papers on diffusion and adoption of methods, techniques and tools for innovation. *Rai - Revista de Administracao e Inovacao*, 13(2):107–115.

Teza, P., Dandolini, G., Souza, J. A. d., Miguez, V. B., Fernandes, R. F., and Miguel, P. A. C. (2015). Modelos de front end da inovação: similaridades, diferenças e perspectivas de pesquisa. *Production*, 25(4):851–863.

Venuvinod, P. K. (2010). *Technology, Innovation and Entrepreneurship Part I: My world, My nation*. Smashwords.

Warren, M. (2004). A Study of Innovation : Anatomy of the Key Success Factors Henley Management College. *Analysis*.

Wowak, K. D., Craighead, C. W., Ketchen, D. J., and Hult, G. T. M. (2016). Toward a "Theoretical Toolbox" for the Supplier-Enabled Fuzzy Front End of the New Product Development Process. *Journal of Supply Chain Management*.