Universidade de Aveiro Departamento de Economia, Gestão e Engenharia Industrial
2009

Leonildo Varela Monteiro

A inovação na indústria de bens de equipamento

Um estudo na perspectiva dos processos, modos e riscos de inovação

Innovation in the capital goods industry

A study in the perspective of processes, modes and risks of innovation

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Gestão de Informação, realizada sob a orientação científica da Doutora Celeste Amorim Varum, Professora Auxiliar e do Doutor Carlos Manuel dos Santos Ferreira, Professor Associado com Agregação, no Departamento de Economia, Gestão e Engenharia Industrial da Universidade de Aveiro.

Dedico este trabalho à minha família, em especial aos meus pais, pelo incansável apoio.

o júri

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Aos meus orientadores, por todo o apoio prestado. Às empresas e pessoas contactadas, por terem facilitado o acesso aos dados utilizados. A todos os que de alguma forma encorajaram ou apoiaram a realização desta dissertação.

palavras-chave

Processo de Desenvolvimento de Produto, Modos de Inovação, Riscos e Incertezas, I&D, Bens de Equipamento, Engenharia por encomenda, PME.

resumo

A inovação de produto é um processo subtil, conduzindo frequentemente a alteração dos factores de competitividade das organizações. Desenvolver produtos num ambiente de constantes mudanças tecnológicas está sujeito a riscos e falhas frequentes, mesmo em organizações sofisticadas e bem estabelecidas. Para lidar com a incerteza na inovação, as organizações utilizam diversos processos de inovação.

Do ponto de vista teórico, a literatura genérica sobre o processo de desenvolvimento do produto é explorada e depois comparada com a escassa literatura específica sobre a engenharia por encomenda (ETO), contribuindo assim para ajudar expor ou colmatar a lacuna. Um resultado importante encontrado inclui a completa ausência do modo ETO na literatura sobre o processo de desenvolvimento do produto.

Do ponto de vista da inovação de produto a nível do projecto, é explorada as diferentes perspectivas dos processos, modos de inovação e incertezas na indústria de bens de equipamento. Desse ponto de vista mais prático, a contribuição desta dissertação é na análise de quatro casos de estudo de produtores líderes de bens de equipamento, relativo á inovação de produto, tendo em conta o contexto e características específicas deste sector da indústria, as incertezas no projecto, os modos de inovação, e o peculiar processo de inovação da ETO. Desta forma, é explorada as principais características destas empresas com implicação para a inovação, e análise de incertezas dominantes associados ao seu processo e modos de inovação. Outro resultado inclui a completa ausência do modo de inovação baseada na experiência (DUI) nos casos estudados, e até a característica de baixa aprendizagem em uma das empresas. Adicionalmente, é apresentado um processo ETO apurado empiricamente com resultados encorajadores, e finaliza sugerindo direcções interessantes para futuras pesquisas.

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keywords

Product Development Process, Modes of Innovation, Risks and Uncertainties, R&D, Capital Goods, Engineer-to-order, SME.

abstract

Product innovation is a subtle process, frequently leading to shifts in the competitiveness of firms. Developing products in an environment undergoing technological change is given to frequent failure, even in well-established and sophisticated organizations. In order to tackle competitiveness and to deal with innovation uncertainty, firms develop diverse innovation processes.

From a theoretical perspective, the general product development process (PDP) literature is explored and further compared with the scarce specific literature identified, contributing to expose or bridge the gap in the literature. Key findings include the complete absence of engineer-to-order (ETO) operations mode in the PDP literature.

Looking at product innovation at project level, it is explored the different perspectives of processes, modes of innovation and uncertainty in capital goods industry. From this practical perspective, this dissertation's contribution is on the case study analysis of four leading capital goods producers concerning product innovation, giving the context and specific characteristics of the industry sector, the project uncertainties, the modes of innovation, and the particular engineering-to-order innovation process. Doing so, it is explored the main features of these producers with implications for innovation, and analyse the dominant uncertainties associated to their innovation process and modes of innovation. Key findings include the complete absence of the experience based innovation mode (DUI) in the cases studied, and even a low learning characteristic in one company. Additionally, it is presented an empirically-based ETO-process with encouraging results, and ends up suggesting interesting directions for further research.

Mais vale responder de forma incompleta a uma pergunta pertinente, que responder completamente a uma pergunta irrelevante.
in Leite, J. C. (2007), Metodologia de Investigação, Universidade de Aveiro.

CONTENTS SUMMARY

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Abbreviations & Acronyms

AEP – Portuguese Entrepreneurial Association

AdI – Innovation Agency

ATO – Assemble-to-order (operations mode)

CE – Concurrent Engineering

CMMI-DEV – Capability Maturity Model Integration for Development

CMTO – Customised Make-to-order (operations mode)

DUI – Doing, Using and Interacting (mode of innovation)

EU – European Union

ETO – Engineer-to-order (operations mode)

ISO - International Organization for Standardization

IPD – Integrated Product Development

MC – Mass Customization

ME – Mechanical Engineering

MP – Mass Production

MTO – Make-to-order (operations mode)

MTS – Make-to-stock (operations mode)

NACE – Statistical Classification of Economy Activity in the European Union

NITEC – Small R&TD teams in enterprise sector (with public funding)

NPD – New Product Development

OSL – Order-independent Specification Level

PD – Product Development

PDCA – Plan, Do, Check and Act

PDP – Product Development Process

PLM – Product Life-cycle Management

R&D – Research and Development

R&TD – Research and Technological Development

SCTN – National Scientific and Technologic System

SME – Small and Medium Enterprise

STI – Science, Technology and Innovation (mode of innovation)

TTM – Time-to-market

PART I - INTRODUCTION AND CONTEXT

1. INTRODUCTION

This chapter introduces the research setting upon which this dissertation is based. The introduction consists on the definition of the problem, scope, aim and objectives, following a description of the research programme of this dissertation. In addition, the dissertation structure is presented with a brief description of each chapter.

1.1. Problem definition

The original setting of this dissertation is related with the research agenda of a particular research project in the University of Aveiro. That is, following a work assignment as assistant researcher of the Enterprise Competitiveness Research Centre (CECE), in a project called Enterprise of the Future (EdF). This project was divided in two key research areas, Industry and Tourism. The main theme of the industry research assignment quickly became the research theme of this dissertation – the study of innovation in the capital goods industry. In this context, the industrial product innovation is viewed as a major determinant of competitiveness of firms (Varum *et al.*, 2009). Moreover, the capital goods industry sub-sector was chosen due to the relevance of this industry in the Aveiro region. In section 2.2 it is discussed in more detail the relevance of the capital goods industry, at both national and European level.

Capital goods production constitutes an important industry of the economy. The main activities of these firms are the design, manufacture, and construction of machinery and equipment. They supply highly customized products, in low volume, on a make-to-order (MTO) or engineer-to-order (ETO) basis. Their markets are usually mature and cyclical with supply exceeding demand and customers requiring faster and more reliable delivery. This industry plays a key role in the economy as supplier of capital goods (machinery and equipment) for all other sectors. Hence, it determines overall productivity and acts as catalyst for technological innovation. Therefore, the performance of all economy is dependent on a highly efficient mechanical engineering (ME) sector.

Within the context of the EU expansion to the East and the increasing role played by emergent economies in the international commerce, Portuguese capital goods industry faces escalating competition, where only those able to offer the best mix of product and services with competitive price will survive.

Those factors contribute to and require a competitive and efficient innovation process. However, the literature addressing the specificities of innovation at companies that produce in response to customer’s orders is astonishingly modest (Hicks *et al.*, 2001). These companies have been consistently neglected by academic research, as already stated by many authors (Lu *et al.*, 2008; Rahim and Baksh, 2003; Hicks *et al.*, 2001; Maffin and Braiden, 2001; Alderman *et al.*, 2001). In addition, most of the tools and frameworks for innovation process are mainly meant for large volume manufacture or what is classified as make-to-stock (MTS) manufacture. However, as production volumes become smaller, there is a need to address problems of manufacturers that produce small volume of products to meet the needs of specific customers. Producers of capital goods face high levels of uncertainty, namely in terms of specification, demand, and duration of processes and lead-times (Hicks *et al.*, 2000), which makes the whole planning and control of the innovation process difficult. Due to the differences in operations and product design activities between MTS and ETO, a study of four popular models for product development process (PDP) found that they were not suitable for ETO (Rahim and Baksh, 2003).

All these make the capital goods design, development and manufacturing to be an interesting area to study and research the management of product innovation. Consequently, it is relevant to study the innovation in capital goods, by identifying and analysing the steps and activities taken along the innovation process, the uncertainty factors and how firms cope with them, the innovation modes and learning dimensions practiced by these firms.

1.2. Research scope, aim and objectives

The scope of this dissertation is mainly located within product innovation management. Organized around the study of product development processes, modes of innovation and risk management, the scope covers these three dimensions of product innovation and development, at both business and project level, in the capital goods industry context.

The main *aim* of this dissertation is to *provide a better insight into innovation process in capital goods producers*, focusing on issues regarding management of development and manufacturing of machinery and equipment.

To accomplish these aims, a number of research objectives have to be addressed. The research objectives of this dissertation are:

1. To understand the particularities of developing and manufacturing engineered-to-order (ETO) capital goods;
2. To review the literature on theoretical models of product development process and to evaluate them in terms of their applicability to the capital goods industry;
3. To evaluate the apparent gap in the literature, *i. e.* to confront the claim that ETO companies and their innovation process have been neglected by academic research;
4. To evaluate how these capital goods' producers pursue product innovation in practice, i.e. the processes and modes of innovation used, and to evaluate the typical challenges and uncertainties they face.

1.3. Research programme

The programme of this dissertation was developed in order to achieve the above-mentioned aims and objectives. After setting the problem that this thesis aims to solve and describing the specific industrial context, two strategic stages were designed:

- *Analysis of process models theory*:

  One purpose of this dissertation is on the analysis of the current state of knowledge related to innovation process in capital goods ETO industry, giving the context and specific characteristics of this sector. Therefore, the general literature is explored and further compared with the scarce literature identified addressing ETO-process;
- *Analysis of innovation practice in the capital goods industry*:

  The empirical study is conducted in the Aveiro region, Portugal, a region where the capital goods industry is particularly important and dynamic. It is also a region characterized by small and medium-sized firms. The approach was as follows:

  A number of capital goods producers from the Aveiro region were initially selected according to their official economic activity classification (NACE / CAE 29 Rev.2), size and innovative capabilities. *In sito* research has been undertaken through interviews in the companies selected. The interviews focused on modes of innovation, identification of sources of risk and uncertainty, and on their product development process.

1.4. Dissertation outline

This dissertation is organised as follows (figure 1): after the contextualization of *chapter 2*, *chapter 3* reviews the theoretical models of product development process in the literature, which leads to a more detailed bibliometric analysis of the literature in *chapter 4*. *Chapter 5* explores the theoretical aspects that support the industrial case studies on innovation practice conducted in *chapter 6*. Finally, *chapter 7* discusses and summarizes the main findings of the research.

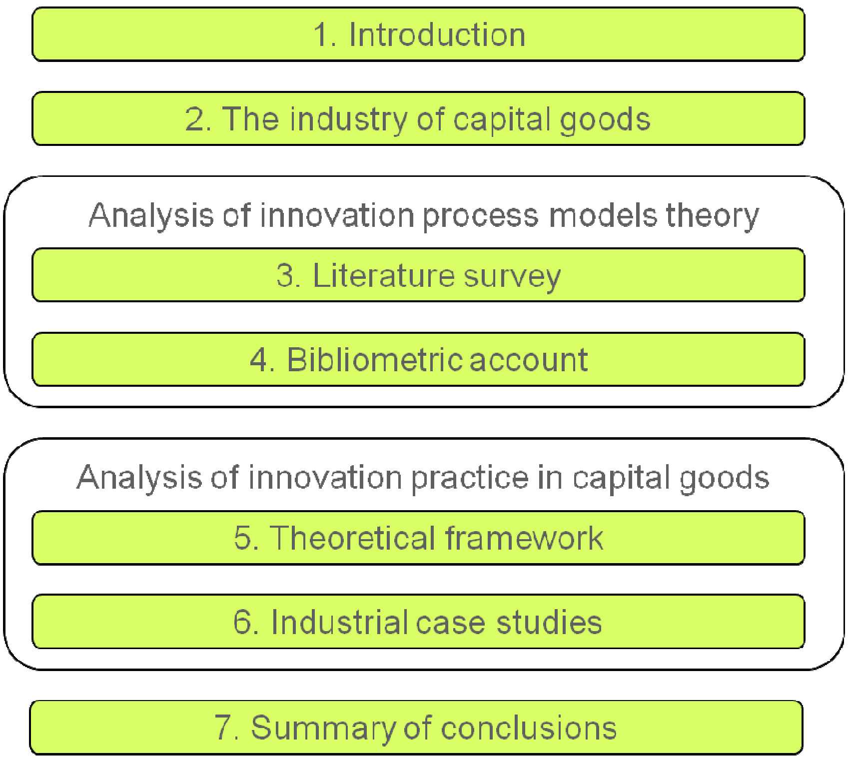

Figure 1. Dissertation outline

2. THE INDUSTRY OF CAPITAL GOODS

This chapter introduces the context upon which this research was made, namely the relevance, the particularities and distinguishing features of the industry under focus.

2.1. The relevance of the Industry

Manufacturing of capital goods (machinery and equipment) is included in the broad Mechanical Engineering (ME) industry, one of the largest industrial sectors in the European Union (EU). According to recent data on the European industry (see Table 1), the ME sector corresponds from 7 to 8 per cent of the EU (15) manufacturing in terms of production, employees and value added. Value-added per person employed is lower in machinery and equipment than in total manufacturing, the only exceptions being Germany, Italy and Portugal (Eurostat, 2003). The EU mechanical engineering industry, is highly export oriented, accounting to over 36 percent of the EU manufacturing exports (DG Enterprise, 2007a). The EU is the world’s largest producer and exporter of mechanical equipment.

Germany is the leading European producer and exporter of ME. Portugal by contrast, has one of the smallest ME sector within the EU, and has fallen slightly in recent years (as well as in Italy and Ireland).

Table 1. Figures of the ME Sector in Europe and Portugal

	Production		Exports		Value Added		No. employees		R&D
Countries	Million €	% total Manuf. Industry	Million €	% Total Manuf. Industry	Million €	% total Manuf. Industry	1000 units	% total Manuf. Industry	% Intensity
EU (15)	360.086	7	131.517	36	124.668	8	2.244	7	2,3
Portugal	1.842	n.a.	1.586	n.a.	728	1) 5	26	5	0,5

Portugal data refers to 2006, except 1) that refers to 2000. Sources: DG Enterprise (2007b) and Eurostat (2003).
EU data refers to 2003. Source: DG Entreprise (2004).

The relevance and importance of the ME sector is well beyond the figures presented in Table 1. According to several studies (EnginEurope, 2007; DG Enterprise, 2004; IFO, 1997) ME is a highly innovative and globally active industry, where small and medium enterprises (SME), mostly family owned, predominate. This sector plays a key role in the economy as supplier of capital goods for all other sectors. Hence, it determines productivity and acts as catalyst for technological innovation. Thus, on the one hand, the performance of all industries is dependent on a highly efficient ME sector. On the other hand, the industries included in the sector are particularly vulnerable to cyclical fluctuations in economic activity. Not only are their main customers other manufacturers but a large part of their sales is directly linked to investment, which tends to vary much more than in proportion to activity.

Established producers in Europe face competitive threats from within and from outside Europe. Competition with suppliers of mechanical equipment from new member states poses a competitive threat to traditional European producers. The challenges are probably greater for countries like Spain and Portugal who are further away from the centre of gravity of the EU market, supply overlapping product ranges, occupy an overlapping market position, are not far ahead in technology, and still compete on below EU-average labour costs (DG Enterprise, 2004).

According to the reports mentioned above, the competitiveness of European firms in this sector rests mainly on the scale of the market, on the ability to solve customers' problems, on the possession of key expertise, and on product quality. Not surprisingly, there is a high degree of specialization, and many firms are niche players.

After describing the ME sector in general, as the key supplier of capital goods to all other industries and sectors, this dissertation focuses on the specific case of capital goods companies belonging to NACE "Subsection DK.29: Manufacture of machinery and equipment n.e.c.". In a sectoral characterisation suggested by OECD (1987), the capital goods subsector, and the NACE.29 in particular, is described as an industry where the capacity to differentiate products is the main factor of competitiveness.

These factors contribute to and require a competitive and efficient innovation process. Producers of capital goods face high levels of uncertainty, namely in terms of specification, demand, and duration of processes and lead-times, that may make the whole planning and control of the innovation process difficult. Hence, it is relevant to study those uncertainty factors and analyze how firms cope with them. Therefore, the focus is on the relationship between the mode of innovation and risk and uncertainty in the innovation process. This dissertation addresses this relationship in four competitive firms operating in the capital goods industry located in the Portuguese region of Aveiro.

2.2. Characteristics of the industry: the low volume engineering-to-order

"The *low-volume industries* cover a wide range of companies associated with *capital goods* and intermediate product markets. Their products tend to be manufactured for downstream industrial producers to use in the production of other goods and services, rather than for final or household markets" (Maffin and Braiden., 2001). "These range from large, complex, high-value capital goods (e.g. offshore structures, power generation plant, etc.) through to low-complexity intermediate products (e.g. pumps, valves, etc.) and are supplied to a range of industries (e.g. mechanical handling, power generation, oil exploration and recovery)."

"The characteristics of companies in the low-volume industries (*i. e.* organisation, products, markets, and so forth), their competitive environments and their range of strategic and operational choices, are both complex and diverse. Companies frequently serve, and have to be responsive to, a number of different markets, being subject to different competitive environments, and having different positions, roles and influences within supply chains, for example" (Maffin and Braiden., 2001). In addition,"a distinctive feature of the development of products in engineering companies is the need to *manage* various types of development project". These include "*contract projects* where the product is developed to a customer's particular requirements, and *product development projects* to develop a new or improved product either for sale as a standard item or customising to customers' individual requirements. The diversity of context in which products are developed will give rise to differing requirements and company practices vis-à-vis the roles of manufacturing and suppliers in product development. Interpreting the recommendations of best-practice in relation to the innovation process inevitably represents a significant challenge to many companies" (Maffin and Braiden., 2001).

In order to show the particularities of low-volume industries, Lu *et al.* (2008) made a key business process comparison between mass production (MP), mass customization (MC) and engineer-to-order (ETO) companies. Figure 2. shows the relationship between volume and variety for different company types, and which influences the sequence of their key business process in figure 3.

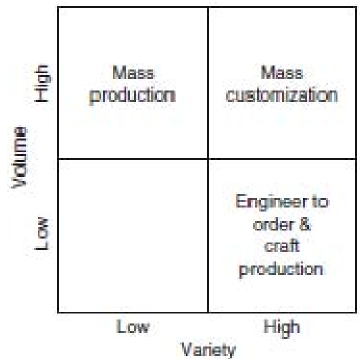

Figure 2. Relationship between volume and variety for different company types (Lu *et al.*, 2008)

The distinct characteristics of engineered-to-order capital goods products contribute to and require a competitive and efficient innovation process. Producers of capital goods face significant financial and commercial risk and high levels of uncertainty, namely in terms of specification, demand, and duration of processes and lead-times, that may make the whole planning and control of the innovation process difficult. "The overlapping of manufacturing and design activities as well as engineering revisions often complicates production. This is a major source of uncertainty, which complicates the management of capital goods manufacturing" (Hicks *et al.*, 2000).

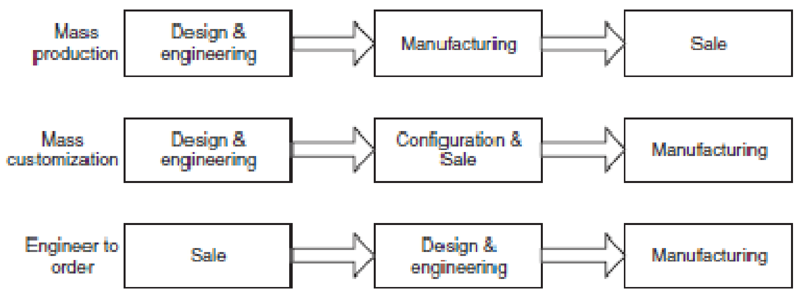

Figure 3. The sequence of key business processes in MP, MC, and ETO companies (Lu *et al.*, 2008)

However, the literature addressing the needs of companies that produce in response to customer's orders is astonishingly modest. These companies have been neglected by academic research. The limited research that has been undertaken in the low-volume engineer-to-order sector has focused on production control, information systems, manufacturing systems, and the coordination of marketing and manufacturing. Research relating to make-to-order (MTO) companies has focused on strategy and on planning in subcontract engineering job-shops (Hicks *et al.*, 2001).

In addition, most of the tools and frameworks for innovation process are mainly meant for large volume manufacture or what is classified as make-to-stock (MTS) manufacture. However, as production volumes become smaller, there is a need to address problems of manufactures that produce small volume of products to meet the needs of specific customers. Due to the differences in operations and product design activities between MTS and ETO, a study of four popular models for product development process (PDP) found that they were not suitable for ETO (Rahim and Baksh, 2003). Consequently, this new orientation will require a modified new product development (NPD) process for engineered-to-order products.

2.3. Concluding remarks

This chapter introduced the context upon which this research was made, the relevance of the industry of capital goods, for both in Portugal and in Europe, the particularities and distinguishing features of this low volume engineering-to-order industry.

A brief comparison of this sub-sector with the more traditional high volume MTS operations mode was also made. It finished describing the alleged gap of academic research addressing the needs and behaviour of the companies operating in these industries.

PART II – ANALYSIS OF INNOVATION PROCESS MODELS THEORY

3. LITERATURE SURVEY

3.1. Introduction

This chapter introduces and complements the main research themes identified in new product development (NPD) literature by an early review (Craig and Hart, 1992), and provides an overview of popular process models, setting the basis for the bibliometric analysis of the next chapter. One of the objectives of this dissertation is the analysis of the current state of knowledge related to innovation process in engineering-to-order (ETO) capital goods industry, giving the context and specific characteristics of this sector, and the particular product development process compared with the main literature. Therefore, an overview of popular theoretical models is provided, and further analysed in terms of their target organizations, in order to explore the mentioned gap in the innovation process development literature.

3.2. Main research themes

3.2.1. Introduction

Angie Craig and Susan Hart (1992), in their review on new product development (NPD) research over 30 years, take the reader through the literature into the dynamics of NPD. The article considers and comments on the variety of approaches reported in the literature, describes the plethora of "critical success factors" thrown up by the *generalist* studies in NPD in order to identify the recurring themes within the literature, and focuses on these prevalent research themes to explore the particular research interests within each (the *specialist* approach). Therefore, the authors divided NPD research into generalist and specialist approaches.

3.2.2. Critical success factors

The generalist approach includes key research studies which have sought to identify the critical success factors in NPD, by specifying a set of variables and measuring the relationship between these variables and the outcome of NPD activities – whether success or failure.

According to Craig and Hart (1992), the results of the generalist studies in NPD tend to be quite similar, and for that reason, it is possible to collapse the long list of critical success factors that result down to a number of key themes. The themes capture the similarities between the variety of factors cited, while highlighting the differences between particular areas of interest.

Therefore, the detailed content analysis of the generalist NPD research literature and subsequent method of categorization, and refinement, derived the following key themes:

- **Product development process (PDP):** timing, pre-development activities, development activities, marketing activities, launch activities;
- **Management:** authority, support, technical aspects, communication;
- **Information:** general, marketing, external, communication;
- **Strategy:** orientation, objectives, synergy, product characteristics;
- **People:** multi functional, co-ordination, product champion, communication;
- **Company characteristics:** technological prowess, existing credibility.

Taking the lead from the generalist approach, the specialist studies include those researchers that have made in-depth investigations of particular issues under each of the key research themes, and this lead to a number of different areas of research under each main theme.

The specialist approach is then divided in strategic and project themes. The authors points to a natural split in the themes between those regarding NPD projects, *i. e.* the way in which products are developed, and those related to the way in which an innovating company approaches the development of new products. The former can be referred to as “strategic” and the latter as “project” (see figure 4).

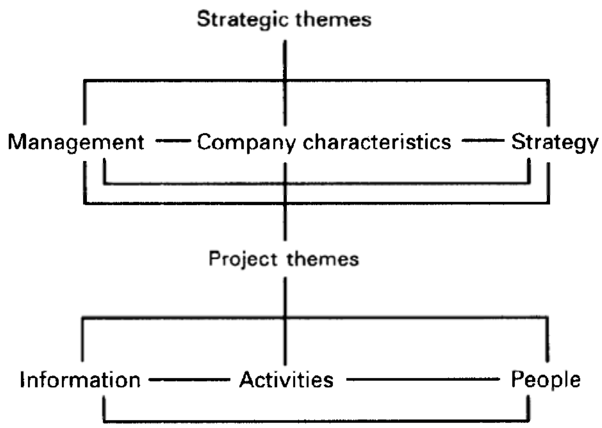

Figure 4. Strategic and Project themes in NPD research (Craig & Hart, 1992)

The strategic issues are relative to the organization in which the innovation is being undertaken. They are not particular to one project, but instead exert an influence over each and every project. This observation is important given the discussion surrounding the different types of product developments. It may be that it is those issues which refer to individual projects, the project themes, which vary by product development, whereas those success factors at the strategic level are more constant over the different types of product development. Furthermore, particular levels of analysis may be better suited to one rather than the other set, e.g. project level of investigation may be better suited to investigating project level factors.

Hence, the project themes of *process*, *people* and *information* are closely interrelated. According to Craig and Hart (1992), the *process* of NPD involves the activities and decisions from the time when an idea is generated until the product is commercialized.

The authors further discuss the research which focuses on the particular activities of the development *process*: the construction of models (*PDP activities*), the proficiency of companies in carrying out these activities (*Completion of PDP activities*), and investigating how the different stages may best be integrated (*Simultaneity of PDP activities*).

3.2.3. Product development process themes

3.2.3.1. Process activities models

According to Craig and Hart (1992), there have been many commentators, from the domains of marketing, management, design and engineering, who have developed normative and descriptive models of the PDP, and a selection of four models were reproduced in their paper as examples.

The authors further consider that the notion of reducing uncertainty as the main objective of the project development activities is reiterated throughout the literature and, since information is closely associated with uncertainty reduction, the project activities can be considered as discrete information processing activities aimed at reducing uncertainty. Therefore, although the *detail of the process models may vary*, they essentially comprise a series of *decisions* that are made by evaluating information of both technical and commercial natures. Indeed by considering the models for product development process (PDP), Craig and Hart (1992) referring to work done by Cooper & Kleinschmidt (1986, 1987, 1990), state very clear that the *evaluation activities* within the process are extremely important. Evaluation activities include gathering and disseminating information and making decisions based on this information. Particular reference is made by Cooper & Kleinschmidt (1986, 1990) to "initial screening; preliminary market assessment; preliminary technical assessment; detailed market study or marketing research; and business/financial analysis". Cooper (1988) argues that evaluation activities should be carried on throughout the process, and suggests that decision points should be set up at different stages of the project, in order that the quality and progress can be checked. The main point made by the writers who consider the importance of evaluation activities is that they must include evaluations of both market and technical aspects and Cooper & Kleinschmidt (1987) emphasize that market and technical appraisals should precede any serious development activities.

There have been many models of the PDP, developed by the authors from various domains and with different purposes and techniques. Process modelling consists essentially in the design, modelling and implementation of PDP models.

There are various purposes for modelling and simulation of process. For example, models may be more appropriate for visualization, planning, execution and control, or improvement and optimization of the processes. Applications of process modelling for process improvement comprise, according to Wynn (2007), knowledge capture, management support and process analysis and reconfiguration.

3.2.3.2. Completion of process activities

According to Craig and Hart (1992), the models of PDP tend to be idealized and, for this reason, may be quite far removed from reality. To provide an empirical contribution, which explores the relationship between these models and the actual development activities which firms carry out, a number of authors have researched the extent to which the prescriptive activities of the PDP take place. Cooper & Kleinschmidt (1986) investigated the product development activities of 203 NPD projects. They used a "skeleton" of the process, taken from a variety of normative and empirically based prescriptive process developed by other authors, which has 13 activities as detailed below:

1) Initial screening;
2) Preliminary market assessment;
3) Preliminary technical assessment;
4) Detailed market study/market research;
5) Business/financial analysis;
6) Product development;
7) In-house product testing;
8) Customer tests of product;
9) Test market/trial sell;
10) Trial production;
11) Pre-commercialization business analysis;
12) Production start-up;
13) Market launch.

They found that there is a greater probability of commercial success if all of the project activities were completed. It should be emphasized that these studies refer to "new" product developments and that in the case of, for example, product improvements there may be very sound reasons for skipping some of the steps in the prescribed process (Craig and Hart, 1992). Further, while it may be desirable to have a complete process of NPD, each additional activity extends the overall development time and may lead to late market introduction. Therefore, a *trade-off* has to be made between completing all the suggested activities in the product development process and the time which these activities take. The importance of *timing* in the PDP is emphasized by earlier studies (Craig and Hart, 1992).

3.2.3.3. Simultaneity of process activities

In recognition of the time pressures facing those developing new products, some authors suggested that there should be "parallel processing" (Craig and Hart, 1992). This means that the PDP activities are performed parallel in time, which Takeuchi & Nonaka (1986) refer to this as the "holistic" or "rugby" approach to product development process, as opposed to the traditional, linear or "relay race" approach. In this method of PDP the stages of the process, rather than being sequential, overlap. The concept of parallel processing differs from the type of development process described in the traditional models. While some models allow for interfaces between the different stages of development by way of feedback loops, parallel processing means that the stages actually overlap. The extent to which stages overlap may vary from project to project (Craig and Hart, 1992).

An integrated process has a number of benefits (Craig and Hart, 1992). The first has already been hinted at, namely the reduction of time to market, allowing for a more complete and therefore potentially more successful process without incurring the penalty in profits. The second benefit of an overlapping is that there is a smoother transition between phases and therefore the bottlenecks which often occur in a sequential process causing slowing, and sometimes halting, the whole development are avoided. Takeuchi & Nonaka (1986) also indicated a number of "soft" advantages relating to those who are involved, sharpened problem solving focus, initiative, diversified skills and heightened sensitivity towards market conditions.

3.2.4. Information, communication and collaboration

Information, communication and collaboration are important concepts for NPD, and in which exist evident links between them. Craig and Hart (1992) in their review on NPD research argue that while information is referred to throughout the literature on NPD, especially in relation to the process and functional co-ordination themes, it does not receive specific research attention. The information which is fed in to the new product development process, the way in which it is disseminated and, as a consequence, the degree of communication within the organization, have been identified as important issues in determining the outcome of NPD. Moreover, the authors advocate that the essence of the NPD process (or PDP) is the information inputs, both technical and commercial, on which the evaluation and decision are based, and that similarly, information is the key to communication throughout the process and is therefore an essential element in helping to foster a spirit of integration. Despite the importance of process activities integration and cross-functional communication, Craig and Hart (1992) in their review identified few studies dealing with information, its quality, dissemination and use, and as a result, the authors suggested on the need for specific research attention to focus on information within NPD.

Another important related concept is collaboration. Collaboration is, according to Elfving (2007), dependent on communication between individuals. To have collaboration, in the easiest form, communication and exchange of information is needed. To exchange knowledge, a higher level of collaboration is needed (see Nonaka and Takeuchi, 1995). Depending on how distributed the collaboration is, different means of communication are needed.

Meanwhile, since the extensive review on NPD research made by Craig and Hart in 1992, our world has experienced many changes due to the rapid emergence and evolution of new Information and Communication Technologies (ICT), leading to and supporting what is called nowadays as the knowledge-based economy. As a result, a new research agenda on Information Technology (IT) and Product Development has emerged (Nambisan, 2003). The infusion of IT in NPD contributed to a growing perspective on NPD research as an IT-enabled innovation process (see for instance: Büyüközkan *et al.*, 2007; Nambisan 2003; Balakrisham *et al.*, 1999; Salminen *et al.*, 2000; Ozer 2000; Yassine, *et al.*, 2004). This new research topic, IT-enabled NPD processes, have been referred to in many ways, for example, as the *IT driven Product Development* - IT-PD (Joglekar and Yassine, 2001), as the *Electronic New Product Development* - e-NPD (Yang and Yu, 2002; Büyüközkan *et al.*, 2007), and as the *Distributed* or *Collaborative Product Development* – CPD (Tseng and Abdalla, 2006; Salminen *et al.*, 2000). These IT-enabled NPD processes are somewhat very similar and often used with the same meaning.

The key focal themes and issues of this new research agenda are, according to Nambisan (2003), the knowledge management (KM), the support for collaborative and distributed innovation, and the integrated process and project management.

3.2.5. Summary

This section introduced and complemented the main research themes identified in NPD literature by an early review (Craig and Hart, 1992). Despite recognizing the importance of information and communication, Craig and Hart (1992) identified few studies dealing with these issues, and as a result, the authors called for a specific research attention on information within NPD. The answer came few years later with the emergence of a new research agenda on Information Technology (IT) and Product Development, or the IT-enabled NPD process.

The overall research themes identified are used to generate the list of major terms of the literature applied in the bibliometric account: NPD terms (generalist literature) and the PDP terms (project literature).

One of the objectives of this dissertation is the analysis of the current state of knowledge related to innovation process in capital goods ETO industry. In the next section is provided an overview of twelve common process models.

3.3. Overview of development process models

3.3.1. Introduction

Firstly, one should conceptualize some terms in order to improve understanding of this dissertation. A *model* is an abstract representation of reality that is built, verified, analyzed, and manipulated to increase understanding of that reality. Models can reside in the mind (mental models) or be codified (Browning *et al.*, 2006). A *process* is "an organized group of related activities that work together to create a result of value". According to Ulrich and Eppinger (1995) a *process* is a sequence of steps that transforms a set of inputs into a set of outputs.

Therefore, a *product development process* (PDP) is the sequence of steps or activities that an enterprise employs to conceive, design, and commercialize a product. Moreover, many of these steps and activities are intellectual and organizational rather than physical (Ulrich and Eppinger, 1995). There are different terminologies in the literature for a PDP. Some of the common terminologies include *Product Creation Process, Product Realisation Process* and *Product Design Process* (Ulrich and Eppinger, 1995).

Some organizations define and follow a precise and detailed development process, while others may not even be able to describe their process. Furthermore, every organization employs a process at least slightly different from that of every other organization. In fact, the same enterprise may follow different processes for each of several different types of development projects.

A well-defined development process is useful for several reasons, as for quality assurance (assuring the quality of the resulting product), coordination (defining the roles of each of the players on the development team), planning (containing natural milestones corresponding to the completion of each phase), management (assessing the performance of an ongoing development effort by comparing the actual events to the established process) and improvement (documentation of process often help to identify opportunities for improvement).

In the following sections, it is presented an overview of product development (PD) processes and models, after describing the different categories of models identified in the literature. Due to the large quantity of literature on this subject, it is selected some exemplary approaches which is believed that most influenced on research or practice.

3.3.2. Categories of models

The organizational activities undertaken by the company in the process of developing new products have been represented by numerous models. These product development (PD) models can be considered as guidelines for the management of the PD process (Trott, 2005). Among the management literature on the subject it is possible to classify the numerous models into seven distinct categories (Trott, 2005; Hart & Baker, 1994):

1. departmental-stage models;
2. activity-stage models;
3. cross-functional models;
4. decision-stage models;
5. conversion process models;

6. response models;
7. network models.

1. The *departmental-stage* models view the PD process in terms of the departments or functions that hold responsibility for various tasks carried out. This basic and traditional approach has a sequential character, which means that the project moves step by step from one phase/ department to the next one. Such models are also referred to as 'over-the-wall' models, so called because departments would carry out their tasks before throwing the project over the wall of the next department (Trott, 2005). This insular departmental view of the process hinders the development of new products (Trott, 2005). It is widely accepted that the "pass-the-parcel" approach to PD from one department to the next, is deficient in several respects (Hart & Baker, 1994). This both increases the time from product concept to product launch and increases the number of engineering changes late in the process. Also implicit in the term 'over the wall' engineering is a complete lack of team working and understanding of other department's problems, which can result in late, over-expensive and poor quality products.

2. *Activity-stage* models are initially similar to departmental-stage models, improving though in that they focus on actual activities carried out, including various iterations of market testing. They also facilitate iteration of the activities through the use of feedback loops, something that the departmental stage models do not. Activity-stage models, however, have also been criticized for perpetuating the 'over-the-wall' phenomenon, since the activities are still seen to be the responsibility of separate departments of functions (Hart & Baker, 1994). Refinements to the activity-stage models have been proposed in order to counter this problem and more recent activity-stage models have highlighted the simultaneous nature of the activities within the PD process, hence emphasizing the need for a cross-functional approach.

3. Common problems that occur within the PD process centre on communications among different departments. In addition, projects would frequently be passed back

and forth between functions. Moreover, at each interface the project would undergo increased changes, hence lengthening the product development process. The *cross-functional teams* approach removes many of these limitations by having a dedicated project team representing people from a variety of functions (Trott, 2005). This approach has a parallel character that speeds the process by relying on project teams whose members work together from start to finish. Substantial savings are made due to the more intensive work and to the improved spontaneous co-ordination.

4. *Decision-stage* models describe the PD process as a series of decisions or evaluation points, where the decision to carry on or abandon the project is made. Like activity-stage models, many of these models also facilitate iteration through the use of feedback loops. However, a criticism of these models is that such feedback is implicit rather than explicit (Trott, 2005). And yet, such feedback loops are critical, since the PD process is one of continual refinement, until an ideal technical solution, which is easily manufactured and still relevant to customer needs, is produced (Hart & Baker, 1994).

5. *Conversion-process* models view PD as numerous inputs into a 'black box', where they are converted into an output, in an attempt to eschew the imposed rationality of departmental-based, activity-based and decision-based models. For example, the inputs could be customer requirements, technical ideas and manufacturing capability and the output would be the product. Such a holistic view underlines the importance of information in the process, but the lack of detail is the biggest limitation of such models (Hart & Baker, 1994).

6. *Response* models exploit a behaviourist approach to analyse change at the beginning of the PD stage. In particular, these models focus on the individual's or organisation's response to a new project proposal or new idea. This approach has revealed additional factors that influence the decision to accept or reject new product proposals, especially at the screening stage (Trott, 2005; Hart & Baker, 1994).

7. *Network* models suggest that PD should be viewed as a knowledge-accumulation process that requires inputs from a wide variety of sources. Various parties, both internal and external to the firm, are portrayed as key players throughout the process (Hart & Baker, 1994). The knowledge-accumulation process is built up gradually over time as the project progresses from initial idea through development. Basically, network models, which represent the most recent thinking on the subject, emphasise the external linkages coupled with the internal activities that have been shown to contribute to successful product development (Trott, 2005).

Some of these models represent a generalised and theoretical view of the process. However, according to Trott (2005) most commonly discussed and presented models in literature are *activity-stage* and *decision-stage* models. Actually, a stage-gate representation for PD, which is a combination of activity-stage models and decision-stage models, is a common tool used within organisations today to facilitate the process. The most practiced PD models are activity-stage models and decision-stage models because they explicate the steps in the process and define a roadmap from idea to launch. Indeed, Cooper, Edgett & Kleinschmidt (2004) identified the use of a systematic process with stages, stage activities, gates, deliverables, and gate criteria as the strongest practice observed in their sample of businesses.

3.3.3. Summary of common models

There may be as many models and approaches as companies in the world, because the innovation process must always be adapted to the way they do business. Due to the large quantity of literature on this subject, it is selected twelve exemplary approaches which is believed that most influenced on research or practice. Therefore, it is presented a summary of twelve different product development theories identified and how they relate to different approaches, based on and extending early reviews made by Elfving (2007) and Rahim and Baksh (2003).

The content of the different authors' approaches are categorised according to their major theme, as illustrated in tables 2, 3 and 4.

Table 2. Common models – Process activities model theme. Inspired in Rahim & Baksh (2003) and Elfving (2007)

Authors	Target organization	Type of process	Phases	Focus	Major theme	Category
Kotler (1980)	MTS	Generic	1 Idea generation 2 Screening 3 Concept development & testing 4 Marketing strategy 5 Business analysis 6 Product development 7 Market testing 8 Commercialization	Market-orientation. Key role of marketing & business planning.	Process activities model	Activity-stage model
BSI (1989)	MTS	Generic	1 Trgger 2 Product planning 3 Feasibility study 4 Design 5 Development 6 Production 7 Distribution 8 Operation 9 Disposal	General approach. Idealized product evolution	Process activities model	Activity-stage model
Pugh (1991)	MTS	Generic	1 Market needs 2 Task clarification 3 Concept design 4 Detail design 5 Production 6 Marketing and sales	Emphasis on design flow. Technical areas, relevant for design engineers.	Process activities model	Activity-stage model
Peters et al. (1999)	MTS	Generic	1 Idea 2 Concept 3 Design 4 Pre-production validation 5 Production / distribution 6 Post-company	Comprehensive. Facilitation issues, process summary, tools & techniques	Process activities model	Activity & decision-stage model

By analysing the summary tables 2, 3 and 4, one can notice that there are no clear boundaries between the twelve different approaches presented, and many of them merge. Following a similar review made by Elfving (2007), one can also observe that these models have much in common, consisting of variants of the following phases:

1. recognition of need;
2. planning;
3. concept development;
4. detail design;
5. testing and validation;
6. production preparation;
7. launch.

These phases are typical of innovation process meant for large volume manufacture and reflect MTS operations mode. Considering the characterization of ETO capital goods industry and the clear differentiation of key business process between mass production and engineer-to-order, one can conclude that the process models here exemplified:

i) are not suitable for ETO capital goods producers;

ii) reflects high-volume MTS operations mode.

Table 3. Common models – Process activities model & simultaneity theme. Inspired in Rahim & Baksh (2003) and Elfving (2007).

Authors	Target organization	Type of process	Phases	Focus	Major theme	Category
Andreasen & Hein (1987)	MTS	Integrated Product Development	1 Investigation of need 2 Product principle 3 Product design 4 Production preparation 5 Execution	The interfaces between product design, productiion & marketing.	Process activities model & simultaneity	Activity & decision-stage model
Boothroyd et al. (1994)	MTS	Concurrent Engineering	1 Design concept 2 Design for assembly 3 Selection of materials & process, early cost estimates 4 Best design concept 5 Desugn for manufacture 6 Prototype 7 Production	Emphasis on minimum manufacturing cost & DFMA techniques. Meant for designers.	Process activities model & simultaneity	Activity & decision-stage model
Ulrich & Eppinger (2000)	MTS	Product design / Generic	0 Planning 1 Concept development 2 System-level design 3 Detail design 4 Testing & refinement 5 Production ramp-up	Marketing, design & manufacturing.	Process activities model & simultaneity	Activity & decision-stage model
Carlson-Skalak (2002)	MTS	Concurrent Engineering	1 Project planning 2 Product design & development 3 Production process development 4 Production prepararing 5 Production service	The interaction between product development & production. IT-tools.	Process activities model & simultaneity	Activity & decision-stage model

These twelve common models analyzed encompass typical features described earlier by Rahim and Baksh (2003), extending and confirming the results found in his study with four models. These common features reflect MTS operations mode.

Moreover, these models do not address the particular needs and problems of ETO companies and therefore, are not suitable for ETO products, due to the differences in operations and product design activities between MTS and ETO operations mode (Rahim and Baksh, 2003). The authors pointed six features missing in the four studied models to support this allegation:

1. Do not include external parties in the process (such as customer, supplier, and contractors);
2. Do not show post assembly or post manufacturing activities such as delivery, commissioning, handover to the customer, which is common for ETO product;
3. Do not show concurrency between activities;
4. Targeted for designers and manufacturers and leave out other parties;
5. Do not show the use of CE tools and techniques in detail at different stages;
6. Flow of activities represents MTS operations.

Table 4. Common models – Process activities model w. evaluation gates & simultaneity theme. Inspired in Rahim & Baksh (2003) and Elfving (2007).

Authors	Target organization	Type of process	Phases	Focus	Major theme	Category
Ottoson (1999)	MTS	Dynamic Product Development	1 Concept development & administration 2 Product development 3 Process development 4 Marketing and sales 5 Production	Creativity & end-user. Dynamic organization.	Process activities model w. evaluation gates & simultaneity	Activity & decision-stage model
Cooper (2001)	MTS	Stage-Gate	1 Discovery 2 Scoping 3 Building the business case 4 Development 5 Testing and validation 6 Launch	The quality of execution, market-orientation, resource focus. The gates where the decisions are made.	Process activities model w. evaluation gates	Activity & decision-stage model
Ullman (2003)	MTS	Generic	1 Project definition & planning 2 Specification definition 3 Conceptual design 4 Product development 5 Product support	General approach	Process activities model w. evaluation gates	Activity & decision-stage model
INCOSE (2004)	MTS	System Engineering	1 User requirements 2 System requirements 3 Architectural design 4 Component development 5 Integration & verification 6 Installation & validation	Engineering complex systems. Managing technical complexity. Interdisciplinary approach & means. V-model.	Process activities model w. evaluation gates & simultaneity	Activity & decision-stage model

3.4. Concluding remarks

This chapter introduced and complemented the main research themes identified in NPD literature by an early review (Craig and Hart, 1992), and provided an overview of common process models for product innovation, setting the basis for the bibliometric analysis of the next chapter.

In the second section of this chapter, the overall research themes were identified - by Craig and Hart (1992) and the new ones – which is used to generate the list of major terms of the literature applied in the bibliometric account: NPD terms (generalist literature) and the PDP terms (specialist literature).

The last section of this chapter provided an overview of common process models for product innovation. This comprised the analysis of the applicability of twelve common models, which were found to be not suitable for ETO capital goods operations because they do not address their particular needs and problems. The above mentioned themes and the categories described in section 3.3.2 were used to group and describe these models.

4. BIBLIOMETRIC ACCOUNT

4.1. Introduction

Following the analysis of twelve common models, where none of them were found to be suitable for ETO companies, it became apparent the alleged gap between the models for product development process (PDP) and ETO operations' particular situation. This chapter addresses the bibliometric analysis made on the PDP literature, in search of evidence of the extremely small attention given by research to the ETO operations in general, as mentioned before, and to the ETO development process in particular. After describing the methodological aspects, the results and discussion are presented.

4.2. Bibliometric data

4.2.1. Methodology

The bibliometric analysis was pursued through electronic search on ISI Web of Knowledge (ISI Web of Knowledge, 2008), a comprehensive and versatile research platform on the Web. Two major databases were used: the Science Citation Index Expanded (SCI) and the Social Sciences Citation Index (SSCI). This setting allowed a throughout analysis of published articles, in terms of comprising useful analytical resources on significant journals, scientific research fields, citations and other relevant information.

The research time-span was used in pairs, *i. e.* an extensive and a narrowed search. As pursuing a bibliometric analysis in the extant PDP literature over the last fifty years would be overwhelming, a narrowed search of the last six years (2003-2008) will be carried out, and further compared with some data of the whole period allowed by the platform (1900-2008). In the ETO-process specific literature the extensive search is provided as the small number of publication allows this setting. In terms of research fields, it was included eight categories, allowing the interdisciplinary contribution of different research fields, which characterize the NPD literature: Management, Economics, Business, Operations Research & Management Science, Industrial Eng., Manufacturing Eng., Multidisciplinary Eng. and Multidisciplinary Sciences. The complete methodological steps taken in this analysis is illustrated in figure 5.

The bibliometric analysis of the results comprised both quantitative and qualitative aspects of the articles. The quantitative analysis was based on the indicators automatically generated by the platform. The qualitative analysis was based on abstract and full text content analysis, together with conceptual grouping of the articles.

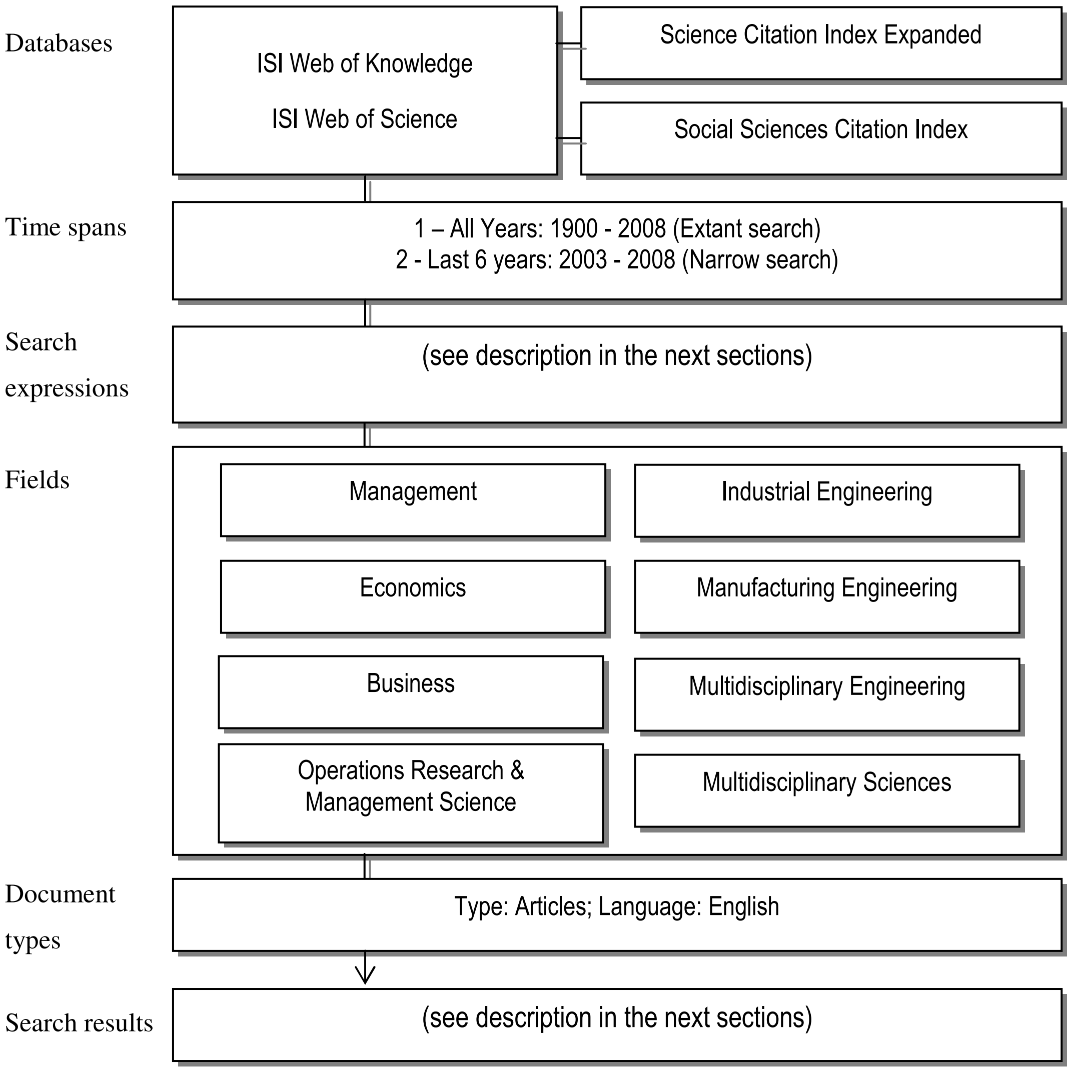

Figure 5. Steps followed in the bibliometric analysis

Although this was settled to allow a throughout analysis of the literature, there is always the possibility of leaving out of this analysis any relevant journal or publication not included in the ISI platform, e.g. the *International Journal of Industrial and Systems Engineering*. Moreover, research papers without the selected keywords in the title, subject or abstract, will not be included in this analysis.

4.3. Results

4.3.1. PDP research: where do we stand?

A systematic search was performed in two databases of ISI Web of Knowledge (ISI-WOK), the Science Citation Index Expanded and the Social Sciences Citation Index. This is initially a twofold research in terms of the publication date range, performing an extensive and global search of all years' time span (1900-2008) and a narrow and refined last six years (2003-2008) only. The latter (smaller dataset) will be further refined and, as our base of analysis, some preliminary results compared with the initial wide-ranging search (larger dataset).

For both searches was used a combination of five search expressions, including terms suggested by some authors (e.g. Ulrich and Eppinger, 1995; Craig and Hart, 1992): *product development process, product innovation process, product design*[1] process, product realization process,* and *product creation process*. These were looked in the title, abstract, topic or keywords of English articles available in the databases.

The extensive search provided a number of 669 results, and further refined to the following eight subject areas: Management, Economics, Business, Operations Research & Management Science, Industrial Engineering, Manufacturing Engineering, Multidisciplinary Engineering and Multidisciplinary Sciences. This yielded 529 results. The same were made in the narrow search which yielded 236 results, corresponding to 35% of all-time publication. This allows the focus on papers from the last 6 years without losing too much perspective of the whole literature published, while ensuring up-to-date results. Therefore, the initial results of last 6 years publications for each search expression are presented in Table 5. Note that each paper can use more than one expression.

Table 5. Distribution of papers according to search expressions – small dataset

Expression	n. º of papers	
Product development process	194	82,2%
Product design process	37	15,7%
Product innovation process	9	3,8%
Product realization process	4	1,7%
Product creation process	4	1,7%

[1] The asterisk * stands for the variations of the word "design", *i. e.* "designing".

The results were then exported to EndNote (EndNote, 2008), to perform a preliminary abstract analysis in order to ensure that they correspond to the intended search theme, which is limited to the Product Development Process articles with perspective of the process or activities involved (Craig & Hart, 1992). The refinement was also made for positive confirmation, scanning the full text document when available. Two papers were not available. Only 35 papers passed this filter, which correspond to our final base of analysis (see results list in Appendix B.1).

In addition, the analysis function available in ISI-WOK was used to perform descriptive analysis of the 35 papers, where is obtained information of the most frequent authors, the disciplines that have most contributed to these papers and, consequently, to the current theoretical framework of PDP (table 6), and the journals that published these papers (figure 7). In figure 6 it is presented the yearly evolution of these papers.

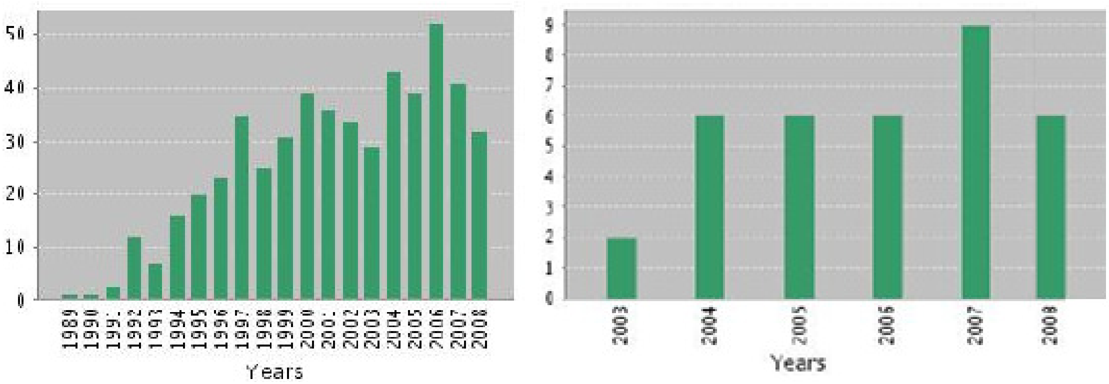

Figure 6. Number of PDP articles per year - large and small datasets

It was possible to identify two major journals which published articles in this field in the last six years: (i) the *Journal of Engineering Design* and (ii) the *Concurrent Engineering – Research and Applications*, with 20% and 14% of the identified articles, respectively. Another six top journals can also be identified as having published at least two scientific articles on the matter, representing 6% each: (iii) *Industrial Marketing Management*, (iv) *International Journal of Operations & Production Management*, (v) *Journal of Product Innovation Management*, (vi) *Journal of Engineering Manufacture,* (vii) *IEEE Transactions on Engineering Management* and (viii) *International Journal of Production Economics*. Altogether, these eight journals have published 69% of the articles identified in the last six years. The remaining was published by other eleven journals, with one publication each during this period.

These results are consistent with the extensive search results, since the two major journals (i) and (ii) are in the top three major publishing journals in global terms and three of the remaining journals (iii), (v) and (vi) are also in the top seven major publishing journals. Note that, in global publications, the *Journal of Product Innovation Management* (v) is clearly the most published journal, with roughly double of publications than the second major journal (i).

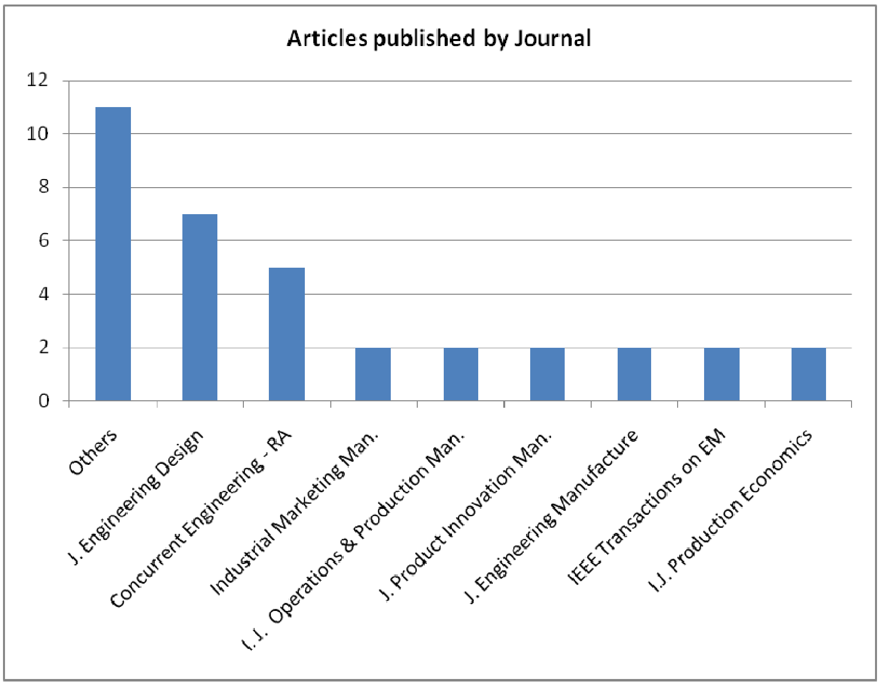

Figure 7. PDP articles publication by journal (%) - small dataset

The authors with the highest number of articles published are Hong-Zhong Huang and Ying-Kui Gu co-authoring four articles, followed by Sándor Vajna and André Jordan, and Hong-Bae Jun and Hyo-Won Suh, co-authoring two articles. They total eight articles published in six years, which correspond to about 23% of the 35 selected articles. As these couples of authors published in one Journal each, they contributed to the emergence of the three major journals identified above. In fact, Huang and Gu's articles represent four in five publications (80%) of *Concurrent Engineering – R.A.*, while Vajna and Jordan's articles represent two in seven publications (29%) of *Journal of Engineering Design*, in the period analysed. Jun and Suh published the only two publications of *IEEE Transactions on Engineering Management* journal.

However, the most cited article was co-authored by (i) Debra Zahay, Abbie Griffin and Elisa Fredericks with 10 citations, and published in 2004 by the *Industrial Marketing*

Management with the title "Sources, uses, and forms of data in the new product development process".

According to the analysis made in ISI-WOK the h-index was 6, therefore there was five other highly cited articles:

(ii) "Shifting paradigms of product development in fast and dynamic markets", by Minderhoud and Fraser, with 8 citations and published in 2005 by the *Reliability Engineering & System Safety*;

(iii) "Simulation of the new product development process for performance improvement" by Bhuiyan, Gerwin and Thomson, with 8 citations and published in 2004 by the *Management Science*;

(iv) "Modified Stage-Gate® regimes in new product development" by Ettlie and Elsenbach, with 7 citations and published in 2007 by the *Journal of Product Innovation Management*;

(v) "Product development process with focus on value engineering and target-costing: A case study in an automotive company" by Ibusuki and Kaminski, with 6 citations and published in 2007 by the *International Journal of Production Economics*;

(vi) "On identifying and estimating the cycle time of product development process" by Jun, Ahn and Suh, with 6 citations and published in 2005 by the *IEEE Transactions on Engineering Management*.

These six articles sum up 45 citations, which correspond to 54% of total citations of the 35 selected articles.

There is a certain balance between management and engineering perspective contributing to the PDP theory, confirming the multidisciplinary nature of this science field, including disciplines like the *Interdisciplinary Applications of Computer Science*. The latter may be a sign of a certain focus on process modelling, simulation and optimization, or even the potential of IT tools integration in the PDP.

Compared to global results, the top seven disciplines are consistently the same, although with different ranking positions. While the disciplines of *Manufacturing Engineering* and *Operations Research & Management Science* correspond to 79% of the refined last six years publications, the *Management* and *Industrial Engineering* disciplines contribute to 86% of global PDP theoretical framework.

Table 6. Top disciplines contributing to the PDP theory

Subject Area	Records	% of 35
Engineering, Manufacturing	14	41.4 %
Operations Research & Management Science	13	37.9 %
Management	12	34.5 %
Computer Science, Interdisciplinary Applications	10	27.6 %
Engineering, Industrial	8	24.1 %
Engineering, Multidisciplinary	8	24.1 %
Business	6	17.2 %
Engineering, Mechanical	2	6.9 %
(2 Discipline value(s) outside display options.)		

4.3.1.1. Research themes and conceptual groups

Subsequently, these records were analysed with RefViz bibliographic software (RefViz, 2008) in order to comprehend the sample of 35 journal articles. RefViz is a bibliographic data visualization and analysis software that works with indexed references set from reference manager packages like EndNote (which are from the same makers – Thomson Reuters). It allows to "visually explore literature references. RefViz analyzes large numbers of references by thematic content and then presents an at-a-glance overview of the main topics discussed in the reference set" (RefViz, 2008).

First, RefViz automatically selects the major terms that are best suited to partition the document set into groups of similar papers, by applying standard mathematical clustering algorithms. Unlike other literature sorting applications, RefViz *defines key themes and concepts based on the context of the entire reference set rather than using predefined rules*. The bibliographic software suggested a long list of major terms[2], based on a mathematical algorithm that selects the best ones for distinguishing and creating

[2] A Term is a single conceptual entity in the vocabulary of a set of references. Usually, those terms are single words as defined automatically by the software to be in one of four groups (RefViz, 2008):

- Major Terms - those determined to be the best for distinguishing and, therefore, creating groups;
- Minor Terms - those that influence group assignments, but not as strongly as the Major Terms;
- Other Terms - the remainder of the vocabulary for the currently selected references;
- Stop-words - very common words such as *the* or *and* that do not contribute to understanding the content of a reference. These are discarded during analyses.

concept-based groups. However, this resulted in a long list of terms. As one learns more about the themes in the reference set, it is often productive to influence the perspective of the analysis by applying a customized set of rules for grouping the references. Modifying these topics, the clustering of references is affected by the terms one chooses to include in the process.

Table 7. List of major terms used for PDP conceptual grouping

NPD terms (Generalist literature)	NPD Process terms (Specialist literature)	Additional terms
Management	Activities	Collaboration
Strategy	Models	Production
Information	Decisions	Modelling
Timing (*Time*)	Evaluation activities (*Staged-gate process*)	Optimization
People (*Team*)	Simultaneity (*Concurrent Eng.*)	
Marketing	Completion (*Proficiency*)	
Communication		

Major terms were identified to be used with the bibliographic software in order to form the conceptual groups of literature or research streams. The new product development (NPD) terms and the product development process (PDP) terms were based on Craig & Hart's (1992) generalist and project themes, as described in section 3.6.2.

Additional terms were included in order to complement the list of major terms. Therefore, the long list of major terms automatically selected by RefViz was reduced and limited to relevant topics, as shown in table 7. The distribution of papers in conceptual groups formed by RefViz is shown in figure 8.

The majority of the articles are aligned along the horizontal axis, with fewer articles separating out along the vertical axis. This implies that the greater part of research practiced aligns along one major axis of variability. Based on the clustering of publications along these two axes and their respective list of key terms used in the abstracts, these papers were visually separated into five groups (see figure 8).

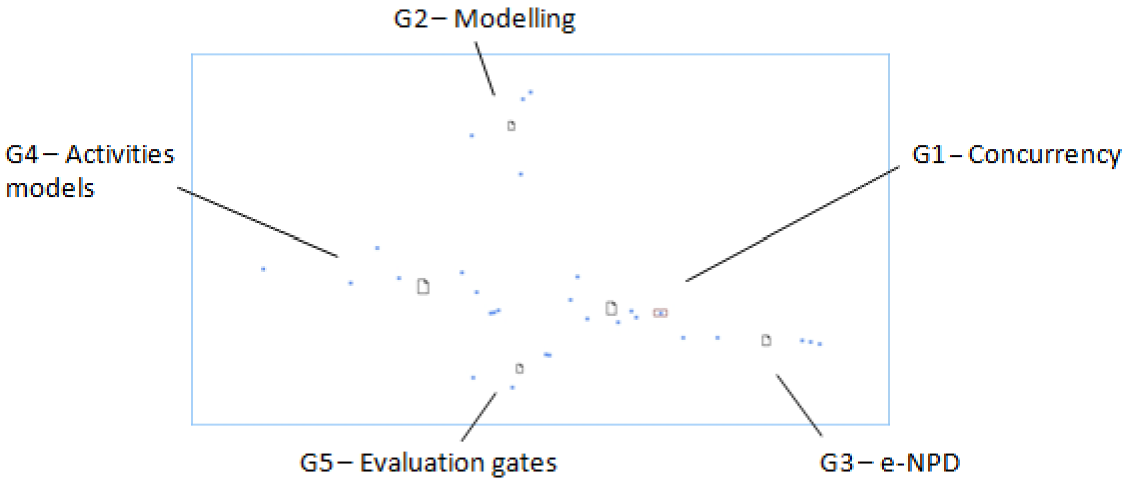

Figure 8. Distribution of PDP articles in conceptual groups - small dataset

The horizontal axis, along which most of the sampled articles aligned, spans the range of PDP research literature on the last six years, from (generic and specific) *models* of process *activities*, through *phase-gate process*, *concurrent process*, and ending up in *electronic new product development* (*e-NPD)* environments. A smaller source of variability developed from those NPD researchers who have authored research articles with stronger links to modelling of PDP (positioning on the opposite corner of phase-gate process). Therefore, PDP related papers focus on five different types of key topics, as follows:

1. Group 1 focuses on *concurrent engineering*, process *concurrency* and the role that *information* plays in the PDP, with special attention being paid to *time* and *team* management;
2. Group 2 focuses on *modelling* and *optimization* of process *activities*, with special attention being paid to *design methodology* concerning the re-organization of design *constraints* and *information*;
3. Group 3 focuses on *e-NPD* environment, *i. e.* on *integrative* and *collaborative* processes used to manage the NPD as an inter-functional and inter-organisational process, with the help of *technological* and managerial tools, e.g. information and communication technologies (ICT), and knowledge management (KM) tools;
4. Group 4 focuses on managing the process *activities* and analyzing or developing *models* of PDP, mostly on mapping these *activities* and the *decisions* involved at different *phases* of the process;

5. Group 5 focuses on managing phase-review or *staged-gate* process and the alignment to company *strategy*, and more specifically on the use of evaluation gates (or review / control activities) at predetermined *stages* of the PDP.

There is always the possibility of papers making use of terms identified with a defined group theme, but not necessarily addressing the specific topic of the group theme. In fact, the article may be addressing another theme, although applying less terms, or even different terms, from those identified as the key terms of that group theme. Moreover, an article can address more than one theme, and consequently should belong to more than one group theme.

Therefore, after identifying the distribution of papers and dividing them into groups with RefViz software, an extra step was needed to confirm their accuracy and re-distribute the papers if needed: a full document text reading. In addition, complementing with full document text analysis allows identifying themes not pointed by the bibliographic tool. The papers that were identified or re-distributed to group themes by full document text analysis are marked by asterisk sign (*) in tables 8 and 9.

By applying the conceptual group formation one can notice the clustering pattern in the PDP literature, and confirm two key themes suggested by Craig & Hart (1992). Although not evident in the distribution of papers in figure 8, the *process completion* theme was finally confirmed in the full document text reading phase:

i) the *process activities* theme (groups G4 and G5);
ii) the *process simultaneity* theme (group G1);
iii) and the *process completion* theme.

These themes and their corresponding publications are presented in table 8 as follows.

Table 8. PDP research group themes identified according to Craig & Hart's taxonomy

Activities		Completion	Simultaneity
Models	Evaluation gates		
Alonso-Rasgado, T. & G. Thompson (2006)	**Ettlie, J. E. & J. M. Elsenbach (2007)**	**Ettlie, J. E. & J. M. Elsenbach (2007)***	**Kincade, D. H. et al. (2007)**
Hasenkamp, T. et al. (2007)	**Huet, G. et al. (2007)**	**Tzokas, N., et al. (2004)***	**Kusar, J. et al. (2004)**
Osteras, T. et al. (2006)	**Kumar, S. & W. Krob (2007)**	**Fairlie-Clarke, T. & M. Muller (2003)***	**Mileham, A. R. et al. (2004)**
Ibusuki, U. & P. C. Kaminski (2007)	**Tzokas, N. et al. (2004)**	Ibusuki, U. & P. C. Kaminski (2007)*	De Toni, A. & G. Nassimbeni (2003)*
Rein, G. L. (2004)	Minderhoud, S. & P. Fraser (2005)*	Kincade, D. H. et al. (2007)*	Esterman, M. & K. Ishii (2005)
Varela, J. & L. Benito (2005)			Kumar, S. & W. Krob (2007)*
Vajna, S. et al. (2005)*			Minderhoud, S. & P. Fraser (2005)*
Vajna, S. et al. (2007)*			
Genaidy, A. et al. (2008)			
Gumus, B. et al. (2008)			
Vanek, F. et al. (2008)			

Two new groups were identified, thus complementing the Craig & Hart's themes, as presented separately in table 9:

iv) the *process modelling* theme (group G2);

v) and the *e-NPD* theme (group G3).

The *e-NPD* topics include concepts of Nambisan’s (2003) new research agenda on IT-enabled NPD process, as suggested before by Craig & Hart’s (1992) information theme, and the Network models category, as described in sections 3.2.6 and 3.3.2 respectively.

Therefore, the traditional mainstream of PDP research can be represented by the groups composed by *process activities* theme, which includes process *models* and e*valuation gates*, and the concurrent processes or *simultaneity* theme. While *e-NPD* theme can be regarded as a new research theme and representing the most recent thinking on the subject, the process *modelling* theme stands more as an umbrella field that link to (or “be part” of) any of the aforementioned conceptual themes. Process modelling is viewed here as the designing, modelling and implementation of process models, and e.g. used for the simulation, planning, control, improvement and optimization of the processes.

Table 9. Additional PDP research group themes identified

Modelling	e-NPD
Bhuiyan, N. et al. (2004)*	**Buyukozkan, G. et al. (2007)**
Huang, H. Z. & Y. K. Gu (2006b)	**Tseng, K. C. & H. Abdalla (2006)**
Huang, H. Z. & Y. K. Gu (2006b)	**Zahay, D. et al. (2004)***
Huang, H. Z. & Y. K. Gu (2007)	Gausemeier, J. (2005)
Huang, H. Z. & Y. K. Gu (2006a)*	Minderhoud, S. & P. Fraser (2005)
Jun, H. B. et al. (2005)*	Lee, A.H.I. et al. (2008)
Fairlie-Clarke, T. & M. Muller (2003)*	
Jun, H-B. & Suh H-W. (2008)	
Lee, H. & Suh H-W. (2008)	

While analysing this bibliometric search, one can't help to notice the *complete absence of articles focusing on ETO process*. Moreover, the main researches published in PDP theory focuses on "product development projects" type, typically related to MTS operations, leaving untouched the issues concerned with the "contract projects" type, common in ETO operations - see description of these types suggested by Maffin and Braiden (2001) already described in section 2.2.

In view of these results, further research is needed in the specific ETO-process literature, which is presented in the next section.

4.3.2. The specific ETO-process research

Subsequent to the study described above, another systematic search was needed to be performed following the same methodology, but this time in the specific ETO theory field.

Therefore, the search expression "engineer to order" was used in the same databases, providing a scarce number of 34 results only and making further subject areas refinement unnecessary. Again, the results were exported to Endnote (Endnote, 2008), where "false positive" articles that are not related to engineer-to-order research were removed, yielding 25 results. This is the global ETO theory dataset, which will be compared to specific ETO-process dataset. The results shows (figure 9, left side) that most of the research in ETO theory were published in recent years, with 80% published after 2000, and the earliest publication date back to 1994, thus all research were published in the last 15 years.

A preliminary abstract analysis was done in order to choose only those papers corresponding to the intended search theme, which is limited to the Product Development Process articles with perspective of the process or activities involved. For positive confirmation, the full text documents were read. Only 7 papers passed this filter (figure 9, right side), which correspond to our final base of analysis (see results list in Appendix B.2).

This follows a twofold research, this time not in terms of the publication date range but of research range itself, *i. e.* researching not only the specific and scarce ETO-process theory, but also including the more generic ETO body of literature. It makes sense due to the scarcity of research publications found in specific ETO-process field.

Because of the small number of valid ETO-process articles, a limited analysis is possible and can be described shortly.

Most of the 7 ETO-process articles were published very recently: one in 2008, three in 2007, and one in 2006, 2000 and 1997 each (figure 9, right side). That is, with the exception of the latter, all the ETO-process papers were published in this decade.

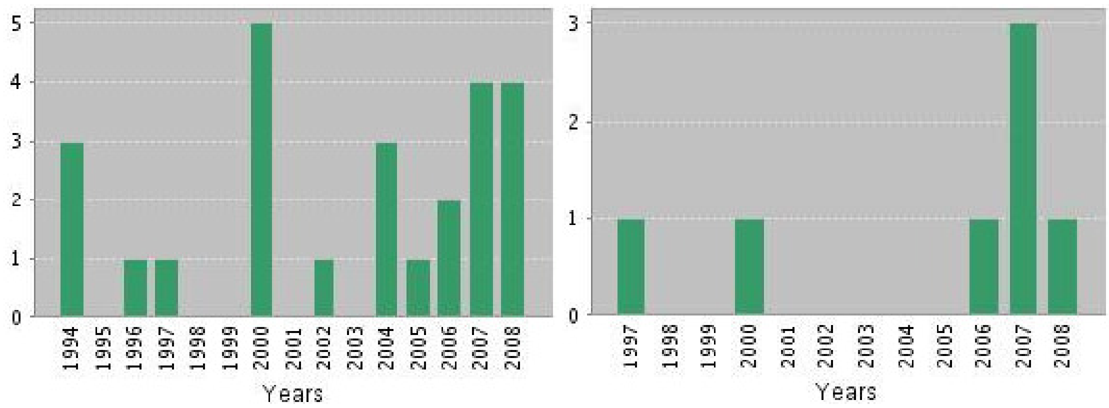

Figure 9. Number of articles per year - large (ETO) and small (ETO-process) datasets

The co-authors Zahed Siddique and Jiju A. Ninan are the only ETO-process researchers with two publications, co-authoring one of the three papers ever cited. Their article adds up 4 citations, and was published in the *Integrated Computer-Aided Engineering* journal in 2006 with the title “Modeling of modularity and scaling for integration of customer in design of engineer-to-order products”.

The article from David Little, Ralph Rollins, Matthew Peck and J. Keith Porter, was cited 8 times, and published in the *International. Journal of Computer Integrated Manufacturing* in 2000 with the title “Integrated planning and scheduling in the engineer-to-order sector”.

However, the paper with highest impact in ETO-process theory was co-authored by Brian Kingsman and Antonio Artur de Souza, with the title “A knowledge-based decision support system for cost estimation and pricing decisions in versatile manufacturing companies”, published in the *International Journal of Production Economics* in 1997. This less recent article adds up 12 citations.

Table 10. Top authors contributing to the ETO theory

Author	Records	% of 26
Hicks, C	5	19.2 %
Braiden, PM	2	7.7 %
Earl, CF	2	7.7 %
Mcgovern, T	2	7.7 %
Ninan, JA	2	7.7 %
Siddique, Z	2	7.7 %
(40 Author value(s) outside display options.)		

In terms of the more extensive ETO theory, there is presently a leadership by Chris Hicks with 5 papers, and his “alma matter” institution the University of Newcastle Upon Tyne with 6 papers. A group of 5 authors followed with some distance with 2 papers each, including above mentioned ETO-process authors Siddique and Ninan (Table 10). There are, however, 40 other authors who contributed with one article only.

Interesting to notice the predominance of the American continent in terms of territory of origin of the 7 ETO-process papers, where three articles were from USA, three from England, two from Mexico and the remaining one from Sweden. Nevertheless, when comparing with the global results, England clearly dominates with 9 papers, followed by USA with 5 papers and Netherlands with 3 papers. The England prevalence is explained by the strong contribution of “Newcastle stream” where Hicks is included.

In the global results (ETO theory dataset), there are two major journals that stand out in terms of publication: the *International journal of Production Economics* (with 9 papers) and the *International journal of Production Research* (with 4 papers). These journals are both present in the small dataset (ETO-process theory) but, as the 5 articles were published in different journals, it was not possible to identify major journals. However, it was noticed the contribution of the *Journal of Engineering Design*, which is a major journal in PDP theory indicated by the previous study above.

The engineering perspective clearly dominates the ETO-process theory, where *Multidisciplinary Eng., Manufacturing Eng.,* and *Industrial Eng.* disciplines contribute with three, three and two publications respectively. Along with *Operations Research & M.S.* and *Computer Science* disciplines, the top six disciplines are consistently the same when compared to global ETO results, although with different ranking positions. These disciplines are also shared with the more multidisciplinary PDP papers (Table 11).

Table 11. Top disciplines contributing to the ETO-process theory

Subject Area	**Record Count**	**% of 7**
Engineering, Manufacturing	3	42.9 %
Engineering, Multidisciplinary	3	42.9 %
Operations Research & Management Science	3	42.9 %
Computer Science, Artificial Intelligence	2	28.6 %
Computer Science, Interdisciplinary Applications	2	28.6 %
Engineering, Industrial	2	28.6 %
(2 Subject Area value(s) outside display options.)		

Most of the research in ETO theory, which was all published in the last 15 years, followed the Production or Manufacturing research perspective, which often aims to solve Production Planning & Scheduling issues, or focuses on concepts related to Mass Customization and Supply Chain Management (SCM).

In terms of publication related with the subject in research, *i. e.* that directly addresses the product development process, one article described the whole ETO-process: Pandit and Zhu (2007) with the title "An ontology-based approach to support decision-making for the design of ETO products". The process is given here as example of a typical ETO process composed of the six phases:

1- Place the ETO product order

2- Procure the ETO product order

3- Manage the ETO product

4- Design the ETO product

5- Build the ETO product

6- Use the ETO product

Phase 4 is composed of the two processes, with the focus of Pandit's study being on Process 4.1:

• Process 4.1: Engineer Product

• Process 4.2: Design Product in Detail.

4.4. Concluding remarks

This chapter addressed the bibliometric analysis of NPD process research in general, and the ETO-process literature in particular, in search of evidence of the extremely small attention given by research to the latter. The results found largely *confirm the claim that ETO companies and their innovation process have been in fact neglected by academic research* and instead, they mainly focus on high-volume MTS operations mode. In another words, the ETO operations in general, and the ETO process in particular, have been consistently overlooked. However, two additional research groups, together with those suggested by Craig and Hart (1992), were identified in the literature – see global table in appendix C.

The complete absence of articles focusing on ETO process in the main product development process (PDP) literature can also be explained by the fact that the scarce ETO specific literature identified typically uses the Production or Manufacturing perspective. This may result from the fact that ETO organizations typically face operational difficulties to respond to customer requirements in terms of lead time and delivery promises, and may indicate that the product development process (PDP) are usually viewed as a production process in this reality and by academic research as well. The explanation advanced here makes sense as the PDP terms (e.g. "product development process" and "product design process") are not employed in the ETO-specific literature, and as a consequence, the subject of ETO development process is not included in the PDP body of literature, which probably dampers the research of ETO process models within a product development perspective.

PART III – ANALYSIS OF INNOVATION PRACTICE IN CAPITAL GOODS

5. THEORETICAL FRAMEWORK

5.1. Introduction

The aim of the dissertation is to shed light on innovation in competitive producers of equipment and machinery. The innovation at business level may emerge from specific features of the industry, of the market and of the firm itself. In this chapter, it is advanced industry and market taxonomies that may determine the innovation at firm and project level, the risks of innovation, the modes of innovation, and alternative models addressing ETO process.

5.2. Company classification typologies

5.2.1. Introduction

Maffin *et al.* (1995) in their research paper "*Company classification: A new perspective on modelling the Engineering Design and Product Development Process*", distinguish between, and provides a critique of, the development of 'models' in engineering design and product development. The authors discuss that many of these models are general in their scope and prescriptive in nature, and have in consequence a number of inherent shortcomings, not least of which is the need for the user of these models to interpret them in the context of their company's environment and a particular project's requirements. Consequently, Maffin *et al.* (1995) proposed a new perspective based on the concept of company classification, as a logical step forward to identify those generic and company specific features of engineering design and product development and how generic models might be tailored to reflect these characteristics.

The authors analyzed a number of existing classification typologies available and further proposed a comprehensive framework of company classification dimensions and key factors (see table 12) that defines the organization and the product, and which are influential upon the product development process. Classifying companies according to this framework could lay the foundations for guiding the application of models in industry. Many of these factors can be regarded as constant, inside the boundaries of a company and for a particular line of products.

Table 12. Company classification dimensions and key factors (Maffin *et al.*, 1995; 1997)

Company structure factors	**Process factors**	**Supplier factors**
Establishment size	Process complexity	Rationalization
Ownership	Process flexibility	Degree of control
Autonomy	Process constraint	Collaboration
Independence	Production volume	Locality
Centralization	Internal span of process	
Market and customer factors	**Product factors**	**Local and global environment factors**
Market type	Product type (standard/ special)	Local labour market
Market size and share	Product variety / range	Skills
Market complexity	Product complexity	Training
Exports	Product status	Financing and grants
Number of competitors	Innovation rate	Legislation and regulation
Competitive criteria	Design capability	Political and economic

According to the authors, market and customer factors concern the relationship between the manufacturer and the market, which above all determines the competitive criteria and the way the order delivery process is configured. Furthermore, market type in particular is considered by the authors as a critical factor, and that the key distinction to be made is between make-to-stock (MTS), make-to-order (MTO) or assemble-to-order (ATO), and customized make-to-order (CMTO) or engineer-to-order (ETO).

Therefore, in the next sub-sections company classifications are presented, based on industry and market taxonomies that may determine the innovation at firm and project level.

5.2.2. Production control and customization

Sari (1981) classified companies along a continuum in terms of production control situations, their characteristics in relation to the market situation and the nature of customer orders, and the role they play in the production process:

i) Make-to-stock (MTS);

ii) Assemble-to-order (ATO);

iii) Make-to-order (MTO);

iv) Engineer-to-order (ETO).

While MTS produces finished goods from raw materials and semi-finished goods held in inventory, independent of customer orders, ATO produces previously defined semi-finished goods and the subsequent assembly of these parts to produce finished goods after the receipt of a customer order. In MTO, production of finished goods is done only after the receipt of a customer order, and in ETO mode the engineering and production of custom-built products are based upon a customer order.

5.2.3. Market type specialization

The IFO Institute (1997) classifies the companies in the Mechanical Engineering (ME) industry sector based on the market type. The authors have highlighted three categories of market type:

v) Series product supply;

vi) Customized engineering and plant supply;

vii) Key Know-how supply.

In the Series product supply, typically the products are not specified for specific customers. Therefore, engineering and design input is not necessary, which may be different with the Customized engineering and plant supply where key parts of the supply have to be developed or reengineered to fulfil demand. What distinguishes Key know-how supply is that it requires a specific know-how that is not usually freely available and which may be state of the art in a niche or specific technological solutions.

5.2.4. Innovative level of SME

As the ME sector in Europe is dominated by Small and Medium Enterprises (SME), it is also important to make a distinction among the different types of SME according to their innovative level. It is used Hoffman *et al.*'s (1998) taxonomy, *i. e.*:

i) Superstar companies;

ii) New technology-based firms;

iii) Specialized supplier;

iv) Supplier dominated.

Superstar companies are small businesses that have benefited from the high levels of diffusion of radical innovations in the fields of robust technological trajectories such as semi-conductors and software. New technology-based firms are a recent phenomenon and involve small enterprises born thanks to spontaneous spin-off from larger companies and research laboratories, above all in the electronics, software and biotechnology sectors. The Specialized suppliers are traditional businesses focused on the design, development and production of specialized productive input, in the form of machinery, instrumentation, components and software, and capable of interacting proactively and in conjunction with their technical client. Finally, many small businesses come within the category of Supplier dominated. In order to innovate these businesses strongly depend on their suppliers and clients.

5.2.5. Summary

The classification types, summarized in table 13, are intended to be used in an independent and complementary approach. Although there is no hierarchy between them, it is considered that e.g. there is some connection between the IFO's and Sari's taxonomy, as the first is based on "market type" and the latter also use the "market situation" of the company. Moreover, the IFO's classification is proposed specifically for the mechanical engineering (ME) industry sector, while the categories suggested by Sari and Hoffman are intended to be industry-independent. Finally, the Hoffman's taxonomy is meant for small and medium enterprise (SME) situation in particular.

Table 13. Summary of industries' classifications (own depiction - Varum *et al.*, 2009)

Production control situation and nature of customer order (Sari, 1981)	Market type specialization (IFO, 1997)	SME type by innovative level (Hoffman, 1998)
Make-to-stock (MTS)		Superstar companies
	Series Product supply	
Assemble-to-stock (ATO)		New technology-based firms
	Customized Engineering and Plant supply	
Make-to-order (MTO)		Specialized supplier
	Key Know-how supply	
Engineer-to-order (ETO)		Supplier dominated

These classification types are used in the empirical analysis to understand the uncertainties faced by these companies and their innovation mode, and may help in determining adequate strategies for these particular company types.

5.3. Innovation uncertainty and ambiguity

5.3.1. Introduction

In the capital goods business, according to Hicks *et al.* (2001), there are many sources of uncertainty with respect to demand, cost, price, specification, duration of processes and lead-times. Missing information and engineering revisions caused by the overlapping of manufacturing and design activities are major sources of uncertainty that complicate the management of ETO manufacturing. Therefore, it is relevant to analyse the risks faced by these companies and how they are dealt with.

5.3.2. Uncertainty type

As in other industries, producers of capital goods face substantial risks and uncertainties that may constrain the companies' innovative capability, and make the whole planning and control of the innovation process difficult. In the empirical analysis (Chapter 6), those uncertainties and the approaches used by firms to cope with them are investigated. In this part of the dissertation, dominant typologies and frameworks that will help to characterize the risks and uncertainties in the industry under research are reviewed.

De Meyer *et al.* (2006) follow the common definition of risk as the implications of the existence of significant uncertainty about the level of project performance achievable, and is seen as having the two components of probability of occurrence and the consequences/impacts of occurrence. While the details differ, all established project risk management methods recommend actions to identify risks beforehand, to classify and prioritize them according to probability and impact, to manage them with a collection of preventive, mitigating and contingent actions that are triggered by risk occurrence, and to embed these actions into a system of documentation and knowledge transfer to other projects.

De Meyer *et al.* (2006) observed that established risk management methods enable us to handle mainly the foreseeable risks and what they call residual risk or variations. ‘Foreseeable risks’ are those whose influences are known, but not the probability of occurrence and precise impact, ‘variations’ are those small impact occurrences that cause some variation around targets. However, the authors suggest that current risk management methods do not enable us to handle the unknown or unforeseeable influences, or what engineers refer to as ‘unknown unknowns’ or ‘unk-unks’, and decision theory and economics disciplines call ‘unawareness’ or ‘incomplete state space’, and technology management scholars call ‘ambiguity'.

5.3.3. Managing uncertainty

Pich *et al.* (2002) concluded that there are fundamentally three approaches to managing risk in projects, namely, (i) instructionism, planning and then execution of the plan, (ii) learning, and (iii) selectionism, as explained below:

i) Instructionism, in this case contingency plans are drawn up as instructions for the project management team to follow, and contingencies and flexibility are pre-planned and only then “triggered”. This approach works well as long as all risks are identified and their impact on the project can be predicted;
ii) Learning ‘as you go’ involves a flexible adjustment of the project approach to the changing environment as it occurs, making adjustments based on information obtained during the development process, as opposed to at planned trigger points;
iii) Selectionism refers to generating variety (via independent parallel trials) and then choosing the solution with the most favourable outcome.

In table 14 it is summarized the approaches to managing risk according to the description of Pich *et al.* (2002). The combination of selectionism and learning strategies gives rise to a mixed approach named learning and selectionism.

Table 14. Summary of approaches to managing risk. Adapted from Pich *et al.* (2002)

	Optimization	Selectionism
Learning	**Learning Strategies** Learning: scanning for 'unk-unks', then new, original problem solving • Learn about unforeseen uncertainty • Learn about complex causal effects of actions	**Learning and Selectionism** • A project may be stopped based on favorable progress of another candidate • Exchange information among candidates to increase learning: candidate projects become complements
No Learning	**Instructionist Strategy** Decision adequate causal mapping • include buffers in plan • plan project *policy* • monitor project influence *signals* • trigger *contingent action*	**Selectionist Strategy** Launch multiple "candidate" project efforts and choose the best one • Hedge against unanticipated events • Explore larger part of complex action space to find better solution

Current risk management methods for project management coincide to a large extent with instructionism. Existing project management approaches advocate partially conflicting approaches to the project team, such as the need to execute planned tasks, trigger pre-planned contingencies based on unfolding events, experiment and learn, or try out multiple solutions simultaneously. While all of these approaches encompass the idea of uncertainty, it is important to analyse, on the one hand, the current practices in companies and how project managers perceive different risk and uncertainties in the projects. On the other hand, it is also important to analyse the different approaches they choose and when to prevent project failures, like budget and schedule overruns, compromised performance, and missed opportunities.

5.3.4. Summary

In this section, the different types of risks and uncertainties that can affect firms' projects were described, and several recommended approaches to managing those risks were advanced. These constitute the conceptual model for analysing the innovation risks in case study companies.

5.4. Modes of innovation

5.4.1. Introduction

According to the results of a study conducted by Jensen *et al.* (2007) in Denmark, there is a tension between two ideal modes of learning and innovation, both at the level of the firm and of the whole economy. One mode, called Science, Technology and Innovation (STI), is based on the production and use of codified scientific and technical knowledge. A second mode is more informal and experienced-based, and learning is based on Doing, Using and Interacting (DUI). The main objective of this framework has been to demonstrate the usefulness of the conceptual distinction between the DUI- and STI-modes of innovation and to demonstrate that these concepts can be made operational.

5.4.2. Forms of knowledge

The different modes of innovation are connected to different types of knowledge. Jensen *et al.* (2007) apply the distinction between implicit versus explicit knowledge; local versus global; and 'know-what', 'know-why' versus 'know-how' and 'know-who' types of knowledge. The distinction between implicit and explicit knowledge (or rather tacit and codified elements of knowledge) corresponds to the difference between experience-based knowledge that is not written, mobilized by informal interaction and communication, by communities of practice and among organizations, against the written and codified knowledge that can be passed to others who can read and understand the specific language. In addition, by making explicit what is implicit may improve the capacity to share and generalize knowledge, thus making knowledge that is local, global.

However, what is referred to are two ideal types that appear in a much more mixed form in real life. Moreover, it is argued that the zone in-between and the complementarities between the tacit and codified elements of knowledge are often what matter most. The same argument is applied by the authors to the distinction between local and global knowledge, between the two modes of innovation and their relation to the different forms of knowledge. Linking these dichotomies to a more elaborate set of distinctions, it is argued that 'know-what' and 'know-why' correspond to types of knowledge that may be obtained through reading books or attending lectures, while 'know-how' and 'know-who' are acquired more with practical experience. While the STI-mode gives high priority to the production of 'know-why' type of knowledge, where very specialised 'know-what' is often a prerequisite, using and further developing explicit and global knowledge, DUI-mode will typically produce 'know-how' and 'know-who', which are tacit and often highly localized.

Since the distinction among the four types of knowledge seems crucial, some examples would be useful to better grasp the concepts introduced by Lundvall and Johnson (1994):

i) The 'know-what' refers to knowledge about 'facts', and corresponds to generic information (*i. e.*, how many people live in New York, what are the ingredients in pancakes and when the battle of Waterloo was);
ii) The 'know-why' is a more fundamental knowledge with roots in science (*i. e.*, the knowledge about principles and laws of motion in nature, in the human mind and in society);
iii) The 'know-how' refers to skills, like the capability to do something (*i. e.*, a specific expertise or competence developed and kept inside a firm or held by a worker);
iv) And the 'know-who' is the knowledge about who knows what and who knows to do what, but it also involves the social capability to cooperate and communicate with different kinds of people and experts (*i. e.*, the knowledge of the individuals who hold particular competences).

5.4.3. Learning organizations

Following the results of the study conducted by Jensen *et al.* (2007), companies can be classified in four different types of learning organizations (see Table 15). These types result from identifying companies implementing one particular mode of innovation or the other, implementing a mix of both, or even neither of them:

i) The DUI learning organization;
ii) The STI learning organization;
iii) The DUI/STI learning organization;
iv) And the low learning organization.

The authors suggests that there is a tension between the two modes of learning, and that firms combining both modes, in form of DUI/STI learning type, are more likely to create new products or service than those relying primarily on one mode or another. This may have important implications for benchmarking innovation systems and for innovation policy, which will be further expanded in the discussion section.

Table 15. Summary of innovation and learning modes. Adapted from Jensen *et al.* (2007)

STI mode Based on production and use of codified scientific and technical knowledge: Codified, global, 'know-what' and 'know-why' types of knowledge	**STI / DUI mode** Tension between the two modes Firms are more likely to innovate than those relying primarily on one mode or another
Static or Low learning Lack of DUI and STI modes	**DUI mode** Informal and experienced-based knowledge: Tacit, local, 'know-how' and 'know-who' types of knowledge

5.4.4. Summary

This section introduced two ideal modes of learning and innovation, and described how they relate to production and use of different forms of knowledge. It discussed the usefulness of this distinction, how these concepts can be made operational and the resulting different types of learning organizations.

5.5. Alternative models for engineer-to-order (ETO) process

5.5.1. Introduction

The literature addressing the needs of companies that produce in response to customer's orders is astonishingly modest, and as already mentioned before, these companies have been consistently neglected by academic research (Lu *et al.*, 2008; Rahim and Baksh, 2003; Hicks *et al.*, 2001; Maffin and Braiden, 2001; Alderman *et al.*, 2001). Furthermore, most of the tools and frameworks for innovation process are mainly meant for large volume manufacture or what is classified as make-to-stock (MTS) manufactures (Rahim and Baksh, 2003). Therefore, it is argued that there is a need for alternative frameworks for ETO products.

Following the discussion of the distinguishing features of capital goods companies, their market and the industry sub-sector where they operate (Chapter 2), the review and discussion of the applicability of twelve common models (Chapter 3), and the bibliometric analysis of recent literature (Chapter 4), four alternative models addressing ETO process have been identified.

This section introduces to the exceptionally scarce literature identified addressing theoretical models of product development process that may be more suitable for engineered-to-order (ETO) capital goods products in particular.

5.5.2. Variants of generic development process

The development process described in sub-section 3.3.3. by Ulrich and Eppinger (1995) is generic, and is recognized by the authors that particular processes will differ in accordance with a firm's unique context. The generic process is most like the process used in a *market-pull* situation: a firm begins product development with a market opportunity and then seeks out whatever technologies are required to satisfy the market need (that is, the market pulls the development decisions).

In addition to the *market-pull* process, several variants are common and correspond to the following: *technology-push* products, *platform* products, *process-intensive* products, and *customized* products. Each of these situations is described below. The characteristics of these situations and the resulting deviations from the generic process are summarized in table 16. While describing the customization variant, Ulrich and Eppinger (1995) stated that:

> "Customized products are slight variations of standard configurations and are typically developed in response to a specific order by a customer. Development of customized products consists primarily of setting values of design variables such as physical dimensions and materials. When a customer requests a new product, the firm executes a structured design and development process to create the product to meet the customer's needs. Such firms typically have created highly detailed development process involving dozens of steps that, because of the structured flow of information and well-defined sequence of steps, are quite similar to production process. For customized products, the generic process is augmented with detailed description of the specific

information processing activities required within each of the five phases. Such development processes may consist of hundreds of careful defined activities."

Table 16. Variants of generic development process (Ulrich and Eppinger, 1995)

	Generic (Market Pull)	Technology-Push	Platform Products	Process-Intensive	Customization
Description	The firm begins with a market opportunity, then finds appropriate technology to meet customer needs.	The firm begins with a new technology, then finds an appropriate market.	The firm assumes that the new product will be built around the same technological sub-system as an existing product,	Characteristics of the product are highly constrained by the production process.	New products are slight variations of existing configurations.
Distinctions with respect to generic process		Additional initial activity of matching technology and market. Concept development assumes a given technology.	Concept development assumes a technology platform.	Both process and product must be developed together from the very beginning, or an existing production process must be specified from the beginning.	Similarity of projects allows for a highly structured development process. Development process is almost like a production process.
Examples	Sporting goods, furniture, tools.	Gore-tex rainwear, Tyvek envelopes.	Consumer electronics, computers, printers.	Snack foods, cereal, chemicals, semiconductors.	Switches. Motors, batteries, containers.

However, doubts can be raised about the suitability of this framework for engineer-to-order (ETO) operations mode. According to Rahim and Baksh (2003), this framework is too simplistic and incomplete to guide ETO companies. Moreover, the generic framework proposed is mostly suited for make-to-stock (MTS) companies, as described in section 3.3.3.

Although the authors recognizes that particular processes will differ in accordance with a firm's unique context, doubts can be raised about *how they differ,* or ultimately, *how and if the generic process outlined could be adapted to meet ETO operations needs*. It is recognized by the authors that a customization situation results in a deviation from the generic process, and it is made an effort to point the differences that customized products process would have compared with the market-pull process. However, considering customized product process as a variant of the market-pull process, by merely augmenting a detailed description of the specific information processing activities, results in a framework too simplistic and incomplete to guide ETO companies.

In the following section, the two generic types of process (market-pull versus customized products) are contrasted and explained the fundamental differences between them.

5.5.3. Off-line and contract processes

Alderman *et al.* (2001) followed the critique of models for product development process, e.g. Maffin *et al.* (1995) in sub-section 5.2.1, and raised doubts about the universal usefulness of these models in all industries, firms or establishments.

The authors argue that much of the literature on product development appears to ignore sections of manufacturing industry concerned with low volume, engineered-to-order production and the particular characteristics that go with it. Likewise, the same literature implicitly assumes a development process aimed at creating a standardised product for a large or mass market, ignoring the important distinction between such standardised production and production of one-offs to individual customer requirements. For manufacturers that serve their markets on an engineer-to-order (ETO) or customised made-to-order (CMTO) basis in this way, this development route is by far the most common.

The authors' case study research (Alderman *et al.*, 1996) identified two generic models of the product development process at a high-level of abstraction:

- the *off-line product development process* (figure 10), which is broadly consistent with the traditional models (e.g. market-pull, high-volume MTS operations);
- the *contract process* (figure 11), where the firm undertakes some degree of development of the product under contract to a specific customer.

Off-line process

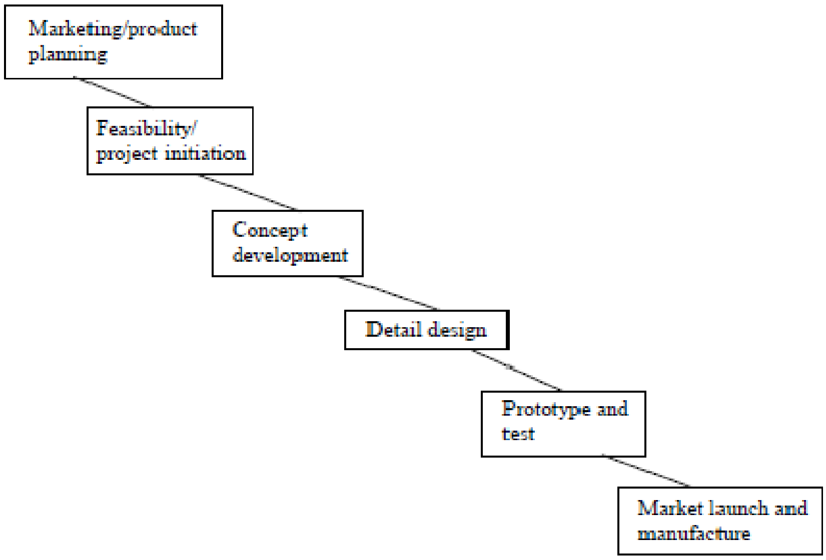

Figure 10. Stages in the generic off-line process (Alderman *et al.*, 2001)

Contract process

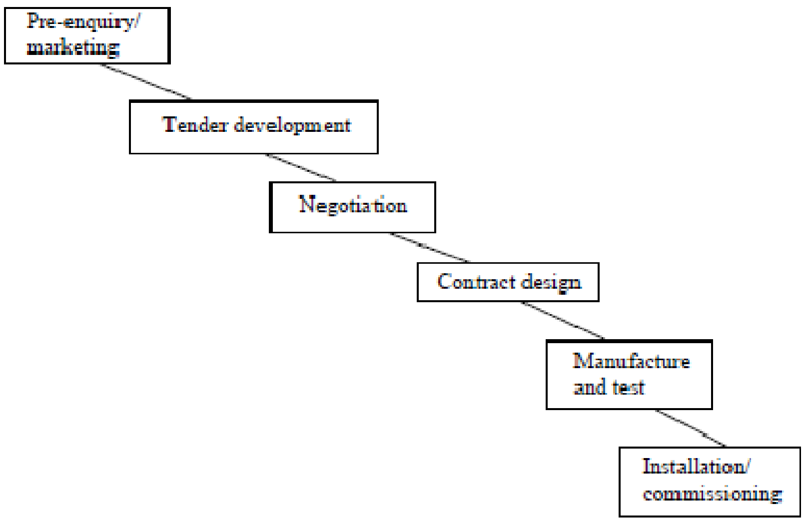

Figure 11. Stages in the generic contract process (Alderman *et al.*, 2001)

Although each *generic model consists of six phases*, the authors (Alderman *et al.*, 2001) further complemented that in practice companies operate a range of variants of either of these two models, with some phases being redundant or additional phases being required depending upon the characteristics of the particular development project. Moreover, in testing propositions regarding these two generic processes, it became apparent that a number of common hybrid forms exist (Alderman *et al.*, 1996). These fell into three broad types:

a) "Those where the company initiated the development of a low volume, high complexity product but, owing to the scale of the development, in order to complete it, a firm contract for sale had to be obtained — the model therefore had an off-line product development front end followed by a contract;
b) Those where the product was a high volume, low complexity one developed for a specific customer under agreement, but largely following the off-line model, with a view to the company becoming a preferred supplier; and
c) Those where a low volume product was developed for an end customer, following a specific request, but with the intention of entering the resulting product into the company's standard catalogue or range in order to exploit a wider market opportunity — this followed the off-line model with elements of the contract process, such as negotiation, etc."

The detailed features of the processes outlined in figures 10 and 11 therefore depend, amongst other things, on attributes of the product such as its complexity or depth of structure, and the nature of market relationships between the manufacturer and its customers. Regardless of detailed differences in the number or precise nature of stages in the process, the distinction between the presence and absence of a contract is a fundamental characteristic of development projects (Alderman *et al.*, 2001).

5.5.4. Customer-order driven development

Oorschot (2001) made, after Alderman *et al.* (2001), a similar distinction of the two generic types of process, a contrast based on the customer order: the *customer-order driven development* (or engineer-to-order) and the *customer-order independent development.*

According to Oorschot (2001), in engineer-to-order (ETO) product development, the development process is initiated by a customer order, in which the customer specifies what has to be developed. When product development is independent of a customer order, the development process is initiated by the development organization (based on market research). The specifications of the new product are then defined by this development organization.

Munstlag (1993), on his research on managing customer-order driven engineering, distinguished in the primary chain of ETO operation activities two major streams or stages of activities: a non-physical stage and a physical stage. The non-physical stage comprises the quotation phase, the custom engineering of the product and process planning activities. A number of activities to be performed within various independent production departments can be identified within each of these stages. According to the author, the major non-physical stage of activities can be divided into the engineering and process planning departments, and the physical stage into the manufacturing and assembling departments. The global flow of goods and information within an engineer-to-order production plant is illustrated in figure 12.

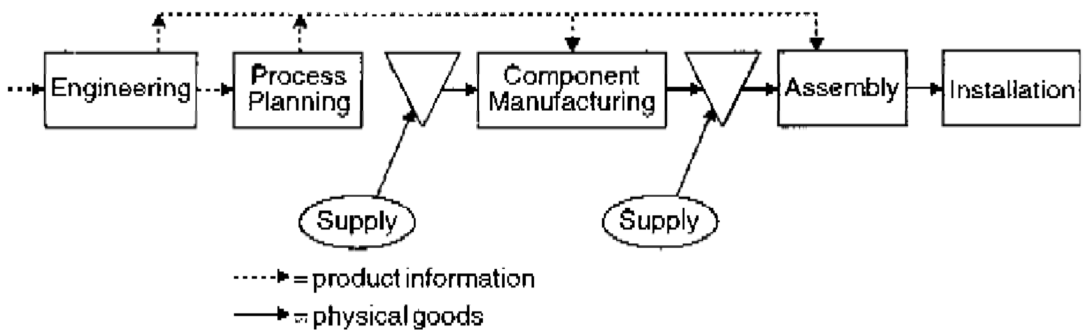

Figure 12. Global flow of goods and information for ETO operations (Munstlag, 1993)

Munstlag (1993) distinguished different degrees of customer-order independent engineering. Based upon a further analysis of various engineer-to-order production situations, two aspects which taken together, can be used to determine the degree of customer-order independent engineering:

- the Order-independent Specification Level (OSL);
- the degree to which the customer is allowed to specify a custom-built product.

A classification scheme to make a distinction between different types of customer-order driven engineering can be defined, based upon these two aspects.

According to the author, the degree of customer-order independent engineering can vary, of course, from none to global functional specifications to the complete design of complex new industrial equipment. The degree to which the engineering activities are performed independently of the customer orders has a major impact on the quality management during the customer-order driven engineering activities. When only the global specifications for a product family have been specified, the product uncertainty is greater than in a situation in which the product has been fully specified.

Therefore, the author introduces the Order-independent Specification Level (OSL) concept to express the degree of customer-order independent engineering. The OSL represents the lowest level of product description that is still independent of any given customer order. There is, of course, an important relationship between the different OSL's and the engineering process. A certain OSL essentially indicates to what extent the engineering process has already been completed before customer order is accepted. Munstlag (1993) identified five OSL's in the customer-order driven engineering phase:

- OSL-1: engineering based upon a specific technology;
- OSL-2: engineering based upon pre-defined product families;
- OSL-3: engineering based upon pre-defined product sub-functions and solution principles;
- OSL-4: engineering based upon pre-defined product modules;
- OSL-5: engineering based upon finished goods.

5.5.5. Concurrent engineer-to-order

A more recent study of Chen (2006) proposed a comprehensive framework with high level of detail. The author presented the concept of concurrent engineer-to-order (ETO) operation, defined its relevance to other contemporary manufacturing operation concepts and proposed a concurrent ETO operation framework to explain interactions among the sales, production, engineering, and manufacturing operations with a focus on hierarchical planning, incremental scheduling, and operation control. The purpose of the author intention was for laying a foundation for design and development of an effective concurrent ETO operation system. By synchronising the production activities in a product development process, a concurrent ETO operation can effectively improve and assure the product development lead-time.

Concurrent ETO, according to Chen (2006), is a make-to-order operation that starts with a product specification and finishes with delivery of a customized product. It focuses on an integrative operation of the sales, engineering, manufacturing and test activities in order to economically minimize product development lead time and assure delivery commitment, by applying the concepts of concurrent engineering, mass customization and lean manufacturing.

The author distinguishes concurrent ETO from a conventional ETO operation in its concurrence in carrying out engineering and manufacturing processes and treating them both as a production activity. Concurrent ETO differs from an MTS operation in that it does not have an existing BOM and process plans to drive material and capacity requirement planning. The function of material requirement planning in concurrent ETO operations reduces to a series of materials requests and acquisitions for each production order. Master production scheduling is closely related to the sales operation in the proposed framework, because ETO is a make-to-order only operation and in principal, it commits resources for each active bid item in the bidding process, in light of its acceptance.

Chen (2006) also differentiates concurrent ETO from conventional Concurrent Engineering. Concurrent Engineering does not concern itself with process design, production planning or manufacturing. Process design and production planning are considered premature at this stage, because product design has not been finalised and demand is unknown. From a classical concurrent engineering point of view, manufacturing will occur only at a much later time. Therefore, concurrent engineering has been largely applied to ensuring that a product design is somehow possible to produce. It does not consider concurrent execution of engineering and manufacturing activities.

The concept of concurrent operations in Concurrent ETO goes beyond manufacturability evaluation of a product in design from a traditional Concurrent Engineering sense. A concurrent ETO operation is geared toward running an ETO operation at the efficiency and cost effectiveness of a mass production operation while continuously minimising the product development lead-time. By treating *engineering as a production activity*, a concurrent ETO operation engages in concurrent planning and execution of sales, engineering, material acquisition and manufacturing activities.

Summarised below is a set of common attributes required of a concurrent ETO operation:

- Project based operations integration;
- Concurrent execution of sales, engineering and manufacturing operations;

- Integrative decomposition of project's work, budget, lead time and quality;
- Incremental work planning and scheduling;
- Handling frequent managerial and technical changes;
- Engaging in mass product / process customisation;
- Close collaboration with customers, suppliers and subcontractors;
- Management of product lifecycle (PLM) data and history.

The proposed concurrent ETO operation framework is illustrated in figure 13 identifying four major business processes and shows how they relate to one another.

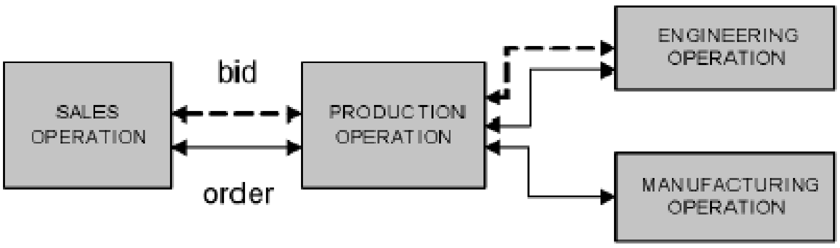

Figure 13. Sketch of concurrent ETO operation framework (Chen, 2006)

The sales operation in the proposed framework is the driving force and is typically triggered by a request for quotation from the customer. Each sales process is a production activity and collaborates closely with the production operation. For each bidding activity, the production operation coordinates with the engineering operation for preparing a product specification, conducting an engineering analysis and estimating product costs. Based on the engineering data, the production operation estimates resources requirement and evaluates development lead time for each bid item. When a bid is submitted, the production operation reserves the estimate of resources requirement for the proposed time period. After a customer order is accepted, the sales operation converts the order into production orders and releases the orders to the production operation. The production operation then plans and organises the engineering and manufacturing operations for each production order.

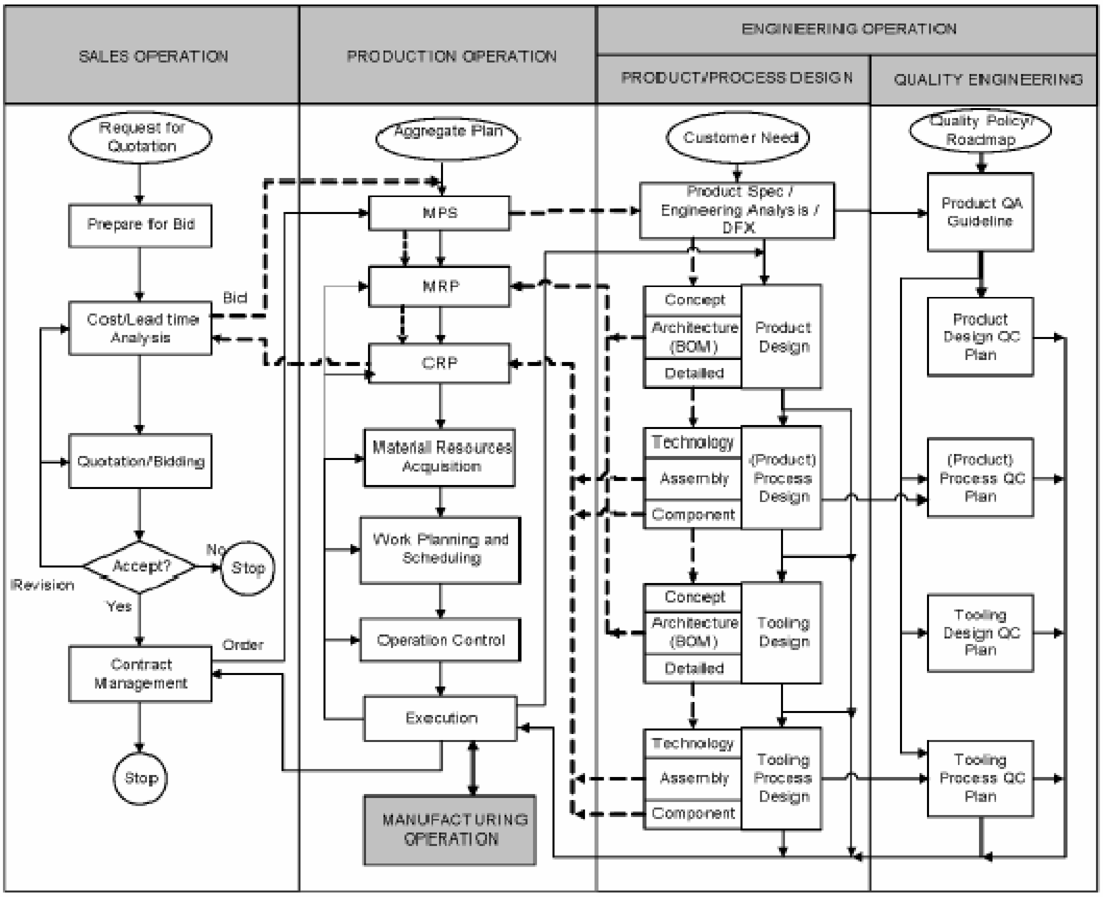

Figure 14. Concurrent ETO operation framework (Chen, 2006)

As detailed in figure 14, a sales process goes through the steps of bid (opportunity) evaluation, cost analysis, lead-time estimation, quotation preparation, bidding, negotiation, order acceptance and contract management. In the bidding process, multiple versions of a product specification and quotation may be prepared in sequence or in parallel with a possibly different solution technology, until the bid is accepted or terminated. From a bidding point of view, the most difficult task is lead time and cost estimation, which both require participation of various technical personnel.

5.5.6. Summary

The four presented models had different purposes and levels of detail. While the first three authors proposed high-level generic models (Ulrich and Eppinger, 1995; Alderman *et al.*, 2001; Munstlag, 1993), the last one advanced a more detailed analysis of ETO process (Chen, 2006).

Ulrich and Eppinger (1995) proposed a generic market-pull model and described the customization process as a deviation or variant of the generic model. This was argued to be insufficient to guide ETO companies. Alderman *et al.*'s (2001) two contrasting generic models explored the fundamental differences between off-line and contract processes, assuming that a number of hybrid forms of these two are more common in practice. Munstlag (1993) study analysed further the ETO process and introduced the Order Specification Level (OSL) concept in order to distinguish the different degrees of customer-order independent engineering. Finally, Chen (2006) provided a comprehensive framework dedicated to ETO process intended to be performed in concurrent fashion, introducing the concept of concurrent ETO operation. This framework applies the concurrent engineering, mass customization and lean manufacturing concepts, in order to economically minimize lead-times and assure delivery commitment, and therefore addressing critical problems affecting ETO companies.

5.6. Concluding remarks

In this chapter the main theoretical domains which will be applied to analyse innovation at competitive producers of machinery and equipment in the next chapter has been discussed. It was advanced industry and market taxonomies that may determine the innovation at firm and project level, the risks of innovation, the modes of innovation, and alternative models addressing ETO process.

The classification types, depicted in section 5.2, are intended to be used as independent and complementary approaches, and there is no hierarchy between them. Some distinctions and connections were made between the taxonomies presented.

In terms of innovation uncertainty, while all of the risk managing approaches encompass the idea of uncertainty, it is important to analyse the practices and risk perception in the projects, and the different approaches employed to prevent project failures, like budget and schedule overruns, compromised performance, and missed opportunities.

The two ideal modes of learning and innovation were described, together with their relation to the production and use of different forms of knowledge. It was also discussed the usefulness of the distinction between them and how these concepts can be made operational, resulting in different types of learning organizations.

Finally, it was presented four alternative models for ETO, which had different purposes and levels of detail. Although the practical use of some of these models could be contested, their description and discussion provided a multitude of views related to ETO process, contributing to put this subject into perspective.

After presenting the main theoretical domains, one can pursue to the analysis of innovation practice at competitive producers of machinery and equipment located in the Aveiro region, in the next chapter.

6. INDUSTRIAL CASE STUDIES

6.1. Introduction

This dissertation aims to shed light on innovation in competitive producers of equipment and machinery. The innovation at business level may emerge from specific features of the industry, of the market and of the firm itself. In this chapter the methodological aspects of the case study, background information of the companies, the results and discussion are presented. This chapter reports an exploratory and comparative multiple case study involving four capital goods producers located in the Aveiro region. It is explored the main features of these producers with implications for innovation, and analysed the dominant uncertainties associated, together with their process and modes of innovation.

6.2. Empirical data

6.2.1. Research methodology

The main goal of this research is to focus on issues regarding manufacturing of machinery and equipment, looking in detail at the innovation process within successful producers. It is an exploratory research with flexible and qualitative method of data collection, using a multiple case study approach in order to allow rich comparison and triangulation between companies.

The empirical study was conducted in the Aveiro region, Portugal, where the equipment industry is particularly dynamic and may play an important role acting as catalyst for technological innovation and determining productivity gains. The Aveiro district, located in the northern coastal strip, is one of the most industrially dynamic regions of Portugal, based mostly on SME specialized in traditional sectors, including the manufacture of capital goods and several supporting services. A previous study indicated that organizational innovations in Aveiro tend to be incremental in both product and process innovation, as the innovative effort of firms is mainly guided by reactive response to external and internal factors, rather than by pro-active attitudes reflecting strategies to gain dynamic comparative advantages (Castro *et al.* 1998). It is argued that firms usually manage to maintain a set of regular clients and sufficient turnover to survive and, in general, their unique excellence goals are the accomplishment of delivery schedules and of product quality patterns.

This behaviour may be rooted in the pattern of specialization based on mature industrial sectors, which are generally characterized by low to medium technological and informational content, and by traditional methods of management and by a preponderance of unskilled labour. This can explain, on one hand, the rather weak co-operation between firms, and between firms and innovation support institutions. However, the existence of a large number of export-oriented SME suggests a strong entrepreneurial spirit and a sign of industrial dynamism with growth potential (Castro *et al.* 1998).

It was selected firms that had more potential to have a competitive innovation process. The approach was as follows. First, it was asked experts in the industry to identify leading and competitive companies located in the Aveiro region. It was then crosschecked their export and competitive profile in public records like AICEP[3] and PRIME[4] databases. Finally, it was selected those that came with NACE code DK.29 - Manufacture of machinery and equipment n.e.c. In this dissertation the focus was only on the first 4 cases. Table 17 summarises the descriptive of the cases.

Table 17. Details of the studied companies (own depiction - Varum *et al.*, 2009)

Company	NACE code	Product	Sub-Sector	Turnover (M€)	Employees	Type of order	Database records
A	2956	Cutting machinery	Footwear, textile and stone processing	3,5	40	MTO / ETO	PRIME, AdI, AICEP
B	2921	Furnaces and burners	Laboratories and ceramic	0,8	15	MTO / ETO	PRIME, AdI, AICEP
C	2956	Lumber production facilities	Wood and cellulose	2,5	40	MTO / ETO	PRIME, AICEP
D	2956	Robotized integrated systems	Construction and metalwork	15,0	100	MTO / ETO	PRIME, AdI, AICEP

3 AICEP (Business Development Agency) is a benchmark agency for developing a competitive business environment that contributes towards the international expansion of Portuguese companies.
4 PRIME (Incentives Programme for the Modernisation of Economic Activities) is integrated in Area 2 of the Regional Development Plan – "Adjusting the Production Profile towards the Activities of the Future", and was designed to foster the productivity and competitiveness of Portuguese enterprises, and to promote new development capabilities. One of the main objectives is to mainstream research and development on new products and production methods in the enterprises.

Our study thus focused on firms' mode of innovation and knowledge, as well as on and identification of the sources of risk and uncertainty in this industry. The information was obtained during single or multiple visits at the four companies' sites and complemented with public information, direct observation, e-mail and telephone interviews. In the next section it is provide further details of the cases analysed.

6.2.2. The four cases: background information

In this section is presented some of the background information concerning the four capital goods producers, thus complementing the summary of table 17. This includes description of the NACE code, company localization, dimension, main products and markets, and other relevant information on their competitive or innovative profile, where available (Varum *et al.*, 2009).

Company A: NACE 2956 - Manufacture of other special purpose machinery n.e.c.

Company A is a medium-sized enterprise established in São João da Madeira, specialized in laser and water jet cutting machinery mainly for footwear and stone processing industries. Other equipment products relate to cutting, welding and milling machinery and general robotic applications. Company A employs about 40 workers, and is part of a group of complementary companies involved in the development and manufacturing of test equipment, software and electronics for the same business area. This company is also a member of a public funding competence network for fashion related industries, like furniture, textile, footwear and leather goods. Company A uses its own brand and each product is customized according to customer requirements, e.g. definition of equipment type, performance and dimensions are determined by the customer. The complete engineering design is done internally and most of the parts are purchased, like related products for control and instrumentation. Process type layout is used.

Company B: NACE 2921 – Manufacture of furnaces and furnace burners.

Company B is a small enterprise that manufactures mainly electrical furnaces and burners for laboratories and industrial applications, such as institutions from the National

Scientific and Technologic System (SCTN) and ceramic industries. This kind of activity was already a family tradition based in Águeda, and the firm has about 15 employees. Each product is customized according to customer requirements, e.g. equipment type and capacity, control functionalities, dimensions and safety compliance. The engineering design is made in-house by the R&D group created in 2004, within a NITEC[5] programme. Most of the parts are purchased, e.g. valves, pumps and other related products for control and instrumentation. The production layout used is also process-oriented.

Company C: NACE 2956 - Manufacture of other special purpose machinery n.e.c.

Company C is a family based medium-sized enterprise established in Aveiro, that specialized in all machinery needed for the wood and cellulose industries, being able to install complete sawmills or any lumber production facilities, including turnkey solution, exclusively with equipments produced in its workshop. Elements of the production line include everything from handling the raw lumber all the way to banding stacks, like for instance the sawmilling machines, debarkers and chippers, followed by carriages, band and circular saws, and a wide range of ancillary sawmilling equipment. Company C employs about 40 workers. Each product is customized according to customer requirements, such as the equipment type, capacity, feeding type and control functionalities. The complete engineering design is done internally. Most of the parts are purchased, like valves, pumps and other related products for control and instrumentation. Process type layout is also used here.

Company D: NACE 2956 - Manufacture of other special purpose machinery n.e.c.

Company D is medium-sized enterprise based in Ílhavo, and is a main supplier of robotized integrated systems for industrial applications, and a manufacturer of mechanical peripherals, electrical motors, generators, and special welding machinery. Company D also follows a family tradition in the business. Their main customers are in construction,

5 NITEC programme is a PRIME public funding system of incentives for the creation of small R&TD teams in the enterprise sector, implemented under the surveillance of the Innovation Agency (AdI), whose purpose is to support projects that improve productivity, increase competitiveness and aid the insertion of companies in the global market.

metalwork and other industries where the productive processes demand high integration of robotized solutions. Company D employs about 100 workers and belongs to the national enterprise rankings like sectorial top 100 with NACE 29 (A.E.P., 2007) and top 1500 SME (Fórum Empresarial, 2004). Each product is customized according to customer requirements, e.g. equipment type, capacity and control functionalities. The complete engineering design is done internally by the R&D group created in 2006, within a NITEC programme. Most of the parts are purchased, like valves, pumps and other related products for control and instrumentation as Company D is a partner of a world-leading supplier of robotic automation for Portuguese and Spanish markets assuming the position of a System Integrator company[6]. Again, process type layout is used.

6.3. Results

6.3.1. Companies classification

It was found that companies are highly specialized in specific industry markets, such as leather and stone processing, laboratory furnaces, sawmills, and industrial welding robots.

According to the market type specialization used by IFO Institute (1997) the companies studied can be described generally as 'customized engineering and plant suppliers', stemming from medium-to-high customization of products, according to the type of product being considered. Thus, they generally produce custom products in very low volume and very small batches (batch and jobbing production), using process-focused and to-order types of production. Moreover, in relation to market strategy, their competition is based largely on meeting clients' needs, keeping delivery promises, quality, and flexibility.

Jobbing production is characterized by low volume (often one-off) production of a wide range of products with demand for any one single product being difficult to forecast. For one-off production, it is not normally expected that a product once produced will be

6 "A System Integrator company is an independent value-added engineering organization that focuses on industrial control systems, manufacturing execution systems and plant automation that requires application knowledge and technical expertise for sales, design, implementation, installation, commissioning and support." - CSIA Guide to Control System Specification and System Integrator Selection – Volume 1, October 9, 2000.

required in that exact form again (or, if it is, there will be a long period between orders). Plant capacity is difficult to define, being dependent on the current product mix. Routings through this type of production facility are dictated by the manufacturing needs of the individual products and work centre layout is based on manufacturing processes. This class of manufacture, usually labour intensive, requires a highly skilled labour force, working in a flexible production facility, often referred to as a job shop.

A typical example of this class of manufacture is the production of capital goods such as customer specific equipment found in all four companies. Thus, these are mainly identifiable as MTO/ETO type. This characterisation is based on the distinction made by Sari, (1981). Thus, the degree of engineering involvement and the design process distinguish both types, and can also be determined by the balance between the generic and specific aspects of product development. Table 18 summarises the main issues identified.

Table 18. Characterisation of the studied companies (own depiction - Varum *et al.*, 2009)

Production control (Sari, 1981)	Market specialization (IFO, 1997)	SME innovative level (Hoffman, 1998)	Additional characteristics	Competitiveness factors
ETO in core business and special products MTO in semi-standard products and spare-parts	Customized Engineering and Plant Supply, focused on medium-to-high product customization	Specialized Supplier, focused on design, development and production of specialized machinery	Job Shop and Process-focused production Products with Incremental qualitative change Labour intensive	Flexible production facility Meet clients' needs, keeping delivery, quality and flexibility Highly skilled labour force

The specialization of the companies may be due to constraints in technical expertise, experience, skills, capacity, production equipment, parts' procurement or product design. According to the intensity of customization, the products manufactured by the companies in study vary along a continuum from semi-standard to special product.

Semi-standard products are usually low customized products based on existing designs with few changes and adjustments, allowing a great reuse of design specifications with some new requirements. The cost control of this type of product is also easier and known. These products are usually produced in small batches, and are often found in the companies were the products and production situations are closer to MTO reality. All four companies have semi-standard products in their portfolio, of which some of them are manufactured in MTO situation. Companies A, C and D also have a spare part business in a MTO production.

Special products are those which need a greater involvement of engineering in the design, as in pure customization where the formulation of specifications and agreement on the concept and engineering design details are vital in meeting product requirements. Customers must approve every design change before manufacturing. Therefore, these products are usually less frequent but also with higher profit margins, and higher technical and management risk. Production is usually on a one-off basis or in small batches, and is mostly found in the companies where the products and production situations are closer to ETO reality. All four companies in study have their core business settled with ETO production type.

It is also important to clarify the types of SME according to the innovative level. Therefore, the companies are mainly identifiable as ‘specialized supplier’. According to Hoffman *et al.*’s (1998) taxonomy, these companies are typically traditional businesses focused on the design, development and production of specialized machinery. During the interviews, it was also noted that the companies usually use customers as their main sources of information and as their main drivers of innovation.

As expected, the data also indicates that we are mostly confronted with incremental qualitative change rather than radical change, when the companies in study are asked whether they have introduced new products on the market. This finding confirms the results reported in a previous study by Castro *et al.* (1998).

6.3.2. Dealing with innovation uncertainty

Uncertainty factors in innovation activities perceived by the analyzed companies were easier to identify at project-level than at the product development phase-level. As customer driven engineering and manufacturing companies, the risks evaluated at both levels varies significantly, depending on the intensity of customization required by the customer order. At project-level, while frequent deviations or variation uncertainties were identified in both types semi-standard or special products, foreseeable uncertainties were mostly identified in customer specific or special orders. Table 19 summarizes the main uncertainties identified.

Table 19. Summary of main uncertainties in the studied companies (own depiction - Varum *et al.*, 2009)

<table>
<tr><th></th><th>Uncertainty type</th><th>Mitigation methods</th><th>Project uncertainties</th><th>Additional uncertainties</th></tr>
<tr><td>MTO and semi-standard products</td><td>Variation uncertainties</td><td>Instructionist approach
PDCA</td><td rowspan="2">Variety of products and components
Low degree of design rigidity
Poor design specifications
Ongoing design changes</td><td rowspan="2">Demand volatility
Variety of processes and sources of supply
Tendering process and contract agreement
Overlapping of manufacturing and design activities</td></tr>
<tr><td>ETO and special products</td><td>Foreseeable uncertainties</td><td>Senior management involvement
Planning and learning 'as you go'
Improvisation approach</td></tr>
</table>

The most common variation uncertainties identified were deviations on project budget, delivery dates and ongoing minor design adjustments along the process. These uncertainties occur frequently and are perceived as normal deviations in projects, which are managed mainly by implementing corrective actions. These uncertainties may be rooted in the operations complexity, typical of capital goods firms. In the companies covered in our study, there are always ongoing design changes and frequently involve high complexity in terms of volume, variety of products, components, processes and sources of supply. Nevertheless, system integrator company D manages to reduce supply source complexity with a privileged partnership with a world-leading supplier for robotics and automation.

Moreover, a high volatility of product demand makes product forecast practically unfeasible. In addition, the "overlapping of manufacturing and design activities as well as engineering revisions" often complicates design and production, which can make this a major source of complexity in the management of capital goods manufacturing.

In terms of foreseeable uncertainties, they were identified mostly related to product specification changes of a more critical nature, with significant impact on product or component performance, which often requires further design activities. These uncertainties may be the result of difficulties in implementing a particular technical solution, the event of additional customer requests or in response to predictable side effects.

At product development phase level, the four companies identified the design specifications phase, as the most critical in their product development process, as typically part of the product specifications have not yet been defined because they are customer specific. Therefore, it is also common in the analysed companies for senior management to become involved in the product specification and the whole tendering process, as order acceptance is often strategically important, as well as the contract agreement due to legal and commercial consequences.

In defining a project, clients' needs can also be evaluated, and this is a crucial moment that leads to the decision to begin the development of a new product. It was found during interviews that the role of the entrepreneur is the principal innovative source in company B and C, while internal teams and the market tends to have increasing importance as innovative source for companies A and D, although senior management is still involved. The dimension of companies and workforce composition can explain this tendency, as they seem directly related. According to Calabrese *et al.* (2003), the individual entrepreneur typically carries out the evaluation of the clients' requests through the commercial network, the marketing function, or the product manager to whom the task of coordinating the product development activities has been delegated.

As ETO oriented, these four companies offer a range of products based on earlier experiences and product developments related to basic technology used in each machine or installation. The degree of product design rigidity is therefore very important in evaluating uncertainties, as it strongly depends on the customization options offered to the customer. Consequently, innovation is often related to customer orders, and specifications can only be coordinated for specific customer orders. However, during the interviews it was noticed that it was common for these companies to work with poor design specifications from the customers, thus increasing the risks and uncertainties involved in the process.

Uncertainty factors like above-mentioned hinder planning of the process, resources, lead times, and cost controlling. This is consistent with the concerns described by early works (Hicks *et al.*, 2000; 2001; and Little *et al.*, 2000) regarding production planning and scheduling as one of the major problems faced by ETO firms, and delivery performance of most critical nature. This is so because, in the tendering process, if the delivery date is to long there is a risk of not winning the order. On the other hand, if the delivery date is too short, there is a risk of being unfeasible, leading to late deliveries, budget increase, or even contract penalties. The performance of the case study companies reflects these concerns, with all the four companies showing frequent deviations on delivery performance, in terms of completion of projects on time and on budget.

In terms of risk and uncertainty control methods, none of the companies effectively used computerized project management systems. Although they use some planning maps centred on the project structure, their use is limited to documentation purposes and based on word processor systems or paper. Management and control methods are essentially done by the inclusion of cost and time margins in the project plans, the drawing up of contingency plans, definition and control of specific intermediary goals or milestones and less sophisticated techniques like PDCA (Plan-Do-Check-Act).

To conclude, from the analysis, one can identify predominant uncertainties of type variation and foreseeable risks on daily basis operations related to project planning and production, in particular when related to a customer order for semi-standard products. These uncertainties are managed mainly by adopting an instructionist approach. In a rather informal way, planning and learning 'as you go' approach are also used, particularly when the level of customization is high or in case of special products. The most important lessons learned on one project are occasionally passed on to the next one, although there are no procedures for that. In the case of lack of information or higher uncertainty, the detailed planning of activities is done only until the next verification or milestone. The continuous resort to the ability to improvise is a common characteristic in all four companies. This may also be a result of traditional management methods and a certain reluctance to plan their business activity in detail.

The implementation of better product design procedures and instruments that could retain critical information and lessons learned from mistakes in the past could reduce the number of errors and re-designs. Through a better mapping of the risks faced, at both phase- and project-level, and a better mastery of expertise could improve companies' learning and innovation process and reduce projects deviations and failures.

6.3.3. Modes of innovation and learning organizations

"Developing effective systems for capturing and sharing information and knowledge is a critical issue" for capital goods firms (Hicks *et al.*, 2000). Although the intentional use of networks could allow for the linking of activities and sharing of information and knowledge, especially when it comes to project management, in the four companies this is done mainly in an informal way. Much of the knowledge is tacit rather than explicit, which can cause problems when personnel changes occur. There is also a high predominance of local knowledge rather than global, which can be explained as these companies are typically family owned SME (except company A), and they are basically specialized in mature and traditional industrial sectors.

Although with different strategies and intensities, these companies have been trying to incorporate higher technological and informational content in their products, in order to increase their capacity to differentiate products and offer better and broader solutions to customers, which is perceived as a main factor of competitiveness. However, this strategy is challenged by human capital characteristics in this sector, namely patterns of rather unskilled labour and traditional methods of management used, as previously reported in a study made in Aveiro region by Castro *et al.* (1998). It is also considered that the low to moderate employment of scientifically trained personnel can be another difficulty, particularly in ETO or engineering companies, where company A is clearly a positive exception. As described before, the lowest employment of high education/graduated personnel was registered in company C, where only 8% of total employees had a university degree. On the other hand, in company A about 30% of total employees were educated to such a level.

During the interviews, it was noted that these companies manage their projects, product customization and operations in a rather informal way. In addition, on a daily basis companies tend to use mostly their ‘know-how’ and ‘know-who’ knowledge, acquiring ‘know-what’ and ‘know-why’ knowledge through technology transfer facilitators, like the Innovation Agency (AdI) as mentioned above (*i. e.* companies A, B and D). However, these capital goods producers deal with the four types of knowledge while working on a typical customer’s request: generic information like a part list or the technical characteristics of a component (know-what); the knowledge about laws of physics or an engineering science field (know-why); the specific capability to produce the customised product (know-how); and the capability to cooperate with customers, suppliers and experts (know-who).

If one tries to compare our companies with the results found by Jensen *et al.* (2007) in their research on Danish companies, two different types of learning organization can be generally identified: the Low learning mode in company C, and the STI learning mode in companies A, B and D. Thus, neither the DUI nor mixed DUI/STI modes were found in the case study companies. This may be so because the indicators in data collected shows that none of these companies have highly developed forms of organization that can support DUI-learning, or have rarely implemented organizational characteristics typical for the learning organization.

During interviews it was clear that the DUI learning organization dimensions were nearly absent, with few exceptions like cooperation with customers. In Table 20 it is summarised the DUI mode indicators as collected through interviews.

Table 20. DUI-mode indicators in the studied companies (own depiction - Varum *et al.*, 2009)

Indicator	Question used	Coding used		Company A	Company B	Company C	Company D
Softened demarcations	How have the demarcations between the employee groupings within production/service (main field) developed during last 5 years?	More indistinct to invisible	More distinct to remain unchanged	Remain unchanged	Remain unchanged	Remain unchanged	Remain unchanged
	Does the firm make use of some of the following ways of planning the work and paying the employees:						
Cooperation with customers	Cooperation with customers?	High extent	Some extent to not at all	Some extent	Some extent	Some extent	Some extent
Quality circles	Quality circles?	Yes	No	No	No	No	No
Proposals collecting systems	Proposals collecting systems?	Yes	No	No	No	No	No
Inter-disciplinary workgroups	Inter-disciplinary workgroups?	Yes	No	No	No	No	No
Autonomous groups	Autonomous groups?	Yes	No	No	No	No	No
Functions integration	Functions integration?	Yes	No	No	No	No	No

It was found that companies mainly use customers for gathering requirements and ideas about the problems they face, and use suppliers when searching for solutions, without losing sight of what the competitors are doing and what is happening in the market. In addition, this is usually done in informal and casual fashion way by the entrepreneur (companies B and C) and internal teams (companies A and D). Companies A, B and C also acts as OEM - original equipment manufacturer - producing equipments to be marketed abroad under another company's brand.

In relation to quality management focused on engaging employees, they said it was not used or rather used informally, “due to the small size of the companies where everybody knows each other, and thus feels free to ask, suggest or participate in solving daily problems of the company”. This quality management indicator includes the use of quality circles and systems for collecting proposals from employees. As none of the companies uses these systems, one expects it to be difficult to engage the employees in a continuous improvement process. Also absent are the indicators related to organic and integrative organization, as the use of inter-disciplinary workgroups, autonomous groups, functions integration and softened demarcations between employee groupings.

Companies A, B and D can be described as STI learning organizations, although with different intensities. All these companies share a common characteristic, *i. e.* cooperation with researchers, in the recent past or in the present, varying from ‘at least on some rare occasions’ to ‘continuously’. All companies grabbed the opportunity of public funding programmes, that are usually managed by or executed under the surveillance of the Innovation Agency (AdI), and in the process the companies receive key technology transfer in cooperation with institutions of the National Scientific and Technologic System (SCTN). These programmes are of major importance as they help in the assimilation and development of technological competence inside the companies, and stimulate the link between public R&D institutions and enterprises. Companies A and B in particular can be described as having regular cooperation with researchers and public funding programmes champions, as they developed long term cooperation by investing in strategic and innovative projects in collaboration with SCTN institutions.

For instance, companies B and D participated in NITEC programmes (2003 - 2006) in order to set up small internal teams of R&D in the firms, formed by a maximum of three persons with an exclusive and permanent nature. Company D also got involved in a collaborative R&D project, established in 2005 with the University of Aveiro, for the implementation of visualization techniques on welding machines. On the other hand, Company B has a longer relation with AdI, which started with two consortium projects in 2001 and 2002, where the first one was a pan-European network for market-oriented industrial R&D. More recently (2003 - 2006) company B participated in applied enterprise

R&D involving an SCTN institution associated with consortium contracts, also supported by another public incentive system. Table 21 summarizes the STI-mode indicators.

Table 21. STI-mode indicators in the studied companies (own depiction - Varum *et al.*, 2009)

Indicator	Question used	Coding used		Company A	Company B	Company C	Company D
Cooperation with researchers	How often has the firm cooperated with researchers from SCTN institutions during last 5 years?	Rarely to continu-ous	Never	Continuous (long term partnership)	Continu-ous	Never	On some occasions
Workforce composition	Does the firm employ scientifically trained personnel? (how many)	Yes	No	Yes, 30% (12 eng.)	Yes, 20% (3 eng.)	Yes, 8% (3 eng.)	Yes, 17% (17 eng.)
R&D expenditure	Does the firm have expenditure for R&D oriented activities, including external services?	Yes	No	Yes (core strategic investment)	Yes (NITEC)	No	Yes (NITEC)

Company A is clearly the one that has developed the most frequent and strongest cooperation with researchers, and investing in internal R&D has been part of the strategy of this company since from the start, for it is aiming to be a technology leader in its core business in the global market. Actually, this company has several innovative equipments and solutions in national and international markets, achievements resulting from internal R&D and cooperation with SCTN institutions, professional associations and involving cooperation networks.

A long relationship with a sectoral professional association resulted in developing projects related with the modernization of the industry, in the period from 1996 to 2000, resulting in significant increases in productivity. In order to remain competitive and intensify their internationalization strategy, company A implemented two projects last year with PRIME incentives. This company is also member of two cooperation networks with innovation purpose, one is an innovative SME network within an enterprise association and the other a competence network for fashion related industries, both having the participation of SCTN institutions.

Furthermore, company A is also the only company in study that currently owns valid and effective patents, one applied for in 2002 and another in 2004. Company C has also applied for three patents in the past, but they are all expired due to the lost of commercial interest.

In the workforce composition indicator, Jensen et al (2007) defined the scientifically trained personnel as those "having a Bachelor, Master or Ph.D. degree in natural sciences as well as civil engineers". This is used here in a slight broader sense, also including other science field engineers like mechanical, electronic and materials, as we think is reasonable for the kind of companies under study and the industry sub-sector in which they operate. Thus, in terms of data collected, all four companies employed at least some personnel with university degrees. Companies A, B, and D have more balanced rates, reaching 17%, 20% and 30% of total employees, although the small-sized company B faces critical dimension problems. Company A and D employ about 12 and 17 graduate level employees. Nevertheless, it is a common opinion that there is a general lack of qualified technical work force and that competitiveness could be improved with the increase of more qualified personnel in the companies, principally in companies B and C.

In addition, another characteristic in common in companies A, B and D is the R&D expenditure. They all develop R&D activities, both internally and externally by contracting R&D services from SCTN institutions, government laboratories, professional associations or other companies. As the public funding programmes do not fully cover the expenses, these companies choose the projects in which they participate very carefully due to often scarce financial and human resources.

Finally, company C can be clearly identified as a low learning organization, since it has more similar characteristics with the static or low learning organization, rather than with the other modes identified by Jensen *et al.* (2007). During the interviews, it was clear that this company has neither the highly developed forms of organization that can support DUI-learning, nor it is engaged in activities that indicate a strong capacity to absorb and use codified knowledge, the STI mode. Rather it has very limited DUI mode indicators and casual or opportunistic STI mode indicators in the past.

This company does not have any formal policy for R&D expenditure, or for cooperating with researchers. Although in the past it had some isolated initiatives with low impact and success, a complete absence of these policies in their current strategy and operations was evident. This situation may be explained by the fact that, even in comparison with the others, this firm has a low level of employment of scientifically trained personnel, with a bachelor degree or higher. Actually, out of 40 employees in the company C, only three hold a university degree.

Table 22 summarizes the main findings regarding modes of innovation at the analysed companies.

Table 22. Summary of modes of innovation in the studied companies (own depiction - Varum *et al.*, 2009)

Company	Innovation mode	Main indicators	Main innovation sources
A, B, D	STI	Cooperation with researchers Employment of scientifically trained personnel R&D expenditures Lack of DUI mode	Customer orders Competitors and market surveillance Public funding programs, in cooperation with AdI Cooperation with SCTN institutions
C	Low learning	Lack of DUI and STI modes Very low employment of scientifically trained personnel	Customer orders Competitors and market surveillance

6.3.4. Engineer-to-order (ETO) process

A major element of best practice is that companies should establish formal definitions of generic process structures for their main project types (Maffin *et al.*, 2007, citing Andreasen & Hein, 1987, and McGrath *et al.*, 1992).

Although all four companies analysed claimed to have a generally good understanding of their development process, it was confirmed during the interviews that there were no formal procedures for governing their core projects, and no clear definition of the major stages, activities or milestones.

This may be a result of traditional management methods and a certain reluctance to plan their business activity in detail. In addition, none of the firms analysed were compliant (or in the process of getting compliant) with the ISO 9000 Series of Standards, especially ISO 9001. In order to achieve certification, a documented process and evidence that the process is performed as documented are usually required. A process model that is actually used by all people involved in the development activity can provide both (Negele *et al.*, 1999).

As the continuous resort to the ability to improvise is a common characteristic found in all four companies, their development process were poorly standardized and documented, although some phases executed may be considered repeatable and with possibly consistent results. Taking as reference the development process maturity model from CMMI-DEV (SEI, 2006), this finding is consistent with the description of the lowest level of process maturity, the so-called Level 1 or "Initial", where firms often uses *ad-hoc* development processes, which are typically reactive, poorly controlled and thus often unpredictable.

There are some variations on the innovation process activities identified, which depends on the company policies and their core business, the project type, the customer's specific requirements and the level of customization. For instance, in the case of a request for a semi-standard product, most of the design related activities can be reduced or skipped, and the process would follow an operation mode closer to make-to-order (MTO).

Therefore, this process description is of generic and conceptual nature, at a high-level of abstraction, aiming to grasp the main features and patterns related to the ETO business making of the capital goods companies analyzed.

In this section is presented a typical process with the key activities identified in the ETO business making of the capital goods companies analyzed, more specifically those activities related to the new product development (NPD) process. In bold letters are showed the activities or events that seemed critical in their business, which can be used as milestones or phases in their product development process (figure 15).

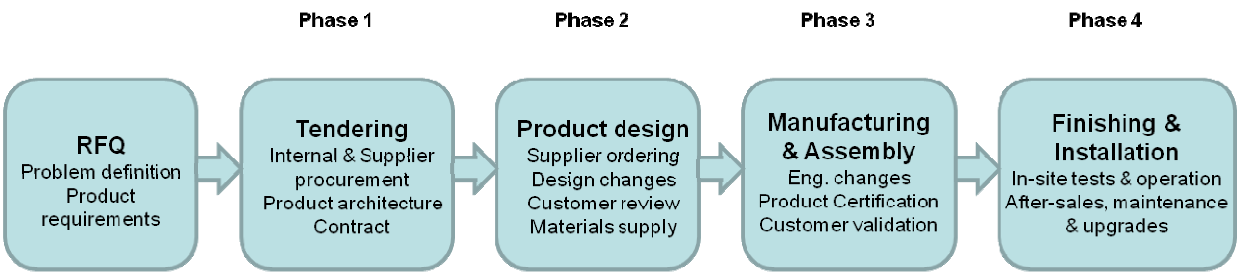

Figure 15. Typical ETO process of the studied companies (own depiction)

The typical development process in these companies is product-focused. They assume a market exists because ideas are generated directly from the customers, usually by a Request for Quotation (RFQ), and related to detailed operations. For this reason, little traditional market research is conducted. The trigger for initiating the next phase of development is consensus in the team that the product is ready to move to the next stage.

By analysing and comparing the process activities depicted above with the PDP models literature, ones realize that there are fundamental discrepancies. This strongly indicates that the *main theoretical models of product development process are not suitable to the ETO reality*, due to significant differences in operations and product development activities carried out by the companies identified in this study.

Comparison with common theoretical models:

- Design is usually exclusive to one customer, who most likely provides the technical product requirements and a contract;
- Customers always get involved in the product design and in the review-validation activities, from beginning to end of the process;
- Execution of different activities or sequence of activities, which is most evident the critical order-winning activities;
- Overlapping of manufacturing and design activities, as well as ongoing engineering revisions;
- Start of detailed product design and manufacturing activities depends directly on the contract agreement or customer order placement;
- The installation and maintenance -related activities are important part of the business process;
- No prototypes are used, and products are tested 100% (as opposed to sample testing), and which are continuously modified or adjusted through the process.

Comparison with alternative ETO models:

- The process here presented is less generic and high-level than the models suggested by Ulrich and Eppinger (1995), Alderman *et al.* (2001) and Munstlag (1993). On the one hand, the process here presented is not intended to fit all situations nor all capital goods companies, but to reflect typical ETO operations in the four studied companies and provide a little more detail of their innovation process.
- Rahim and Baksh (2003) provided a list of six critical features why common models are not suitable for ETO firms. In table 23 it is evaluated and compared

each of the four alternative processes and the studied ETO process in the view of the mentioned six critical points. The direct answer to these points gives a favourable (+) or unfavourable (-) evaluation, in terms of applicability and utility potential of the corresponding process model, to the issues and challenges ETO companies face, in the context of Rahim and Baksh (2003) critic.

Table 23 Comparison between alternative ETO models and studied ETO process (own depiction)

Six critical features why common models are not fit for ETO firms (Rahim and Baksh, 2003):	Ulrich and Eppinger (1995)	Alderman et al. (2001)	Munstlag (1993)	Chen (2006)	The studied ETO process
1. Do not include external parties in the process (such as customer, supplier, and contractors)?	-	-	-	-	+
2. Do not show post assembly or post manufacturing activities such as delivery, commissioning, handover to the customer, which is common for ETO product?	-	+	+	-	+
3. Do not show concurrency between activities?	-	-	-	+	-
4. Targeted for designers and manufacturers and leave out other parties?	-	-	-	-	-
5. Do not show the use of CE tools and techniques in detail at different stages?	-	-	-	-	-
6. Flow of activities represents MTS operations, instead of ETO?	-	+	+	+	+

6.4. Concluding remarks

This chapter reports the results of an exploratory and comparative multiple case study involving four capital goods companies located in the Aveiro region. It is explored the main features of these producers with implications for innovation, and analysed the dominant uncertainties associated with their innovation process and modes of innovation.

In the context of this dissertation, it is summarized some existing theoretical frameworks, relevant for the analysis of innovation processes in an environment of uncertainty, and used these frameworks to analyze empirically four companies. Considering the limited number of firms covered in the empirical analysis, it is proposed that the results should not fall into abusive generalizations. However, the results of our study highlight several avenues that would help researchers to better channel their efforts in studying the phenomenon and help managers to foster innovation at their companies and in this way firms' competitiveness. It is summarized the main avenues in the following passages.

First, at firm level, it is emphasized a recurrent problem associated with knowledge externalisation. All four firms seem too much reliant upon tacit knowledge and informal collaboration. This is positive in the sense that it allows higher and richer knowledge transfer due to human face-to-face interaction. It is, however, problematic in the current context of human resources mobility and spill over of expertise. Key knowledge should be saved in the company, even when key employees leave. Thus, it is pointed a necessity to implement formal procedures for knowledge management, focused towards the development of a knowledge base (organizational memory) making strong versions of the DUI- and STI-modes work together in promoting knowledge creation and innovation. Machinery producers can develop more global and efficient solutions on the basis of local knowledge and learning, as they address many different users, gathering knowledge about the needs and the performance of different technical solutions.

Second, still at firm level, it is emphasized the importance of clients as promoters and enablers of the innovation process. The analysed companies develop new products with a high degree of customization and adaptation to customer requirements. One might say that the quality of the inside innovation appears bound to the quality and exigency of clients. The capacity of these specialized suppliers to innovate is by meeting clients' needs, keeping delivery, quality and flexibility. This seems to rely on their ability to win contracts and interact proactively with the lead users, supported by a highly skilled labour force, flexible production facility and cooperation with researchers. Thus, the client appears to be an important asset and source of innovation for the firms, making tendering process an important success factor for these companies, but also a major source of uncertainty caused by difficulties in gathering correct design specifications and keeping delivery promises.

Third, from a more theoretical perspective, during the study and the data analysis component, it became noticeable that the proposed models for product development process poorly fitted the four companies studied and the apparent innovation dynamics in capital goods industry. Therefore, from a more practical perspective, it is presented a typical process with identified key activities of ETO operations in the four studied capital goods producers. By analysing and comparing empirically-based process here presented with the common theoretical models, ones realize fundamental discrepancies between them. As a result, the main theoretical models of product development process are not suitable for the studied reality. Moreover, the studied ETO process is further contrasted with the alternative ETO models in the literature and with Rahim and Baksh (2003) six critical points for a process model to reflect ETO operations reality, or not. The results are encouraging and moderately favorable to the studied ETO process. Therefore, it is argued that the proposed process depiction with further improvement could help the studied companies to mature and improve their “ad hoc” process, which presents many weaknesses including e.g. lack of predictability and not being able to get ISO-9001 certification;

The last issue relates to one of our difficulties during empirical study and questions the empirical application of the model on modes of innovation. Some adaptations were made in course of this study. It was rather difficult to identify the proper indicators to measure the modes of innovation, which points to a need to develop these modes further, identifying, testing and drawing up reliable indicators and metrics to be used consistently in future empirical research. It is believed that this would be another important contribution.

PART IV – SUMMARY OF CONCLUSIONS

7. SUMMARY OF CONCLUSIONS

Innovation, and product innovation in particular, is an increasing necessity for many companies that is pursued with the expectation of increased profits, sales and market share. However, it can fail due to cost overruns, technical difficulties, and missed market opportunities. For the analysed capital goods companies it is argued that product innovation is mainly part of their daily business of incremental adaptation and improvement of products driven by customer specific requirements. These companies develop and produce machinery and equipment in response to customer's orders, here typified as operating in engineer-to-order (ETO) and make-to-order (MTO) mode.

This dissertation explored the innovation process models theory with a literature review and a bibliometric analysis, followed by a case-study research of innovation practice in the capital goods industry. From the theoretical perspective, the general literature was explored and further compared with the scarce specific literature identified, contributing to bridge a gap in the literature. From a more practical perspective, this dissertation's contribution is on the case study analysis of four capital goods producers concerning product innovation, giving the context and specific characteristics of the industry sector, the project uncertainties, the modes of innovation, and the particular engineering-to-order innovation process.

In the end of each chapter of this dissertation it was summarised the concepts presented and / or discussed the results obtained, depending on the purpose of the chapter. Therefore, this last chapter merely reports the main findings and implications in the context of the whole research. Furthermore, the achievement of the proposed objectives is evaluated, the research limitations are exposed, and finally it is concluded with some suggestions for future research.

7.1. Summary of findings

In the making of this dissertation it is learned the particularities of the business of developing and manufacturing engineered-to-order capital goods, and how these influences and affects their efforts of product innovation. This section reports the main findings in the context of this dissertation, summarizing the avenues in the following passages.

Firstly, from a theoretical perspective, this dissertation fully *supports the claim that ETO companies and their innovation process have been in fact neglected by academic research* and instead, they mainly focus on high-volume MTS operations mode.

- The results confirm that common product innovation models do not address the particular needs and problems of ETO companies, and the studied capital goods producers in particular. Despite this, very few studies dealing with ETO innovation process has been identified in the academic research and publication. Therefore, the alleged gap in the literature is evaluated and largely confirmed by this analysis;
- In view of the particularities and challenges of ETO capital goods companies, the scarce ETO literature identified follows the Production or Manufacturing approach. A possible explanation is that ETO organizations typically face operational difficulties like the scheduling of engineering and production activities, and responding to customer requirements in terms of lead time or delivery promises, in particular. This also indicates that the product development process (PDP) are viewed as a production process in this reality and by the academic research, and thus explaining why the PDP terms like "product development process" or "product design process" are not used in the ETO-specific literature. Therefore, it is argued that the inclusion of ETO process in the PDP body of literature could promote the research of ETO process models within a product development perspective.
- NEW-THEORETICAL-CONCEPTUAL-GROUP-THEMES-OF-PDP-PROPOSED,-BASED-ON-CONCLUSIONS

Secondly, this dissertation *contributes in complementing the literature gap* with the analysis of four case studies where is evaluated *how these capital goods producers pursue product innovation*, by identifying the process and mode of innovation used, and the typical challenges and uncertainties they face, giving the industry context.

- At project level**,** it is presented a typical process with identified key activities of ETO operations in the four studied capital goods producers. By analysing and comparing the process here presented with the common theoretical models, ones realize fundamental discrepancies between them. As a result, the main theoretical models of product development process are not suitable for the studied reality. Moreover, the studied ETO process is further contrasted with the alternative ETO models in the literature and with Rahim and Baksh (2003) six critical points for a process model to reflect ETO operations reality, or not. The results are encouraging and moderately favorable to the studied ETO process. Therefore, it is argued that the proposed process depiction could help the studied companies to mature and improve their "ad hoc" process, which presents many weaknesses including e.g. lack of predictability and not being able to get ISO-9001 certification;
- Still at project level, despite the risks and uncertainties identified, none of the studied companies actually deal with them in organized manner. They rather prefer to improvise and "learn and react as you go", showing a certain reluctance to plan their business. This approach, together with the mentioned lack of DUI-mode, dampers organization learning and expose the company to greater risks. One related recurrent problem seems to be the delay of product delivery date and cost overruns.
- At firm level, it is emphasized a recurrent problem associated with knowledge externalisation. Consequently, it is pointed a necessity to implement formal procedures for knowledge management, focused towards the development of a knowledge base making strong versions of the DUI- and STI-modes work together in promoting knowledge creation and innovation. It is also emphasized the importance of clients as promoters and enablers of the innovation process. Therefore, the client appears to be an important asset and source of innovation for the firms, but also a major source of uncertainty.

7.2. Achievement of objectives

In order to *provide a better insight into innovation process of capital goods producers*, focusing on issues regarding management of development and manufacturing of machinery and equipment, a number of research objectives have been addressed:

5. To understand the particularities of developing and manufacturing engineered-to-order (ETO) capital goods;
6. To review the literature on theoretical models of product development process and to evaluate them in terms of their applicability to the capital goods industry;
7. To evaluate the apparent gap in the literature, *i. e.* to confront the claim that ETO companies and their innovation process have been neglected by academic research;
8. To evaluate how these capital goods' producers pursue product innovation in practice, i.e. the processes and modes of innovation used, and to evaluate the typical challenges and uncertainties they face.

By linking each proposed objectives to the corresponding analysis pursued, and the results and insights obtained, through the chapters and sections of this dissertation, one can believe that the stated objectives were achieved. Consequently, and considering the relevance of the capital goods industry and the identified gap in the literature, one can assume that the global objective of providing a better insight into innovation process of capital goods producers has also been achieved, in the context of this dissertation.

7.3. Limitations

Considering the limited number of PDP theoretical models included in the literature review, it is proposed that the results should not fall into abusive generalizations. The same generalization limitation applies to the bibliometric analysis of product development models theory, since it covers a restricted number of years in detail. Although the bibliometric analysis of articles focusing on specific ETO process covered all years, there is always the possibility that some relevant publication or Journal is not included in the database used. As an example, the four alternative models for ETO presented here were not found in the ISI Web of Knowledge platform. Similarly, in view of the narrow number of firms covered in the empirical analysis, the generalization of the results is very limited beyond the studied capital goods producers.

7.4. Suggestions for further research

One evident future research direction to point is to further develop the field of ETO-process models within product development perspective in general, and e.g. focusing on the new research agenda of electronic new product development (e-NPD) in particular. To pursue the challenge for a new product development framework for ETO products (e.g. as the one thrown by Rahim and Baksh, 2003), or to further test and improve the alternative ETO models presented in this dissertation, in order to help capital goods producers to better deal with their problems, seems to be a relevant research and a noble cause, at least.

Subsequently, another future research agenda is pointed in the direction of fulfilling the need for more and better insights on ETO operations in general, and on capital goods in particular, as the number of publications and articles addressing this operation mode or this industry sector is still extremely small.

The analysis and application of risk management tools, and project management methods in general, could help improve how these companies deal with their uncertainties in more efficient way. The application of knowledge management and business process reengineering techniques could also be another interesting direction to go in future research.

Finally, in view of some difficulties to identify the proper indicators to measure the modes of innovation dimensions, thus questioning the empirical application of the model, another research direction is pointed for further developing the modes of innovation, e.g. by identifying, testing and drawing up reliable indicators and metrics, to be consistently used in future empirical research.

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APPENDICES

Appendix A: Glossary of terms

This appendix is intended to be used as a quick remainder of the meaning of the terms used, considering the context of this dissertation. It is not meant to be a detailed description or definition of these terms.

Capital goods – The main activities of capital goods firms are the design, manufacture, and construction of machinery and equipment. They supply highly customized products, in low volume production. According to Maffin and Braiden (2001), their products tend to be manufactured for downstream industrial producers to use in the production of other goods and services, rather than for final or household markets**.**

Engineer-to-order (ETO) – An ETO company is specialised in the engineering and production of custom-built products based on a customer order (Sari, 1981).

ETO product development process or ETO process - According to Oorschot (2001), in engineer-to-order (ETO) product development, the development process is initiated by a customer order, in which the customer specifies what has to be developed.

Model – A models is an abstract representation of reality that is built, verified, analyzed, and manipulated to increase understanding of that reality. Models can reside in the mind (mental models) or be codified (Browning et al, 2006).

Modes of innovation – There are two contrasting modes of innovation: One, the Science, Technology and Innovation (STI) mode, is based on the production and use of codified scientific and technical knowledge. The other, the Doing, Using and Interacting (DUI) mode, relies on informal processes of learning and experience-based know-how (Jensen *et al.*, 2007).

Innovation – An innovation is the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relation. The minimum requirement for an innovation is that the product, process, marketing method or organisational method must be new (or significantly improved) to the firm (European Commission - Enterprise and Industry glossary of terms). Product innovation is the subject addressed in this dissertation.

Process – According Ulrich and Eppinger (1995) a process is a sequence of steps that transforms a set of inputs into a set of outputs, or in other words, an organized group of related activities that work together to create a result of value.

Product development process (PDP) - Product development process is a sequence of steps or activities that an enterprise employs to conceive, design, and commercialize a product. Moreover, many of these steps and activities are intellectual and organizational rather than physical (Ulrich and Eppinger, 1995)

Risk management - An organized, analytic process to identify what might cause harm or loss (identify risks); to assess and quantify the identified risks; and to develop and, if needed, implement an appropriate approach to prevent or handle causes of risk that could result in significant harm or loss.

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Appendix B.2: Reference list of ETO process articles

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Appendix C: Research groups identified in the literature

Craig & Hart's taxonomy themes				Additional themes		
Activities: Models	Activities: Evaluation gates	Completion	Simultaneity	Modelling	e-NPD	ETO theme
Alonso-Rasgado, T. & G. Thompson (2006)	**Ettlie, J. E. & J. M. Elsenbach (2007)**	**Ettlie, J. E. & J. M. Elsenbach (2007)***	**Kincade, D. H. et al. (2007)**	**Bhuiyan, N. et al. (2004)***	**Buyukozkan, G. et al. (2007)**	**Pandit, A. & Y. M. Zhu (2007)**
Hasenkamp, T. et al. (2007)	**Huet, G. et al. (2007)**	**Tzokas, N., et al. (2004)***	**Kusar, J. et al. (2004)**	**Huang, H. Z. & Y. K. Gu (2006b)**	**Tseng, K. C. & H. Abdalla (2006)**	**Molina, A. et al. (2007)**
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