Modeling the Product Development Process: the RIM Case Study

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Abstract

Early assessment of a material's appropriateness and its inherent production technology applicability in a particular product is fundamental for it to be considered in further product development (PD) steps. Reaction Injection Molding (RIM) technology is noticeably under this paradigm. Often, the development team does not consider this technology in the selection process due to unawareness about it among the members of the team and qualified suppliers. This makes RIM a proper case study to contribute to a better understanding about the PD process, and particularly, the decision-making processes related to the adoption of new materials in the product and new technologies in the production process.

As such, an empirical study was undertaken with two main objectives: i) model PD projects where new (unfamiliar) technology could be adopted to add empirical evidence about the factors and practices that benefit the performance of the PD process; ii) assess the suitability of Business Process Management (BPM) modeling approach to the PD process by the development of a modeling framework and test in the projects under study.

This thesis presents two case studies of PD projects, modeled using the modeling framework developed in this research, based on the Riva method accompanied by textual narrative. The procedure for the implementation of the modeling framework was based on open-ended interviews to the experts involved in each project.

These case studies provide important insights on the constraints that inhibit the consideration of other materials and technologies (and RIM in particular) in the PD process

of rigid parts. Nevertheless, our analysis reveals scope for improvement in dealing with uncertainty and decision making by the introduction of the concept of postponement supported by practices and techniques that enhance flexibility.

Moreover, we propose a modified framework of factors affecting the success of PD projects. Finally, we conclude that the Riva method supported by textual narrative proved to be a good modeling approach to understand the decision processes in these particular PD projects.

Resumo

A avaliação precoce da adequação de um material e da aplicabilidade da sua tecnologia de produção a um determinado produto é fundamental para que possa ser considerado nos passos seguintes de desenvolvimento de produto (PD). A tecnologia de moldação por injeção e reação (RIM) está visivelmente neste paradigma. Muitas vezes, a equipa de desenvolvimento não considera esta tecnologia no processo de seleção devido ao desconhecimento sobre a mesma entre os membros da equipa e fornecedores qualificados. Por esta razão um estudo de caso que considere a tecnologia RIM poderá contribuir para uma melhor compreensão sobre o processo de PD e, em particular, no que se refere aos processos de tomada de decisão relacionados com a adoção de novos materiais no produto e novas tecnologias no processo de produção.

Neste sentido foi realizado um estudo empírico com dois objetivos principais: i) modelar projetos de PD, onde poderia ser adotada uma nova tecnologia (que a equipa de projeto não conhece) de forma a acrescentar evidência empírica sobre os fatores e práticas que beneficiam o desempenho do processo de PD, ii) avaliar a adequação da abordagem de modelação baseada na Gestão de Processos de Negócio (BPM) ao processo de PD através do desenvolvimento de um *framework* de modelação e aplicação nos projetos em estudo.

Esta tese apresenta dois estudos de caso de projetos de desenvolvimento de produto, modelados com o *framework* de modelação desenvolvido nesta investigação, com base no método Riva complementado por narrativa textual. O procedimento para a aplicação do *framework* foi baseado em entrevistas abertas aos especialistas envolvidos em cada projeto.

Estes estudos de caso evidenciaram perspetivas importantes a respeito de constrangimentos que inibem a consideração de outros materiais e tecnologias (e RIM em particular) no processo de PD de componentes rígidos. No entanto, a análise revela possibilidades de melhorias na gestão da incerteza associada à tomada de decisão pela introdução do conceito de *postponement* apoiado em práticas e técnicas que melhoram a flexibilidade.

Propomos um quadro modificado de fatores que influenciam o sucesso de projetos de PD. Por fim, concluímos que o método Riva complementado por narrativa textual provou ser uma abordagem de modelação exequível para compreender a tomada de decisões nos projetos de PD estudados.

Résumé

L'évaluation précoce de la pertinence d'un matériel et son applicabilité technologique inhérente à la production d'un autre produit est fondamentale pour qu'il puisse être pris en compte au cours des diverses étapes de développement d'un produit (PD). C'est pourquoi Injection Molding Réaction (RIM) fait clairement partie de ce paradigme. Souvent, l'équipe de développement ne considère pas cette technologie dans le processus de sélection, généralement par méconnaissance de la part des membres de l'équipe et des fournisseurs qualifiés. Ainsi, RIM s'affirme comme une étude de cas, pouvant fortement contribuer à une meilleure compréhension du processus PD, en particulier, des processus de prises de décisions liés à l'adoption de nouveaux matériaux dans la fabrication du produit et à l'application des nouvelles technologies dans le processus de production.

C'est pour cela qu'une étude empirique a été réalisée, visant deux principaux objectifs: i) modèle des projets de PD où une nouvelle technologie pourrait être adopté à additionner des données empiriques à propos des facteurs et des pratiques qui bénéficieraient la performance du processus de PD; ii) évaluer l'adéquation de l'approche de modélisation basée sur la Gestion des Processus Métiers (BPM) par le processus de PD et grâce au développement d'un cadre de modélisation et de test des projets en étude.

Cette thèse présente deux études de cas de projets de développement de produits, qui ont été modélisés à l'aide du cadre de modélisation développé dans cette recherche; celle-ci basée sur la méthode Riva et accompagnée de narration textuelle. La procédure suivie pour la mise en œuvre du cadre de modélisation a été basée sur des interviews ouvertes aux experts impliqués dans chaque projet.

Ces études de cas ont fourni d'importantes informations sur les contraintes qui empêcheraient la prise en compte d'autres matériaux et d'autres technologies (de RIM en particulier) dans le processus de PD de pièces rigides. Néanmoins, notre analyse révèle qu'il est possible d'introduire des améliorations au niveau du traitement de l'incertitude et de la prise de décision, grâce à l'introduction du concept d'ajournement. Celui-ci serait soutenu par des pratiques et des techniques qui améliorent la flexibilité.

En outre, nous proposons un cadre modifié de facteurs qui opère sur la réussite des projets de perfectionnement professionnel. Enfin, nous concluons que la méthode de Riva, prise en charge par le récit textuel, s'est avérée être une bonne approche de modélisation pour comprendre la prise de décision dans ces projets de perfectionnement professionnel, en particulier.

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To Sandra,
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List of Acronyms

BMC: Bulk Molding Compound

BOM: Bill of Materials

BPEL: Business Process Execution Language

BPM: Business Process Management

BPMI: Business Process Management Initiative

BPMN: Business Process Model and Notation

CAD: Computer Aided Design

CAE: Computer Aided Engineering

CAM: Computer Aided Manufacturing

CE: Concurrent Engineering

CFD: Computational Fluids Dynamics

CP: Case process

CSM: Composite Spray Molding

CTQ: Critical To Quality

DCPD: Dicyclopentadiene

DFA: Design for Assembly

DFM: Design for Manufacturing

DFSS: Design for Six Sigma

DFX: Design for X

DMADV: Define, Measure, Analyze, Design and Verify

DMAIC: Define, Measure, Analyze, Improve and Control

DOE: Design of Experiments

DPD: Dynamic Product Development

DSM: Design Structure Matrix

ESD: Entrepreneur System Designer

EPP: Expanded polypropylene

FEM: Finite Element Method

FMEA: Failure Mode and Effects Analysis (DFMEA: Design FMEA; PFMEA: Process FMEA)

FRP: Fiber Reinforced Plastic

GERT: Graphical Evaluation and Review Technique

GRP: fiber-Glass Reinforced Polyester

ICAM: Integrated Computer Aided Manufacturing

ICOV/IDOV: Identify (requirements), Characterize/Design, Optimize and Verify (the design)

IDEF: ICAM Definition / Integrated Definition

IPD: Integrated Product Development

IPDS: Integrated Product Delivery System

KPI: Key Performance Indicators

LCE: Life Cycle Engineering

LFT: Long Fiber Thermoplastic

LPD: Lean Product Development

NDA: Non-Disclosure Agreement

NPD: New Product Development

OEM: Original Equipment Manufacturer

PAD: Process Architecture Diagram

PCP: Product Creation Phase

PD: Product Development

PDCPD: Polydicyclopentadiene

PDD: Product Design and Development

PDMA: Product Development and Management Association

PDP: Product Development Process

PERT: Program Evaluation and Review Technique

PSC: Project Steering Committee

PU: Polyurethane

QFD: Quality Function Deployment

RAD: Role Activity Diagram

RASIC: Responsible, Accountable, Support, Informed, and Consulted

RIM: Reaction Injection Molding

RIMcop®: Reaction Injection Molding with Control of Oscillation and Pulsation

RRIM: Reinforced RIM

RTM: Resin Transfer Molding

SBCE: Set-Based Concurrent Engineering

SE: Simultaneous Engineering

SIPOC: Supplier, Input, Product, Output, Customer map

SMC: Sheet Molding Compound

SME: Small and Medium Enterprise

SRIM: Structural RIM

STRIM: Systematic Technique for Role and Interaction Modeling

TP: Thermoplastic

TRIZ: Theory of inventive problem solving

TS: Thermoset

TTM: Time To Market

UML: Unified Modeling Language

UOW: Unit of work

VOC: Voice of the Customer

xBML: Extended Business Modeling Language

1 Introduction

1.1 Relevance and Motivation

In the development process of products and its subsystems the development teams have to make several important decisions that have great impact in the project's profitability. These decisions have a major influence in the development lead time and cost and also in the market success of the product (Cooper 2001; Cooper and Edgett 2005; Smith 2007). Early assessment of a material and inherent production technology applicability in a particular product is fundamental for it to be considered in further product development steps. The organizational pressure for speed and efficiency often results in conservative decisions, reducing the chances of studying and selecting other materials and technologies (Bayus 1997; Lukas and Menon 2004).

Reaction Injection Molding (RIM) technology is noticeably under this paradigm. Due to the lack of knowledge about this technology, designers usually neglect it. However, given the proper conditions RIM may be the best option (important factors are functional requirements and expected production volumes). RIM technology for processing polyurethanes (PU) or dicyclopentadiene (DCPD) rigid parts is mostly used in enclosures (also called exterior panels or body of the product), which makes it a good case for study, because these components must usually be developed to differentiate the product, unlike many other components that can be purchased and/or shared (carryovers).

In order to have a deeper understanding about the mechanisms behind the above-mentioned scenario, it is necessary to first describe and analyze the product development process (PDP) of products or subsystems of products where RIM could be a manufacturing option. This business process can be modeled using the Riva method (Ould 2005) or the Business Process Model and Notation (BPMN) standard (White and Miers 2008). A Business Process Management (BPM) approach to model and analyze the product development (PD) process may go against established PD concepts (Browning, Fricke, and Negele 2006). Nevertheless, we believe that with proper adaptations it is an effective and efficient method to enable a clear view of real PD projects.

This thesis offers a contribution to current literature by adding empirical evidence on the role of materials and technology adoption in the PD process. The implementation of Concurrent Engineering (CE) principles in the PD process is investigated and crossed with the effects in the selection of materials and technology. It also presents a new way to model a PD project process. We motivate and support the new approach with theory, describe its representation rules, and begin to validate it with a real application.

1.2 Thesis Objectives

An empirical study was undertaken with two main objectives: i) model PD projects where new (unfamiliar) technology could be adopted to add empirical evidence about the factors and practices that benefit the performance of the PD process; ii) assess the suitability of BPM modeling approach to the PD process by the development of a modeling framework and test in the projects under study.

This thesis presents two case studies, one where RIM was selected and another where RIM was not selected. The PD process is modeled using the Riva method accompanied by textual narrative. The factors that impair a more exhaustive exploration of the selection space are identified. An important factor is the risk aversive nature of the designer, which results in decisions aiming to minimize the uncertainty of the downstream processes. A set of factors (or principles) used by each company in each particular project are explained and compared with theory, in particular the principles of concurrent or simultaneous engineering (CE) and lean product and process development.

The project where RIM was selected is particularly interesting because RIM technology (to process DCPD material) was selected for the production of all the exterior panels of the vehicle and some of the interior components. RIM was far for being the natural choice as will be explained later.

The project where RIM was not selected emphasizes the importance of previous knowledge about the material and technology to consider it in the selection process. The development process is heavily structured however the number of candidate materials is reduced and constrained by previous knowledge of the company or trusted suppliers about the processing technologies. We will discuss the use of validated technology as opposed to adopting unproven technology by the stakeholders involved.

1.3 Thesis Layout

The thesis is organized as follows.

Chapter 1 introduces the subject matter of this thesis. It synthetically explains the motivation behind the development of the research and the relevance for the field of study. The main objectives of this thesis are also presented. It finalizes with a description of the layout of this document.

Chapter 2 is dedicated to the literature review. The first three sections comprise the three main theoretical topics of this research. The fourth section is about RIM technology which is the case study investigated. The last section addresses the research gaps found in literature and the research questions this empirical study aims to answer.

The first section examines the PD process and the major prescriptive methods cited in the literature. It discusses the frameworks that are the theoretical basis for this research, including the principles and practices for PD, from a prescriptive standpoint.

The second section addresses the issue of modeling PD processes from a descriptive standpoint. The different modeling techniques adopted in PD are identified and the Riva method is explained in detail and compared with the existing PD and BPM modeling approaches.

The third section covers the theory about materials and technology selection and adoption. The different selection approaches proposed and used in PD and the relevance of this decision process in the success of a PD project are discussed.

The fourth section of the literature review describes RIM technology for the production of rigid parts. The section is divided in two sub-sections, one for the technical description of the technology and the other for the business description. The technical description includes the raw materials that can be used, the possibilities in terms of characteristics of the final parts and the typical production process that is required. The business description includes the typical applications, markets and production volumes where this technology is competitive. The information presented in this chapter is based on literature review, however most of it is further developed and deepened in Chapter 5 from field work involving interviews and direct observation in three companies specialized in RIM. Finally, the research questions supported by the theoretical background explained in the previous sections are identified.

Chapter 3 covers the methodological procedures used in this research. The research is divided in two main stages that are explained in the two sections of this chapter.

The first section is dedicated to the description of the work performed to understand the current situation of the RIM industry, in particular for the production of three-dimensional (3D) rigid parts. The field research done with the three RIM companies involved in this stage is explained.

The second section deals with the activities performed in the second stage of the study to analyze the PD process of products where RIM is a strong candidate for the production of one or several parts. In this stage, two qualitative case studies were performed, one where RIM was selected and another where RIM was not selected.

Chapter 4 presents the modeling framework developed for this research and the effectiveness of the method for modeling real PD projects is discussed. The two sections of this chapter introduce the two case studies, give a synthetic explanation about the projects that were analyzed and modeled, and finalize with a brief description of the specificities of the implementation of the modeling procedure in each case study.

Chapter 5 presents the findings from the RIM industry analysis and from the case studies and discusses the theoretical implications.

The first section presents the findings related with the current situation of the RIM industry, in particular for the production of 3D rigid parts. It finishes with a synthesis of the findings related with the three RIM companies visited by the researcher.

The second section presents the findings related with the two qualitative case studies. The findings are presented in the form of two process models and narratives, which describe in rigor and detail the two real projects performed by these companies.

The third section is concerned with the discussion of the findings, which seek to contribute to PD and process modeling theory. Finally, the effectiveness of the modeling framework developed for this research is discussed.

Chapter 6 summarizes all the insights gained during this research and couples them with the managerial implications. Finally, the research contributions are reviewed, and the opportunities for further work are highlighted.

Appendix 1 presents a list of companies specialized in the manufacture of plastic parts using RIM technology (RIM users) and their major suppliers.

Appendix 2 presents the process models developed in the case studies research and presented in Chapter 5 in A3 format for better visualization.

2 Literature Survey

This literature survey addresses PD from two contrasting procedural approaches, identified by Finger and Dixon (1989) as:

- Prescriptive: these approaches recommend or prescribe guiding principles, steps/phases or techniques that, in theory, are thought to improve specific aspects of PD. These, in essence, draw on best practices in the area and the focus is on improving PD effectiveness and/or efficiency.
- Descriptive: on the other hand, these approaches result from investigation into actual design practice. Direct observation of the different processes and procedures in the industry are the premises on which these models are based.

On this, Browning, Fricke and Negele (2006) substantiate the ideas set forth by Finger and Dixon (1989), contending that descriptive process models “attempt to capture tacit knowledge about how work is really done. They try to describe key features of the ‘as is’ reality. It is built inductively”. On the other hand, prescriptive process models “tell people what work to do and perhaps also how to do it. It is built deductively, perhaps drawing from an external standard and/or documentation from other projects. A prescriptive process is a standard process or procedure accompanied by a mandate to follow it exactly”.

The first two sections examine the PD process within these two pivotal perspectives. We begin with the major prescriptive methods cited in bibliography and discuss the frameworks that constitute the basis for our research, including the principles and practices for PD. The second section addresses the descriptive approaches, namely the issue of modeling PD processes.

The third section discusses materials and technology adoption methods and strategies. This is followed by a section on RIM technology. We conclude this chapter with the research questions, which prompted our research, and their relevance to our objectives.

2.1 Product Development Methods and Practices

Literature on PD is vast. Several methodologies, methods, techniques and tools can be found in literature (Cooper 2001; Pahl et al. 2007; Ulrich and Eppinger 2008). All of these have mainly a prescriptive nature (Motte 2008; Gericke and Blessing 2011), that is to say they provide a procedural plan for the design process. They assist in identifying what has to be done, but they must be adapted to the specific PD projects. These are mostly based on a step-by-step problem-solving approach, a succession of tasks and decisions. As knowledge increases, the PDP reaches its objective (solution). Thus, they do not explain what and how things are done in practice; rather they give (mostly generic) orientation to the development team. Of course, those recommendations are based in practical experience and empirical evidences (Koskela 2000), yet they do not suffice to perform a PD project.

2.1.1 Product Development: an Overview

Successful PD is essential in today's competitive market as it is seen as a potential source of competitive advantage (Brown and Eisenhardt 1995). It is therefore not surprising that, over the years, noticeable *standardization* efforts (MacGregor et al. 2006) have emerged. In fact, while on the one hand PD process is understood as being unique, unlike other business and production processes, literature on PD relentlessly tends to provide recipes for successfully producing a product. Yet, within this trend, from the most recent literature it is possible to identify nonconformists, advocating that PD complexity and uniqueness cannot be tackled using the same models and practices, given the proven influence issues such as context and intervenients have. It is within these ambivalent bounds that we develop the points that follow.

Product Development as a Process

Various definitions of *process* suggest different managerial and technical perspectives, which can underpin this essential concept within business in general and PD in particular. Amongst the first authors to focus on the importance of reengineering the *business* *process*, Hammer and Champy (1993) viewed it as a “collection of activities that takes one or more kinds of input and creates an output that is of value to the customer”. Similarly, Davenport (1993) also focused his attention on the “specific ordering of work activities across time and space, with a beginning and an end, and clearly defined inputs and outputs”. Curiously, at approximately the same time Ould (1995) argued that actual processes are not as orderly as Davenport’s and Hammer and Champy’s input-output view might suggest. Ould considered business processes as networks, where roles collaborate and interact to attain a given business goal. Thus, Ould (2005) defines a process as “a coherent set of activities carried out by a collaborating group to achieve a goal”.

Later, Becker et al. (2003) defined a business process as “a special process that is directed by the business objectives of a company and by the business environment. Essential features of a business process are interfaces to the business partners of the company (e.g. customers, suppliers). Examples of business processes are the order processing in a factory, the routing process of a retailer or the credit assignment of a bank”.

In all perspectives, except that of Ould, the focus is on the fact that a business process is repeatable and knowledge regarding its development is readily available. This contrasts with that of process within the realm of PD. In the latter, knowledge about a product is progressively generated as part is unknown in the beginning, which generates uncertainty.

Design processes (as is the case of PD) encompass problem-solving characteristics (Lindemann, Maurer, and Braun 2009), which imply a degree of novel knowledge, common in the conception of new products. This uncertainty is gradually overcome through process iterations, however the fact remains that one of the main and unique characteristics of PD is its dynamic nature (see Section 2.1.2 and 2.2).

The development of new products is a process which transforms opportunities into tangible products intended to produce company profits (Trott 2012). As the author acknowledges, the process itself is complex and therefore difficult to identify.

Clark and Fujimoto established this idea of PD as a process in 1991. Drawing on six years of research conducted at the Harvard Business School on how different manufacturing firms around the world approach the development of new products, Clark and Fujimoto (1991) posit PD as a “process by which an organization transforms data on market opportunities and technical possibilities into information assets for commercial production”. In their point of view, PD not only considers concept generation, product planning and product engineering, but also process engineering, which creates the process. This pioneering definition marked the beginning of the process approach in PD. Until then the engineering sector was responsible for PD, thus disregarding the integration of marketing activities, planning and product manufacture.

Other authors (see for example, Hales 1993; Smith and Morrow 1999; Cooper and Edgett 2005; Browning, Fricke, and Negele 2006; Pahl et al. 2007) draw on this idea of PD as a complex process given the wide range of issues that must be addressed, as well as the diversity of people and the different organizational structures involved in the PD efforts. PD thus entails a considerable number of decisions in an extremely uncertain environment.

Curiously, Ulrich and Eppinger (2008) amongst the most cited authors in product design and development define "*Product development* as a set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product", thus omitting the concept of process, opting for a generic approach to PD.

Browning et al. (2006), drawing on their vast experience in PD, clarify some of the main concepts used as they consider *processes* [our emphasis] to be the key aspect of contemporary systems engineering theory and practice. They describe PD as "an endeavor comprised of the myriad, multi-functional activities done between defining a technology or market opportunity and starting production", whose main objective is to create a "recipe" for producing a product (Browning et al. 2006 with credit given to Reinertsen 1997). The authors draw on Kline (1985) arguing that PD implies creativity and innovation and is nonlinear and iterative.

By adopting Hammer's (2001) view of process as "an organized group of related activities that work together to create a result of value" or Pall's (2000) notion of process as "a network of customer-supplier relationships and commitments that drive activities to produce results of value", Browning and his colleagues clearly establish PD as a complex process, asserting that any work (including work related to creativity and innovation) that is carried out in order to obtain a result has an underlying process.

In sum, PDP can be defined as "a disciplined and defined set of tasks and steps that describe normal means by which a company repetitively converts embryonic ideas into saleable products or services" (Kahn, Castellion, and Griffin 2005). Based on the work of Vajna (2005) we summarize the main differences between business processes and PD processes in Table 2.1.

Table 2.1 Differences between a business process and an engineering design process (Vajna 2005)

Business process	Engineering design process
• Processes are fixed, rigid, have to be reproducible and checkable to 100%	• Processes are dynamic, creative, chaotic; many loops and go-tos
• Results have to be predictable	• Results are not always predictable
• Material, technologies, and tools are physical (e.g., in manufacturing) and/or completely described (e.g., in controlling)	• Objects, concepts, ideas, designs, approaches, trials (and errors) are virtual and not always precise
• Possibility of disruptions is low, because objects and their respective environments are described precisely	• Possibility of disruptions is high, because of imperfect definitions and change requests
• No need for dynamic reaction capability	• There is definitive need for dynamic reaction capabilities

The Product Development Project

Another concept that is ever present in PD literature is *project*. While the concept is widely used in PD, very few authors actually define it. Nonetheless, in other scientific areas, namely in Project Management, several authors have attempted to define the concept of project. Noticeably over the last years we have witnessed a shift in the notion of *project* (Shenhar, Levy, and Dvir 1997).

One of the distinguishing characteristics between *project* and other kinds of organizations is its uniqueness. Mintzberg (1983) focuses on this distinguishing feature by defining project as "an organizational unit that solves a unique and complex task".

Weiss and Wysocki (1992) enumerate a series of characteristics they consider delimit the concept of *project*. Although they do not provide a clear definition, they concede a project must have the following characteristics:

- Complex and numerous activities.
- Unique: a one-time set of events.
- Finite: with a begin and end date.
- Limited resources and budget.
- Many people involved, usually across several functional areas in the organization.
- Sequenced activities.
- Goal-oriented.

- End product or service must result.

The Project Management Institute's definition focuses on its time dimension, stating that a project is "a temporary endeavor undertaken to create a unique product or service" (2000). In turn, the British Standards Institute's guide to project management defines project more precisely, as "a unique set of co-ordinate activities, with definite starting and finishing point, undertaken by individuals or an organization to meet specific performance objective within defined schedule, cost and performance parameters" (BS:6079 2000).

It is our belief, that the modern approach to PD process (see Dynamic Model Section 2.1.2) embeds all the characteristics of a *project*.

Towards a Modern Product Development Process

In 1986, Takeuchi and Nonaka acknowledged that the long-established sequential approach to developing new products was no longer adequate, advocating a holistic method, placing emphasis on companies' need for speed and flexibility in the ever growing competitive world.

The authors advocated the need to move from a PDP where one group of functional specialists passed the product on to the next group - known as waterfall or "over-the-wall" (see for example Otto and Wood, 2001) (Figure 2.1), to a PDP emerging from the interaction of a multidisciplinary team whose members work together throughout the entire process, engaging in iterative experimentation throughout all the phases of the development process - known as CE (see Section 2.1.3).

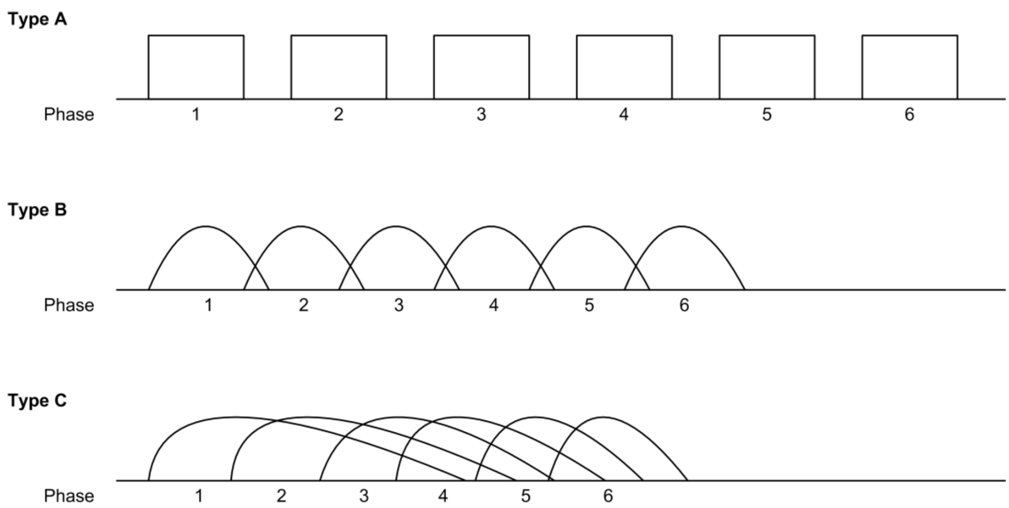


Figure 2.1 Sequential (A) vs. overlapping (B and C) phases of development (Takeuchi and Nonaka 1986)

Takeuchi and Nonaka (1986) criticized the segmented and sequential phase-to-phase process: concept development, feasibility testing, product design, development process, pilot production, and final production, where functions were specialized and segmented, being carried out by different people at different times, separately. They defend an integrated approach, encouraging trial and error, which challenged the status quo.

Nonetheless, the authors admitted that their holistic approach to PD may not work in all situations, due to its limitations, namely in terms of team effort; project specificities, in particular hi-technology or chemistry related projects; project size, where project scale limits extensive face-to-face discussions and “masterminded” projects, where one person makes the invention and hands down a well-defined set of specifications for others to follow.

The traditional conception of PDP was based on functional specialization and standardization (see Taylor 1913), which used expertise as a means of efficiency in the organizational processes. Within the traditional approach, the steps for PD are predetermined, which help control and manage the project. As each step is completed before the next begins, experts can focus their skills and experiences on a specific step or set of tasks. Taylor (1913, cited in Koskela 2000) explained this idea as follows:

> “The work of every workman is fully planned out by the management at least one day in advance, and every man receives in most cases complete written instructions, describing in detail the task which he is to accomplish, as well as the means to be used in doing the work”.

DesChamps and Nayak (1995) summarize the following characteristics of the traditional conception of the PDP, as barriers to effective product creation:

- *Compartmentalized organization and sequential working*: Departments absorb and mold the skills of the people who compose them (engineering, production, marketing, finance, and so on). The PDP is seen and operated in a fragmented way, each group concentrating on their share of work. Communication problems arise because experts often do not understand what is requested. Working sequentially generates errors because knowledge may be withheld or delayed.
- *Needless iterative loops*: The authors contend, compartmentalized organization and sequential working leads to needless iterative loops, as there is no common overall goal of product creation. Thus, if a problem occurs in manufacturing, they will very likely blame the designers.

- *Heavy-handed hierarchy*: In a functional structure, employees think vertically, because they depend on command, control and integration of departmental superiors.

In sum, we can say that traditional approaches use simple, precedence models and thus cannot capture the iterative nature of the PDP (Eppinger et al. 1994; Browning 1997). Nonetheless, these have two clear advantages: it is easy to control and predictable. However, as Takeuchi and Nonaka claimed, in order to face the challenges of fast changing marketplaces, intense competition and rapid technological evolution of today's corporate world, companies need to break with the old approach to PD and embrace a more modern approach.

Indeed, flexible PD processes, which take into account uncertainties, adjust to the process of creating new ideas with practical applications and therefore increase the likelihood of success of PD (Cooper 1990). Smith (2007) for example, drawing on the notion of *agile* within the software domain, proposes a flexible approach to PD, defending that "flexible processes are *emergent*" [emphasis in original], in the sense that there are many interdependencies working together, and thus are not predictable. Adopting a flexible approach to PD can therefore "anticipate the future better".

Hence, we can consider two broad methodological approaches to PD: a traditional, sequential methodology and a modern, more iterative methodology.

Drawing on this idea of a modern approach to PD, literature has grown considerably over the last decades. Some literature describes engineering design and PD in a broad and systematic way as a guide for improved implementation (Rosenau and Moran 1993; Otto and Wood 2001; Cleland and Ireland 2006; Pahl et al. 2007; Ulrich and Eppinger 2008). These authors base their findings on examples of PD experiences and advocate the use of a structured, multi-stage PDP to manage the competing technical and market risks. Other authors (Craig 2001; Leonard-Barton 2007; MacCormack, Baldwin, and Rusnak 2012) relate PD practices with architectural or corporate strategy.

PD literature is, in fact, heavily based on studies of individual companies' successful efforts to improve their PD approach, that range from software products (Cusumano and Selby 1995; MacCormack 2000) to the automobile industry (see authors such as Cusumano 1991, who compares US and Japanese automobile manufacturers processes, or Morgan and Liker 2006 and Ward 2007, who focus on the Toyota product development system).

Despite the array of studies that attest to the fact that rapid and innovative PD can provide critical competitive advantages to firms (Rosenau and Moran 1993; Ulrich and Eppinger 2008), as far as we are aware of, there are currently no established criteria for selecting or designing ideal PD processes, nor is any single process ideal for all circumstances and companies. On this, Krubasik (1988) draws attention to the fact that "one size does *not* fit all" [emphasis in original], as not all PD is alike. Nonetheless, often managers do not consider the context and "tend to fall back, by intuition or reflex, on a kind of generic 'one size fits all' approach to new product development".

As Otto and Wood (2001) explain:

> "Every company has a different development process out of necessity; there is no single 'best' development process; the design process and the product development process are misnomers. The sophistication of the product, the competitive environment, the rate of change of technology, the rate of change of the system within which the product is used: these and many other factors that shape a product development process change for different companies".

Even so, most modern PD approaches do have a common stem, which encompasses general actions, steps or stages. These are, however, non all-inclusive. In fact, companies, depending on their specificity, may have either additional or fewer steps. PD process enacts these actions, steps or stages in an organized way. Understanding the different approaches is an important step to guide future PD processes.

"Technology-Push" and "Market-Pull" Product Development Models

PD models in general include the definition and sequencing of phases or stages, the objectives of each within the model, and methods or tools that developers use to accomplish those objectives. Given the array of new products and contexts in which these are developed, it is not feasible to present one generic model. Nonetheless, the existing literature does delineate two different types of PD models: technology-push product development and market-pull product development.

Technology-push PD starts with a given technology and then incorporates that technology into products that better satisfy market needs – thus the technology "pushes" the PD. The development team begins with a new technology and then finds an appropriate market.

On the other hand, in market-pull PD, the incentive for the product derives from customer needs. Market-pull uses technologies to create a new product or improve an existing product to meet customer needs, thus these "pull" the PD through to completion (Bishop and Magleby 2004).

Leading literature in PD predominantly focuses the market-pull model as predominantly implemented by companies (Otto and Wood 2001; Kahn, Castellion, and Griffin 2005; Ulrich and Eppinger 2008), despite the inferences that a combination of a technology-push and market-pull PD model would be optimal.

Bishop (2004) argues technology-push PD is generally considered more difficult and challenging, thus the reason most PD research has focused on market-pull development and why many researchers favor market-pull over technology-push development. Indeed, market-pull is still the most widely used PD model in companies that develop physical complex products (Ulrich and Eppinger 2008; Terwiesch and Ulrich 2009), as in this situation customer needs have to be understood before developing the technology that materializes the final product.

2.1.2 The Different Prescriptive Methods

Whether technology-push or market-pull, PDP can, as stated above, be described through a number of identifiable steps or stages that represent the generic PD flow from the new idea to the final product, which provide an overview of the complete process. Over the years this process has been represented by numerous different models (some in constant evolution), which attempted to integrate its main activities. We will now discuss the prescriptive PD process models we consider most relevant.

Pahl and Beitz

Pahl and Beitz (2007) conceived the earliest and most important model in engineering design in the late 1970's (originally published in German, *Konstruktionslehre*). The authors proposed plans and procedures "mandatory for the general problem solving process of planning and designing technical products", that must be looked upon as "operational guidelines for action" adapted to each specific situation. They proposed a step-by-step procedure, which focuses on three main themes: optimization of principle, optimization of layout and optimization of production (see Figure 2.2).

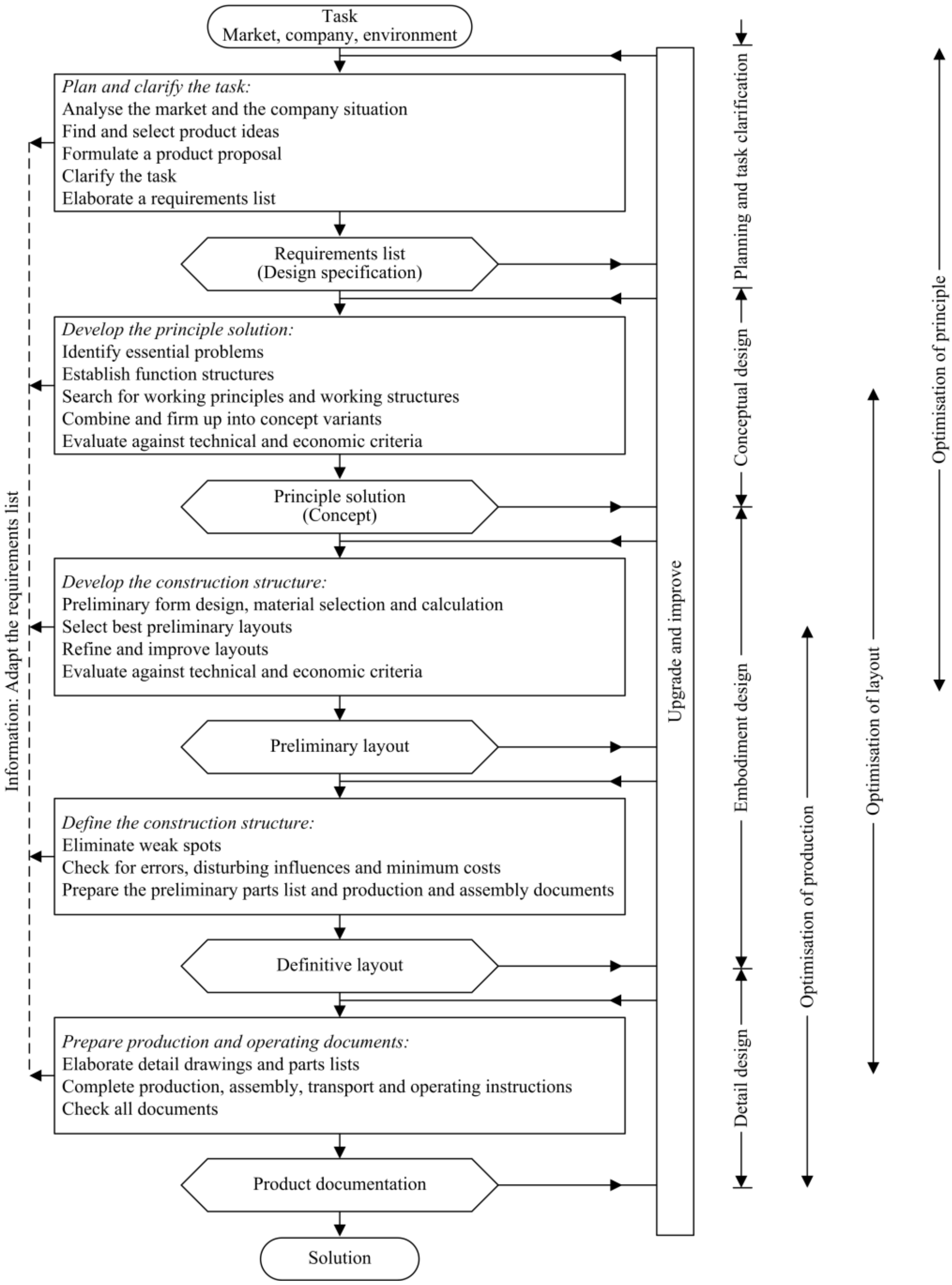


Figure 2.2 Steps in the planning and design process (Pahl et al. 2007)

The workflow proposed by the authors is based on the fundamentals of technical systems, on the fundamentals of the systematic approach and the general problem solving process. The authors focus on a systematic design as a complete process. For Pahl and his colleagues the four main phases in the planning and design process are:

1. **Planning and task clarification**: First it is important to clarify the task in detail, i.e. collect information about requirements, constraints and their importance. The result should be the specification of information in the form of a requirements list.

Subsequent phases should be based on this document, which must be continuously updated.

2. **Conceptual design**: Determines the principal solution (concept) by abstracting the essential problems, establishing function structures and searching for suitable working solutions through the selection of preliminary concepts, the development of a rough dimensional layout and the consideration of technical possibilities. Problems emerge and variants must be evaluated.
3. **Embodiment design**: From the concept, designers develop and define the construction structure of the overall layout. Issues like form design and material selection are addressed. Several layouts may be necessary to determine advantages and disadvantages of variants. Evaluation of technical and economic criteria helps to eliminate weak spots and improve the layout. Phase ends with a definitive layout and a preliminary parts list and production and assembly documents.
4. **Detail design**: It is at this time that information is specified in the form of *product documentation*. In order to do so, detailed information on form, dimensions, and properties of all parts must be established, as well as material selection, assessment of production possibilities, cost estimation and assembly of all production documents.

Pahl and Beitz's overall design process seeks the optimization of principle, layout and production. Although the four main phases may appear to be distinct from each other, the authors acknowledge that it is not always possible to clearly distinguish each phase and that it is not possible to avoid backtracking. In fact, the authors emphasize that procedural plans should be flexible and adapted to each particular situation. Furthermore, they advise that at the end of each step, the approach taken should be assessed and adjusted, if necessary.

Clark and Fujimoto

Although we can consider Pahl and Beitz's as the first steps towards a clearly defined PDP, it was Clark and Fujimoto, who, in 1991 define PD as a "process" (see Section 2.1.1). Although Clark and Fujimoto (1991) portray their four-phase model as linear for the purpose of description, they recognize the development process has "many loops, parallel steps and obscure boundaries that render it far from linear". In fact, the authors advocate a need for coherent and integrated internal and external processes to develop successful products. The generic four-phase model is as follows:

1. **Concept Generation**: In this first phase the characteristics of a future product are defined. This phase should be approached with care, given the difficulty in predicting future requirements and customer expectations.
2. **Product Planning**: The concept is converted into detailed information, including major specifications in terms of style and layout, technical aspects, cost estimates and investment decisions.
3. **Product Engineering**: At this phase plans are transformed into blueprints or CAD-drawings then into prototypes and finally into real parts and components.
4. **Process Engineering**: The fourth phase is where the manufacturing tools are developed, and material flows, work organization and tasks are defined for final production.

Clark and Fujimoto explain the need for product consistency, specifically in terms of function and structure; organizational integrity through cross-functional coordination within the company and with suppliers; and external integrity namely in terms of product performance and customer expectations (1990). This approach to the PDP does not focus on the detailed description of the various stages/phases of the process; it does emphasize the need for integration, and the continuous assessment of the problems encountered and possible solutions. Furthermore, the model underlined the need to understand future customer needs and expectations.

Another strength of Clark and Fujimoto's model resides on the high degree of simultaneous activity (stage overlapping) and bidirectional information flows (intensive communication), which emerges when adopting the proposed integrated problem solving, thus leading to improved development performance, both in terms of lead time and product concept effectiveness, as well as in terms of company management and organization.

Clark and Wheelwright

Drawing on the idea of an integrated approach to PD proposed by Clark and Fujimoto, Clark and Wheelwright (Wheelwright and Clark 1992; also published as Clark and Wheelwright 1993 with cases) proposed the *Development Funnel*, a "graphic structure that depicts the firm's approach to identification, screening and convergence in the product development".

The purpose of PD is to convert an idea from the original concept to the final product. The global PDP starts with multiple inputs (generation of ideas), which are gradually refined and selected from among them, creating feasible and profitable products. This notion is illustrated as a converging funnel, consisting of three major generic stages or challenges, as the authors denote: Investigations, Development, and Shipping Products (Figure 2.3).

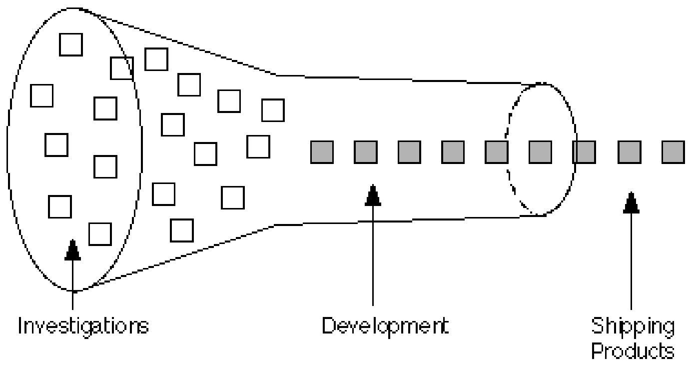


Figure 2.3 The simplified development funnel (Wheelwright and Clark 1992)

The initial challenge placed on organizations is to develop its knowledge base and access to information to be able to increase the number of new product and new process ideas (Investigations). The second challenge is to narrow the funnel neck. The ideas generated must be screened and converge resources on the most attractive opportunities. The authors concede the most difficult part in the process resides precisely in the narrowing process, as a balance must be found (Development). Finally, selected projects should meet the expected objectives when the project was approved.

A more detailed image of the funnel concept (Figure 2.4) graphically demonstrates the integrated approach, which Clark and Wheelwright defend. They analyze how external factors (such as customer needs) and internal factors (such as technological possibilities) influence concept generation and selection, as well as how projects evolve in the later phases until their release, encompassing decreasing levels of uncertainty - which implies reduced flexibility - as the process unfolds.

Ulrich and Eppinger

Amongst the most cited authors in product design and development are Ulrich and Eppinger (2008), who define PD as “a set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product”. The authors identify six phases in the PDP (see Figure 2.5). The concepts attributed to each step are consistent with literature on PD, thus they are relatively common and widely accepted. The model is very generic, as it has been developed in order to be adaptable to various contexts. The authors divide the PDP into six distinct phases and draw attention to the activities and contributions of the PD team during each phase.

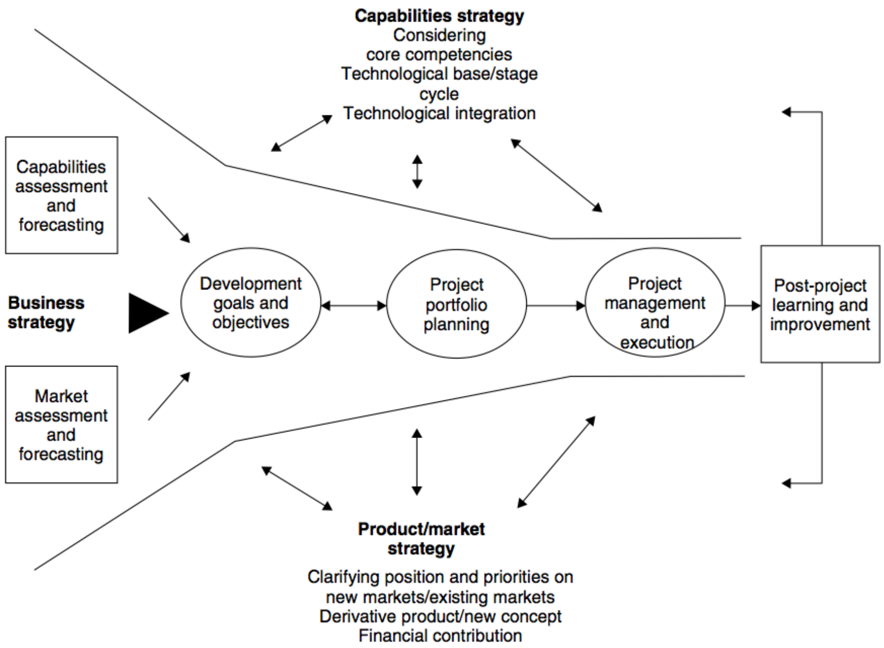


Figure 2.4 The development funnel (Clark and Wheelwright 1993)

The six generic phases identified by Ulrich and Eppinger are:

1. **Planning**: Phase 0 of the PDP, this phase precedes project approval. It includes evaluation of the organization's strategy, assessment of technology developments and market objectives.
2. **Concept Development**: It is in Phase 1 that target market needs are identified, alternative product concepts are generated and evaluated, and one concept is finally selected for further development and testing. Furthermore, business analysis in order to estimate the profitability of the product, and forms of beta testing and market testing can occur at this time.
3. **System-level Design**: Phase 2 includes the definition of the product architecture and the decomposition of the product into subsystems and components. The final assembly scheme for production is defined. The output is a geometric layout of the product and its functional specifications.
4. **Detailed Design**: Phase 3 incorporates the complete specification of the geometry, materials, and tolerances of all the unique parts of the product. At this time all standard parts that need to be purchased are established. The output is the necessary control documentation (drawings representing the geometry of each part and its production tooling, specification for the purchased parts, and the process plans for the fabrication and assembly of the product). Production costs and robust performance need to be addressed.

5. **Testing and Refinement**: Phase 4 involves the construction and evaluation of multiple preproduction versions of the product. This is the validation and testing phase of system-level and detailed design phases. The information obtained is used as feedback for product refinement.
6. **Production Ramp-up**: It is in Phase 5 that the product is made using the intended production system. Preferred customers may be given these early products in order to identify any remaining flaws. The transition to on-going production is usually gradual and at some point the product is launched.

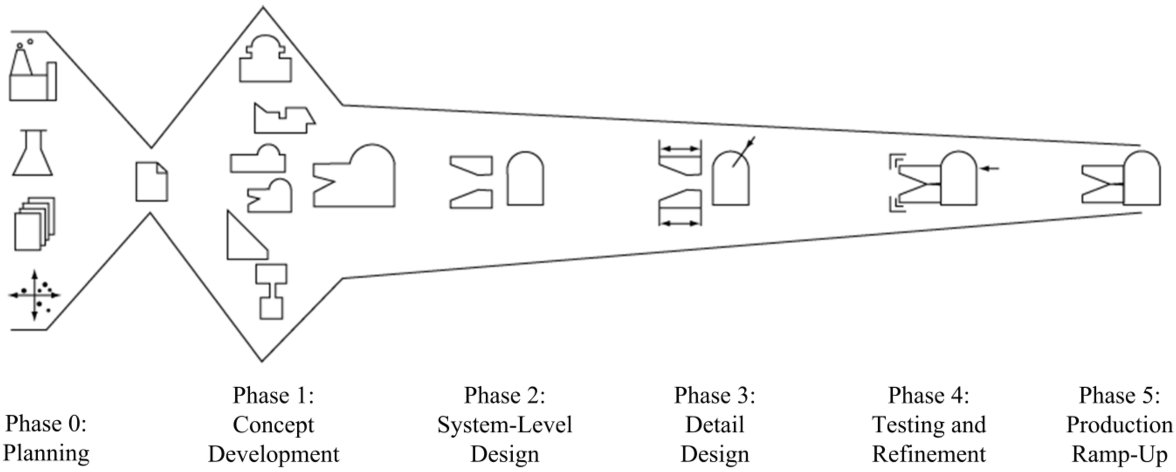


Figure 2.5 The generic product development process (Ulrich and Eppinger 2008)

Ulrich and Eppinger's PDP model is two-dimensional in the sense that on one axis we have the different phases of the process and on the other the tasks and responsibilities of the key functions of the organization for each phase (see Table 2.2).

Outputs are described at the end of each phase, as a phase review to confirm that the phase is completed and to determine whether the project progresses, but there is no clear break between these. The process is seen as a continuum. Although it does appear rather linear, the authors emphasize that it is in fact iterative, as it is possible to obtain new information in almost any stage, which may result in backtracking and the need to repeat earlier activities before proceeding. In their generic model, the authors stress the importance of bringing together the main functions of the organization (marketing, design and manufacturing) to achieve successful PDP.

Cooper

The Stage-Gate® Model, developed by Cooper (1983, 1988), is a "conceptual and operational model for moving a new product project from idea to launch" (Cooper and Edgett 2005). Adopted by most American companies, this model has proven to increase product profitability and curtail time-to-market by observing possible mistakes at early phases (Cooper 2001). Although continuous changes, based on both empirical research and practical experience, have been introduced to the model in order to increase fluidity and iterations, the basic principle still applies.

Table 2.2 Product development process with tasks and responsibilities (Ulrich and Eppinger 2008)

Planning	Concept Development	System-level Design	Detail Design	Testing and refinement	Production Ramp-up
Marketing					
•Articulate market opportunity •Define market segments	•Collect costumer needs •Identify lead users •Identify competitive products	•Develop plan for product options and extend product family	•Develop marketing plans	•Develop promotion and launch materials •Facilitate field testing	•Place early production with key costumers
Design					
•Consider product platform and architecture •Assess new technologies	•Investigate feasibility of product concepts •Develop industrial design concepts •Build and test experimental prototypes	•Generate alternative product architectures •Define major sub-systems and interfaces •Refine industrial design	•Define part geometry •Choose materials •Assign tolerances •Complete industrial design control documentation	•Reliability testing •Life testing •Performance testing •Obtain regulatory approvals •Implement design changes	•Evaluate early production output
Manufacturing					
•Identify production constraints •Set supply chain strategy	•Estimate manufacturing costs •Assess product feasibility	•Identify suppliers for key components •Perform make-buy analysis •Define final assembly scheme	•Define piece-part production processes •Design tooling •Define quality assurance processes •Begin procurement of long-lead tooling	•Facilitate supplier ramp-up •Refine fabrication and assembly processes •Train workforce •Refine quality assurance processes	•Begin operation of entire production system
Other functions					
•Research: demonstrate available technologies •Finance: provide planning goals •General management: allocate project resources	•Finance: facilitate economic analysis •Legal: investigate patent issues			•Sales: develop sales plan	

As the name suggests, in the Stage-Gate® Model the process is divided into a pre-determined set of stages. The entrance to each stage is a gate, whose main purpose is to control the project, serving as quality control and “Go/Kill” check points (Cooper and Edgett 2005).The project is thus reviewed at certain points in its development (*gates*), where a decision on whether or not to proceed must be made based on *deliverables*. Additionally, it is at the gates where the action plan for the next stage is approved, along with resource commitment. Currently, the model comprises 5 stages, each consisting of prescribed, multifunctional, and parallel activities (Cooper and Kleinschmidt 2001). Each clearly identifiable stage is designed to gather the information needed to move the project on to the next decision point (see Figure 2.6). The Stage-Gate model’s key stages are as follows:

1. **Discovery**: Stage 0 is where pre-work designed to discover opportunities and generate new ideas occurs.
2. **Scoping**: Stage 1 consists of a quick and preliminary investigation and scoping of the project (mainly desk research) to narrow the field before Stage 2.
3. **Building the Business Case**: It is in Stage 2 that a more detailed research (market and technical) occurs leading to a *Business Case*, which includes product and project definition, project justification and project plan.
4. **Development**: Stage 3 incorporates the actual detailed design and development of the product, as well as initial testing. It is a lengthy stage that includes full production and market plans. The outcome of the stage is a tested product.
5. **Testing and validation**: In Stage 4 the proposed new product, its marketing and production plans are tested and validated through tests/trials in the marketplace, lab and plant.
6. **Launch**: Finally, in Stage 5, commercialization and full production, marketing and selling occur. Plans for market launch, production/operations, distribution, quality assurance and post-launching monitoring are executed.

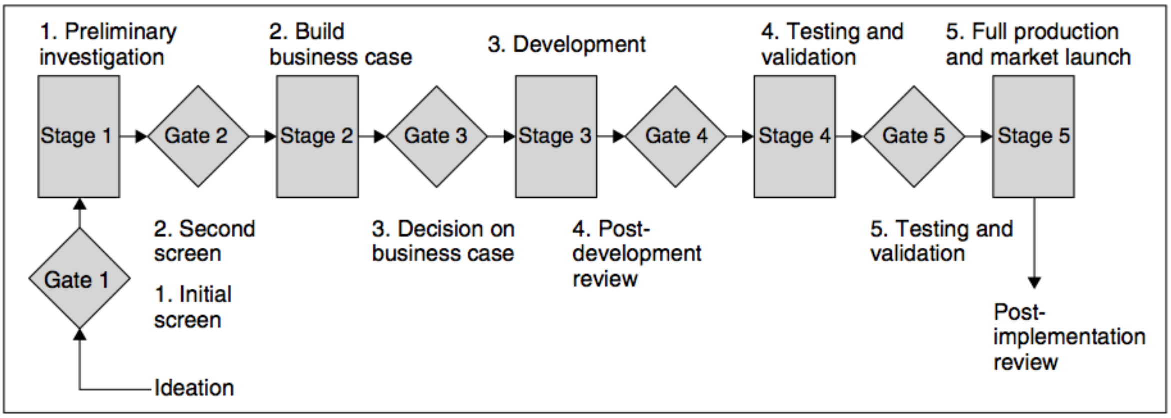


Figure 2.6 The Stage-Gate® Model (adapted from Cooper and Kleinschmidt 2001)

Cooper and Kleinschmidt (2001) emphasize that careful attention should be paid to the early stages, where pre-development work must be done before PD begins. Furthermore, the authors claim the right organizational structure is a key factor in success, advocating the need for multidisciplinary, cross-functional teams dedicated to the projects, accountable for them from idea to launch, and led by strong leaders with top management support.

The model underlines the role of information and knowledge, as it is crucial for decision-making at the different gates (Cooper and Kleinschmidt 1993).

Although the model depicts a simple, logical process, in practice the process is complex. In fact, no model is fixed given the existing multiple variables. As Cooper and Edgett (2005) acknowledge, there is a need to be flexible and adjustable to the scale, nature, magnitude and risk level of the different project types, and therefore there is no longer just one version of the Stage-Gate. The authors advocate a new NexGen Stage-Gate®, which integrates and embodies seven principles of Lean, Rapid and Profitable NPD – a broader, more holistic and multi-dimensional view of Lean PD (see Section 2.1.3) - namely:

- Customer focused;
- Front-end loaded;
- Spiral development;
- Holistic approach driven by multi-functional teams;
- Metrics, accountability and continuous improvement;
- Focused and effective portfolio management – a funneling approach and the resources in place;
- NextGen Stage-Gate® process.

Rozenfeld et al.

More recently, and in an attempt to cover what the authors considered to be relevant but lacking in the PDP models thus far in the literature, Rozenfeld et al. (2006) developed a reference model for the PDP. The model is the result of the authors' experience and research results drawn from the literature in the area.

The Unified Model of Reference combines Pahl and Beitz's (2007) PDP model with the concept of CE, ensuring a model which agglomerates sequential steps (which may overlap), simultaneity and various adaptable tools and methods. The model (see Figure 2.7) is divided into three macro-phases: Pre-development; Development and Post-development. Each macro-phase is subdivided into stages (or phases), which, in turn, are subdivided into activities. The stages are determined by deliverables. The approval of these outcomes is formally carried out during stage reviews (gates), which intend to evaluate in detail the results obtained thus far in order to ensure (or not) the project's continuity. Once approved, the deliverables cannot be changed, unless it is through a controlled process for incremental improvement of the PDP. Management has direct influence on the PDP as it controls information flow. Furthermore, the final Post-development phase clearly distinguishes this model from the ones presented before. The main objective of this phase is to accompany the product through the various stages of its life cycle.

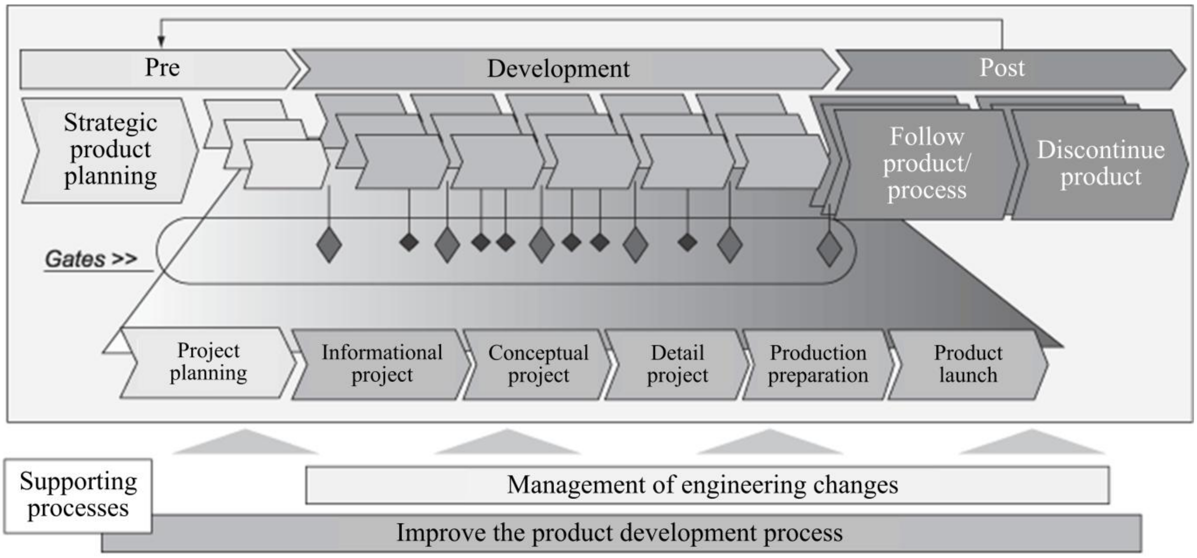


Figure 2.7 PDP Unified Model of Reference (translated from Rozenfeld et al. 2006)

The Unified Model contains phases and activities, similar to the abovementioned models, however in parallel, the authors provide a model to diagnose the maturity of the company's PDP in order to identify the level at which the company is located and thus indicate priority intervention areas according to the company's characteristics, its market and product. The main purpose of the model is to assist companies in the implementation of successful PDP.

By considering the abovementioned models, we can state that most PDP models have an identical structure, while maintaining a degree of heterogeneity, given the specific industry or context to which they refer. Furthermore, and in line with Sharafi et al. (2010), most existing models do not contemplate simultaneous development, PD management and information management, although that is changing as was seen in Cooper and Rozenfeld.

Summary of Methodological Approaches to Product Development

In an attempt to summarize the vast methodological approaches to the PD process, Yazdani and Holmes (1999) proposed four generic models, which illustrates the evolution of the sequential, traditional methodology towards CE. The authors recognize the variety of methods, tools and techniques that companies employ to improve new PD. Furthermore, the authors acknowledge that the pressure companies are subjected to, namely in terms of quality, costs and time, as well as the context determine the different methodological approaches to PD.

Although current trends indicate the need to move towards CE and dynamic models, the truth is that some companies still employ more traditional approaches, while many employ none at all (Fitzgerald 1998).

The Sequential Model

The sequential model (see Figure 2.8) represents the traditional approach to PD. The product is designed and then individual functions contribute in a sequence of activities, with the process being repeated until a satisfactory result is achieved. This approach is functionally oriented with little integration, as opposed to process oriented.

Changes normally occur in the manufacturing stage and, depending on the change, may imply the need to repeat part or the entire process. This has significant effects on costs and time. Furthermore, various management layers predominate in this type of organization.

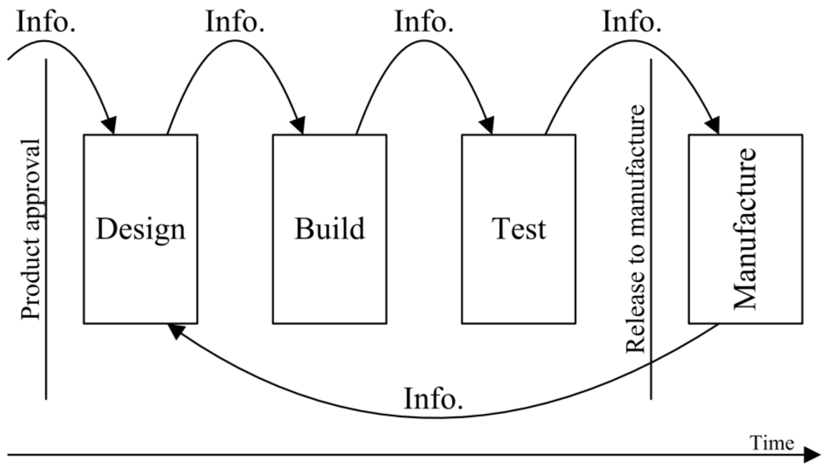


Figure 2.8 Sequencial engineering (Yazdani and Holmes 1999)

The Design Centered Model

Changes at each sequential stage increased costs considerably, thus proving that more life cycle considerations were needed at an earlier stage. The design-centered model shifts the focus of design analysis to the front end of the process (see Figure 2.9).

Although the model does not require the participation of other departments (full integration), attention is given to the downstream activities, minimizing design changes. The process though is still mainly sequential, but there is a greater confidence in design detail. Although such approach improved quality and costs, need to reduce development lead times continued. Furthermore, the emergence of more complex products hindered downstream activities.

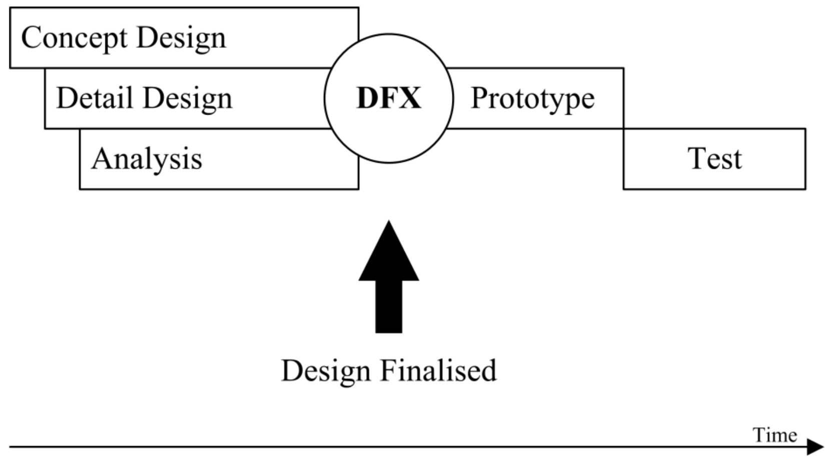


Figure 2.9 The design centered model (Yazdani and Holmes 1999)

The Concurrent Definition Model

Given the demand for shorter lead times, companies felt the need to incorporate specific expertise into the design stage, thus leading to a greater involvement of downstream activities. This was the beginning of concurrent product definition, characterized by the overlapping of the design and planning of process development (see Figure 2.10). Each stage of PD has a formal gate to confer the product's evolution and conformity with downstream activities. The gates allow for many iterations and design changes to occur. At the end of each phase, the process is revised and becomes the basis for the subsequent phase.

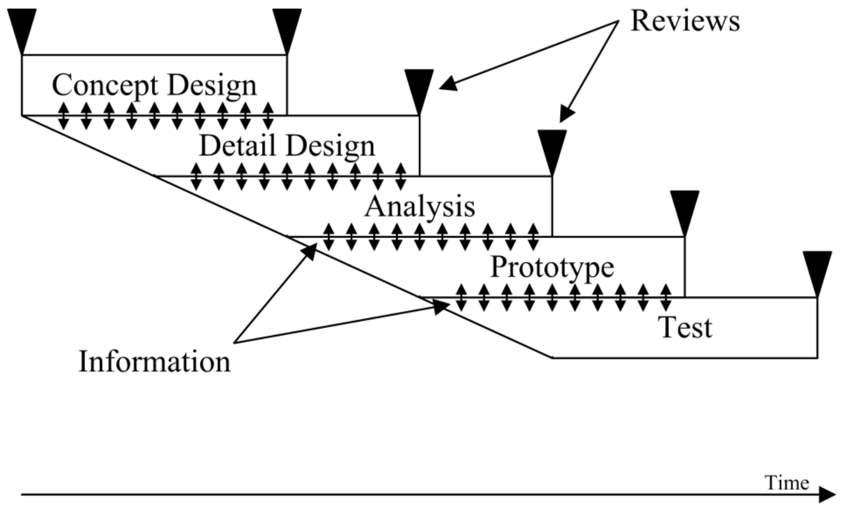


Figure 2.10 The concurrent definition model (Yazdani and Holmes 1999)

The emergence of multi-functional teams allows for informal and more intense information exchange. Within each phase, information acquires a dynamic nature. Product definition is thus more concurrent and not only relies on design analysis, but also on the expertise of each project team, who assumes greater decision-making responsibility.

The Dynamic Model

The dynamic model, a development of the concurrent definition model (see above), surfaced owing to the need for more intense communication amongst the multi-functional team from the beginning of each project. Thus, in this model, information becomes far more informal and intense - a necessity, since all activities begin at the same time. This enables lead time and cost reduction (see Figure 2.11). A fully dedicated project team must possess the necessary technical, business and project management skills in order to be able to make essential decisions at the working level. However, this is only possible in a flat organization model.

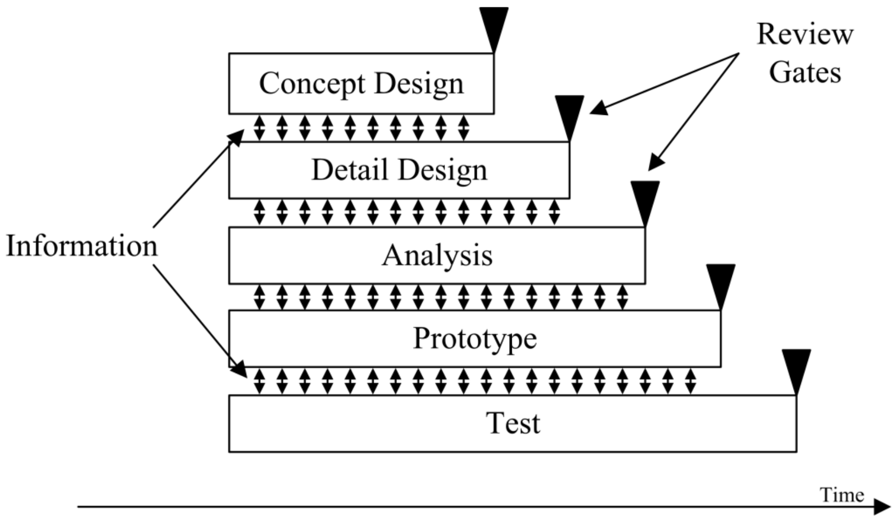


Figure 2.11 The dynamic model of design definition (Yazdani and Holmes 1999)

The dynamic model has been only identified in Japanese automotive companies, and it is also referred to in the literature as “set-based concurrent engineering” (Ward et al. 1995) which is one of the fundamental principles of “lean product and process development” (see for example, Morgan and Liker 2006; Ward 2007). We will continue this discussion in the next section.

The Different Prescriptive Methods: Final Thoughts

Yazdani and Holmes’s (1999) summary of the various methodological approaches to PD represents rather comprehensively the evolution models have undergone over the years.

Despite the differences in the various models presented, perhaps as they derive from different contexts and within different perspectives, all models have evolved towards a more flexible PDP, concurrent with the very nature of PD. Thus, despite the different forces driving each model, new tendencies denote greater degrees of flexibility.

Nevertheless, models continue to seem sequential, focusing on the different process phases or stages in order to reach a satisfactory outcome. The process-based focus intends to improve PD effectiveness and efficiency, by drawing on best practices. A possible explanation may be the need for a graphical representation for easier communication and comprehension. We should however insist that the above mentioned evolution denotes that concepts such as iteration, overlapping activities, flexibility and agility are gaining prominence, to address PD uncertainty.

2.1.3 Product Development Practices

Page and Schirr's (2008) review of the literature published on the PD process reveals the field has grown tremendously with innumerable variables and intricate models being studied throughout the world. Substantial efforts have been made to determine which tools, techniques, and methods produce better results in practice. Nonetheless, most models presented, while based on *best practices*[1], are prescriptive describing what should be done based on these proven practices.

In order to understand the contemporary practices that differentiate highly successful companies, various studies have been undertaken to search for best practices such as the Product Development and Management Association's (PDMA) Comparative Performance Assessment Study (Barczak, Griffin, and Kahn 2009; and more recently Kahn et al. 2012) and the American Productivity Quality Center NPD best practices study (Cooper, Edgett, and Kleinschmidt 2002, 2004a, 2004b). These studies provide a holistic perspective of all practices capable of promoting a successful PDP.

Kahn et al. (2012) empirical study relied on the opinions of American, British and Irish PD practitioners to see what they perceive as *best practice* as opposed to the previous studies where best practices were identified and prescribed by researchers. The study characterized PD practice according to seven dimensions, as defined by the authors:

[1] Kahn et al. (2012) draw on Camp (1989) and describe *best practice* as a "technique, method, process, or activity that is more effective at delivering a particular outcome than any other technique, method, process, or activity within that domain." In the case of NPD practice, the authors claim, best NPD practices are those that promote greater success in developing and launching new products and services.

- Strategy: “defining and planning of a vision and focus for research and development, technology management, and product development efforts at the strategic business unit, division, product line, and/or individual project levels”;
- Process: “the implementation of product development stages and gates for moving products from concept to launch, coupled with those activities and systems that facilitate knowledge management for product development projects and the product development process”;
- Research: “describes the application of methodologies and techniques to sense, learn about, and understand customers, competitors, and macro-environmental forces in the marketplace”;
- Project climate: “the means and ways that underlie and establish product development intra-company integration at the individual and team levels”;
- Company culture: “the company management value system driving those means and ways that underlie and establish product development thinking and product development collaboration with external partners”;
- Metrics and performance measurement: “measurement, tracking, and reporting of product development project and product development program performance”;
- Commercialization: “describes activities related to the marketing, launch, and post-launch management of new products that stimulate customer adoption and market diffusion”.

Their analysis revealed that practitioners are clearly more aware of poor PD practices and have difficulty in identifying and expressing the good practices. Table 2.3 summarizes the characteristics, which practitioners perceived as a best practice across the seven dimensions.

The authors conclude that whilst companies acknowledge these practices, they are difficult to prescribe, in particular when intending to encompass the multiple company-specific PD situations.

Table 2.3 New product development best practices (adapted from Kahn et al. 2012)

Dimension	**Best Practice**
Strategy	Clearly defined and organizationally visible NPD goals.
	The organization views NPD as a long-term strategy.
	NPD goals are clearly aligned with organization mission and strategic plan.
	NPD projects and programs are reviewed on a regular basis.
	Opportunity identification is ongoing and can redirect the strategic plan real time to respond to market forces and new technologies.
Process	A common NPD process cuts across organizational groups.
	Go/no-go criteria are clear and predefined for each review gate.
	The NPD process is flexible and adaptable to meet the needs, size, and risk of individual projects.
	The NPD process is visible and well documented.
	The NPD process can be circumvented without management approval.
Culture	Top management supports the NPD process.
	Management rewards and recognizes entrepreneurship.
Project climate	Cross-functional teams underlie the NPD process.
	NPD activities between functional areas are coordinated through formal and informal communication.
Research	Ongoing market research is used to anticipate/identify future customer needs and problems.
	Concept, product, and market testing is consistently undertaken and expected with all NPD projects.
	Customer/user is an integral part of the NPD process.
	Results of testing (concept, product, and market) are formally evaluated.
Metrics	-
Commercialization	The launch team is cross-functional in nature.
	A project postmortem meeting is held after the new product is launched.
	Logistics and marketing work closely together on new product launch.
	Customer service and support are part of the launch team.
	A launch process exists.

In turn, Smith (2007) adverts that *best practices* in PD “say that one should plan the development project and then follow the plan”. Convergent with the dynamic nature of today’s reality, where uncertainty and change is the rule and not the exception, the author proposes a different approach. Smith advocates *product development flexibility* focused on people factors, as opposed to the more rigid process-based practices. The author defines *product development flexibility* as:

> “The ability to make changes in the product being developed or in how it is developed, even relatively late in development, without being too disruptive. The later one can make changes, the more flexible the process is. The less disruptive the changes are, the more flexible the process is” (Smith 2007).

Although process and structure are necessary, too much process implies a higher degree of rigidity, which is often used as a measure to avoid uncertainty and risk. In contrast, Smith advocates *people* in flexible development, as, through experience, key decision-makers are able to judge and adjust to each specific situation. Although Smith draws on the "individuals and interaction over process and tools" as stated in the Agile Manifesto[2], process is not neglected.

Within this perspective, Smith proposes “customizable tools, techniques and approaches that will help accommodate and embrace change in order to promote a flexible PD”, namely:

- Modular product architectures;
- Front-loaded prototyping and testing techniques;
- Set-based design to preserve options;
- Frequent feedback from customers;
- Close-knit project teams;
- Collaborative decision making;
- Framing decisions and anticipating the information needed to make them;
- Rolling-wave project planning;
- Development processes that maintain both quality and flexibility.

Concurrent with Smith’s opinion that people factors are the most relevant in PD, the tools proposed by the author intend to foster flexible decision-making amongst the PD stakeholders, rather than a procedure to be replicated.

[2] http://agilemanifesto.org/

While in practice individual solutions are applied, studies reveal that unless best practices are combined and applied as a *system*[3], PD will continue to produce less than optimal results (Negele et al. 1999). A holistic approach capable of integrating and employing individual best practices may be the pillar for successful PD processes. Among the many holistic viewpoints that have recently emerged, we'll discuss three – Concurrent Engineering, Toyota's Lean Product Development System and Design for Six Sigma – aware that as research progresses, boundaries have been blurred, perhaps in an attempt to include best practices from other approaches (for example, Lean Six Sigma).

Concurrent Engineering

The shift towards a modern approach to PD proposed by Takeuchi and Nonaka (1986) fostered by Japanese automobile industries may be considered an early example of what is currently denominated as *Concurrent Engineering* - also referred to as Simultaneous Engineering (SE), Integrated Product Development (IPD) and Dynamic Product Development (DPD) (Carter and Baker 1992; Syan and Menon 1994; Ottosson 2004). Although there is no clear definition of CE, Loch and Terwiesch (1998) draw on the work of Gerwin and Susman (1996) to define it as "integrating the new product development process to allow participants making upstream decisions to consider downstream and external requirements". The Institute for Defense Analysis defines it as "the systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support" (Winner et al. 1988). In the area of manufacturing engineering, Nevins, Whitney and De Fazio (1989) were amongst the earliest researchers to advocate the need for concurrent design in the product and manufacturing system.

Clark and Fujimoto (1991), based on the automobile industry, operationalized many important variables of CE such as task overlapping and cross-functional communication, as well as the question of integration (Wheelwright and Clark 1992). Abdalla (1999) argued that also part of CE is the early consideration of aspects related to the product life cycle, namely functionality, manufacturability, reliability, cost and quality in the design process. Haque, Pawar and Barson (2000) reiterate the need for an early involvement of all organizational functions with implication in the process.

Task overlapping and integration requires continuous and clear information exchange among the different functions, therefore a team approach with enhanced communication

[3] Hastings (2004) defines system as "collection of pieces whose collective function is greater than the function of the individual pieces". Negele et al. (1999) apply the concept of *system* to the additional interrelated aspects (besides processes) that should be considered in order to get a comprehensive view of PD, namely customer and user needs; requirements and goals; products; people; resources and organizations.

skills is encouraged. Given the implications, CE cannot be considered in isolation. As Smith (1990) notes, “Concurrent Engineering may well change the way a company operates and it is not to be undertaken without careful thought”. Undeniably CE greatly impacts PDP, as it requires better cooperation, coordination and communication amongst all those involved.

With the growth of CE, its applications have become more diverse, the concept blurred. Literature on CE implementation methods, tools and techniques proliferate as different projects, companies, and industrial contexts tailor CE approaches to meet their specific needs. As Smith (1990) explains, “there is no standard or single way to implement the [CE] principles”. Consequently the literature presents a wide range of CE-based studies but, as far as we are aware of, there is none that systematizes current CE practices.

Smith (1997) traces the roots of CE seeking a deeper understanding of its principles. He summarizes them as follows:

- “manufacturing and functional design constraints need to be considered simultaneously;
- combining of people with different functional backgrounds into a design team is a useful way to combine the different knowledge bases;
- engineering designers must bear in mind customer preferences during the design process; and
- time to market is an important determinant of eventual success in the market”.

From his analysis, the author concludes that CE can be considered a summary of best practice in PD, rather than something new. The year before, Swink, Sandvig and Mabert (1996) carried out a study to understand CE practices amongst 5 well-known companies. Their findings were based on interviews, document analysis and follow-up discussions. They summarize these companies’ CE practices as follows:

- Functional groups integrate their knowledge of techniques, processes and data;
- Teams are fundamental organizational forms for promoting integration;
- Team arrangements include: program management teams, technical team, design-build teams, integration teams and task force;
- The number of teams varies due to size and technical complexity;
- Teams are constituted by: part-time and full-time participants, members from inside and outside the firm, and design and manufacturing co-leadership;

- Teams are often given budget control and access to required resources as well as authority and responsibility for designing a product subsystem or component and the processes needed to produce it;
- The modes, frequency, richness and formality of communications among project participants varies according to information complexity and according to design and timing challenges;
- Concurrent processing of development activities: project phase concurrency, design concurrency and product concurrency.

Given the array of practices in the literature, Koufteros, Vonderembse and Doll (2001) consider three basic pillars in CE practices:

- **Concurrent workflow**: the simultaneous planning of product, process, and manufacturing;
- **Product development teams**: PD employees work as a team. They represent a variety of functions and share information;
- **Early involvement of constituents**: early customer and supplier involvement.

These three pillars are coherent with Swink's and his colleague's work, emphasizing the significance of effective cross-functional teams (with internal and external members), which integrate the development process with simultaneous activities, using both organizational and information management methods. The contribution of teamwork and communication to the anticipation of information denotes a company's capacity to anticipate constraints and opportunities, avoiding late reworks and unexpected problems. Thus teamwork positively influences the capability to anticipate information (Verganti 1998).

Drawing on these findings, Swink (1998) proposes a tutorial on implementing CE in PD, where he describes two foundational management initiatives for CE implementation and identifies a number of widely accepted management methods and tools that have proven to be effective in fostering the intended behavior. Table 2.4 summarizes Swink's proposals.

A recent literature review concluded that CE has seen some relatively drastic decline over the last decade (Addo-Tenkorang 2011), due perhaps to its evolution or maturity from the original. In fact, in current literature CE umbrellas LPD and Six Sigma practices, as the latter are based on the former.

Table 2.4 Core initiatives for concurrent engineering programs (adapted from Swink 1998)

Management initiatives	Management activities	Management methods and tools
Improving cross-functional integration	Setting and analyzing goals	Costumer surveys QFD, see Hauser and Clausing (1988) Cause/effect analysis Product benchmarking Super-ordinate project goals Return map, see House and Price (1991)
	Directing and controlling integration	Organizational rules Project specific rules Pre-project training Project contract Off-program initiative
	Encouraging communication and awareness	Cross functional teams Team incentives Liaison roles Secondment, see Voss, Russell and Twigg (1991) Role combination Collocation Open-door policies Meetings War room Design database Electronic communications
Improving design analysis and decision making	Capturing and applying best design practices	Functional approvals Internal consultants Design axioms, see Suh (1990) DFM guidelines Process design rules Designer's toolkit Boothroyd-Dewhurst DFA method Computer-aided DFM
	Facilitating design generation and analysis	Group technology Preferred parts or supplier classifications Taguchi methods, see Ross (1988) Failure mode and effects analysis Manufacturing process simulation Rapid prototyping Value analysis Design-to-cost methodology

Lean Product Development

Lean Manufacturing emerged in Womack, Jones, and Roos's (1990) famous book *The Machine that Changed the World* where the authors explain the evolution of lean manufacturing practices in the automobile industry. Lean Manufacturing is "a philosophy that when implemented reduces the time from customer order to delivery by eliminating sources of wastes in the production flow" (Liker 1997). The concept of *Lean* was first used by Toyota, as a tool in the manufacturing process in order to increase efficiency by reducing waste. Toyota's production system has become the basis of what has been called *Lean Thinking* (Womack and Jones 1996), which focuses on maximizing customer value while reducing or eliminating waste along the value streams, thus improving quality and reducing cost.

Lean Product Development (Liker and Morgan 2006) is a methodology that attempts to apply the principles learned in Lean Manufacturing into PD. It derives from Toyota's approach to product-process development, which adapts lean thinking into PD systems model with three main pillars: People, Processes and Tools and Technology. Liker and Morgan (2006) define Lean Product Development (LPD) as: "a knowledge work job shop, which a company can continuously improve by using adapted tools used in repetitive manufacturing processes to eliminate waste and synchronize cross-functional activities". The authors shift the focus to knowledge job, rather than material job and underlined the importance of adapting lean manufacturing's tools and techniques to reduce or eliminate waste and optimize PD processes. By considering the three pillars, the human factor becomes preponderant, rather than just processes and tools.

LPD does not aim to provide a roadmap for PD, its intention is to help improve and standardize the existing process in a company. Visualization tools, such as process mapping, show the improvement opportunities in the PD process and allow for a more fluent PD, which in turn will improve the company's reactivity in the market (Reinertsen 2005), thus maximizing customers' value. By concentrating on continuous improvement and visual communication, companies are able to increase product quality from the beginning of a project (Liker and Morgan 2006). Ward (2007) summarizes the lean development system principles, Toyota's internal practices to grow and share knowledge, as follows:

- "Focus on creating knowledge and hardware for consistently profitable operational value streams.

- Embody this focus in entrepreneur system designers (ESDs) – project leaders who are responsible for creating these profitable value streams.
- Support ESDs with set-based concurrent engineering (SBCE) to eliminate risk while achieving high innovation and rapid learning by looking at multiple alternatives at every level of the system.
- Support SBCE with cadenced flow and pull project management to minimize load variation and sequencing, and to get everyone to plan their own work.
- Support flow and pull management with teams of responsible experts who design their own work, learn from conflict, and both create and use new knowledge".

Within lean literature, many authors have explored lean's basic principles in order to perceive the practices (sometimes referred to as tools) being implemented in companies worldwide. As different authors will list different practices, we summarize the recurrent practices as follows:

- **Early supplier involvement/front-end loaded**: By involving suppliers from the start of the process, it is possible to establish long-term partnerships, foster joint development and reduce the number of suppliers. Thus, risks are reduced, as well as cost and lead time (see, for example Clark and Fujimoto 1991; Karlsson and Åhlström 1996; Liker et al. 1996; Ragatz, Handfield, and Petersen 2002; Cooper and Edgett 2005; Petersen, Handfield, and Ragatz 2005).
- **Value Stream Mapping**: A tool to visualize a value stream, which enables the identification of value as well as unnecessary waste or delays. This visual picture of the process allows for the calculation of lead time, in addition to improvements (see, for example Hines and Rich 1997; Morgan and Liker 2006; Locher 2008).
- **Voice of the Customer**: Maximizing customer value was mentioned as the focus of lean thinking. It is therefore essential to incorporate customer's expectations in relation to quality, cost and delivery in the PDP. One of the most widely used tools for this purpose is the Quality Function Deployment (also known as QFD). This tool translates customer needs to design information (see, for example Yang 2008; Cooper and Dreher 2010; and on QFD Akao 1990; Cohen 1995; Akao and Mazur 2003; Ficalora and Cohen 2010).
- **Visual management**: Visual management tools support communication and are used to help drive operations and processes in real time. It allows process intervenients to know what has been done and what work remains to be done, thus bringing transparency to the process. These tools include standard work charts and displays, CAD systems, checklists and so on (see Parry and Turner 2006).

- **Knowledge Library**: By keeping an organized knowledge system with projects developed, it becomes possible to sustain, apply, share and renew previously gained knowledge in order to enhance company performance and create value. Knowledge transfer between projects considerably reduces time-to-market (see Takeishi 2002; Hines, Francis, and Found 2006; Morgan and Liker 2006).
- **Set-Based Concurrent Engineering (SBCE)**: Concurrent engineering (where different activities and tasks are performed simultaneously and in parallel) is considered in terms of lean thinking. In SBCE, a broader set of alternatives (parallel and independent) is taken through the phases of the PDP by the development team which, then gradually eliminate alternatives until a better one is produced from a combination of systems, subsystems and components. In practice, this means delaying decisions (and increasing design team's uncertainty), communicating and pursuing sets of possible solutions, rather than modifying a point solution, in order to reduce cost and time-to-market (see, for example Ward et al. 1995; Sobek II, Ward, and Liker 1999; Hines, Francis, and Found 2006; Doll, Hong, and Nahm 2010; Khan et al. 2011).
- **Standardization**: Standardization is the basis for continuous improvement as it reduces variability and allows for the creation of predictable outcomes with quality. Standardization may be that of the project – the product, its components, materials and architecture – or that of the processes involved. The latter entails frequent tasks, their sequence and length, as well as the standardization of technical skills, which pertains to specific people's skills and knowledge within the development team (see Cusumano and Nobeoka 1998; Liker, Collins, and Hull 1999; Liker and Morgan 2006; Morgan and Liker 2006; Emiliani 2008; Marksberry et al. 2010).
- **Cross-Functional Teams**: Teams with members from different functional areas (such as marketing, production, etc.) work in an integrated fashion. The workload becomes leveled, management cadence is shortened, processes are synchronized across functional departments, and rework may be nearly eliminated (see Karlsson and Åhlström 1996; Cooper and Edgett 2005; Liker and Morgan 2006; Kim and Kang 2008).
- **Chief Engineer System/heavyweight team structure**: The Chief Engineer[4] is the one person in the PD project that pulls the different parts of the project together and creates a coherent whole. He is the person responsible for integrating the technical, process and customer knowledge in order to improve workflow. The

[4] Also denominated as "entrepreneurial system designer" by Ward (2007).

> Chief Engineer assumes not only the role of project manager, but also of leader and technical integrator (see, for example Kennedy 2003; Liker and Morgan 2006; Radeka 2012).

In sum, as Karlsson and Åhlström (1996) discuss, the "collection of interrelated techniques including supplier involvement, cross-functional teams, SBCE, functional integration, use of heavyweight team structure and strategic management of each development" are essential to reach LPD. The authors stress the importance of a "coherent whole" as opposed to the implementation of individual techniques. They argue that implementing one technique does not mean LPD.

Design for Six Sigma

Six Sigma is a methodology that provides businesses with the tools to improve the capability of their business processes. Six Sigma is different from other quality initiatives, as it focuses on all aspects of business operation, seeking to improve key processes, not only product quality. It is therefore a process-based approach to business improvement, which revolves around a "do the right thing, and do things right all the time" rule (Yang and El-Haik 2003).

Linderman et al. (2003) define Six Sigma as "an organized and systematic method for strategic process improvement and new product and service development that relies on statistical methods and the scientific method to make dramatic reductions in customer defined defect rates". This definition underlines the importance of improvements based on what customers perceive to be a defect. The authors perceive as essential in the improvement effort being able to determine exact customer requirements, and then defining defects based on customer's "critical to quality" parameters, instead of internal considerations. Therefore, data and objective measurement at each phase is crucial. The authors emphasize that the careful integration of tools with the methods is unique to Six Sigma.

Tennant (2002) summarizes the concept of Six Sigma from three different perspectives: as a metric, as a methodology and as a philosophy. The philosophy underpinning Six Sigma is total customer satisfaction. The metric is related to the customer experience of quality and the costs associated with the delivery of poor quality (from the customer's standpoint). The Six Sigma methodology links tools and techniques to foster successful process improvement, by identifying and eliminating defects.

The Six Sigma methodology was developed and pioneered at Motorola in the 1980s in order to reduce “quality costs” (i.e. the costs that derive from not doing things “right the first time”). The main aims were to reduce the number of mistakes/defects in the manufacturing process, thus leading to a reduction in manufacturing costs. Six Sigma is therefore considered the “ultimate measure of quality” (Antony 2002).

The methodology was popularized by General Electric in the nineties and, by 2002 many of Fortune 500 companies claimed having implemented Six Sigma (Chowdhury 2003). Indeed, by placing the focus on customer needs and establishing quantifiable measures, Six Sigma projects leads to greater customer satisfaction, organizational performance and profitability (Jones, Parast, and Adams 2010).

Zhang, Hill and Gilbreath (2011) consider five distinctive elements/principles of Six Sigma. These are:

- **Customer orientation**: Customer orientation is an important principle of quality management. In Six Sigma, customer requirements are the main focus. Projects must clearly demonstrate their value to customers, and the benefits must be clearly visible from customers’ standpoint. Furthermore, customer orientation is used to decide on and prioritize projects.
- **Leadership engagement**: Quality management effort entails strong top management support. In Six Sigma a mechanism is set forth to ensure that the leadership team is engaged and that Six Sigma is prioritized. Senior executives are directly involved in projects, which guarantees that the right projects are selected and receive organizational support. Full-time improvement project leaders (also known as *Black Belts*) are selected not only because of their technical knowledge but also their leadership skills.
- **Dedicated improvement organization**: Six Sigma requires organizations to establish a dedicated organizational structure for improvement. This structure includes roles such as Green Belt, Black Belt, Master Black Belt, and Champions. Only the organization’s most dedicated and best employees can occupy Black Belt positions, which lead to effective improvements.
- **Metric focus**: Six Sigma emphasizes the application of metrics and rigorous tracking of the metrics to guarantee benefits derive from improvement projects. All projects must have clearly defined goals, expressed in metrics. Each project is also inspected on its intended and realized benefits, usually in financial terms.

- **Structured method**: Six Sigma is highly prescriptive, as each project must strictly follow a structured method, known as DMAIC. The DMAIC method breaks down as follows: **D**efine the project goals, the customer (internal and external) requirements and the process. **M**easure the process to determine current performance. **A**nalyze and determine the root cause(s) of the defects. **I**mprove or optimize the process by eliminating defect root causes. **C**ontrol future process performance. This allows for the structured exploration of root causes and structured control of the process in order to produce the desired output. By implementing a standard method, a common language is set across the organization, promoting knowledge creation and dissemination.

In order to successfully implement the Six Sigma principles, organizations need more than an understanding of Six Sigma methodology, tools and techniques. Management commitment and involvement is needed. Six Sigma implies changes in the entire organizational infrastructure, based on cultural change and training (Wang 2008).

Six Sigma does not address the original design of the product or process, it merely improves them. Antony (2002) and Chowdhury (2003) contend that for organizations to effectively reach the six-sigma quality level, they need to redesign their products, processes and services. Whereas Six Sigma focuses on reforming the production and business process to eliminate mistakes, improve morale and save money, organizations need to develop or redesign the process itself to prevent downstream errors. This can only be achieved by switching from “reactive improvement” to “proactive improvement” (Mader 2006), by implementing Design for Six Sigma (DFSS).

DFSS is “the Six Sigma strategy working on early stages of the process life cycle” by utilizing “the most powerful tools and methods known today for developing optimized designs”, where the objective is to “design [our emphasis] it right the first time” (Yang and El-Haik 2003). Whereas Six Sigma is used to “react” to or fix unwanted events in the customer, design, or process domains, DFSS is used to “prevent” problems by building quality into the design process across domains at the thinking level (Smith 2001).

Brue and Launsby (2003) define Design for Six Sigma as:

> “A systematic methodology using tools, training, and measurements to enable the design of products, services, and processes that meet customer expectations at Six Sigma quality levels. DFSS optimizes your design process to achieve Six Sigma performance and integrates

> characteristics of Six Sigma at the outset of new product development with a disciplined set of tools".

In terms of systematic methodology, Tennant (2002) posits a structured methodology for PD that consists of a rigorous stage gate ("tollgate") model, with deliverables that must be approved at the end of each stage, before the project continues. In regards to the implementation of tools, Mader (2002) concedes, "the power of DFSS is in the organization of the tools into a coherent strategy that aligns with the NPD process, not the individual tools themselves". Thus, the careful selection and integration of a group of tools and techniques within a stage gate PDP, encompassing Six Sigma principles is regarded as the essence of DFSS.

Kwak and Anbari (2006) draw on De Feo and Bar-El (2002) and summarize seven basic elements of DFSS as follows:

- Customer-oriented design process with six sigma capability;
- Design quality at the outset;
- Top–down requirements flow down with flow up capability;
- Cross-functional design involvement;
- Quality measurement and predictability improvement in early design phases;
- Process capabilities in making final decisions;
- Process variances to verify that customer requirements are met.

Unlike the DMAIC methodology applied in Six Sigma, the phases or steps of DFSS are not universally recognized or defined. Many companies and training organizations will present a tailored model, in order to suit their specific businesses. As a result, there are two widely recognized methodologies with several variants. In attempting to retain the link to DMAIC, one of the most popular DFSS methodology is DMADV (i.e. Define, Measure, Analyze, Design and Verify); the other is ICOV/IDOV (Identify, Characterize/Design, Optimize, Verify). We will present each briefly, as well as some of the associated tools for each phase.

DMADV

Breyfogle (1999) first refers to DMADV approach in opposition to DMAIC, advocating its appropriateness when a "product or process is not in existence and one needs to be developed. Or the current product/process exists and has been optimized but still doesn't meet customer/business needs". The DMADV approach comprises five phases:

- **D**efine the design goals (consistent with customer expectations);
- **M**easure the organization's capability to produce the product and associated risks, as well as identify characteristics that are Critical To Quality (CTQ) based on the Voice of the Customer (VOC);
- **A**nalyze to develop and design alternatives and then evaluate each to select the best;
- **D**esign details, optimize the design, and plan for design verification;
- **V**erify design performance, namely through pilot runs, then implement the production process.

For each phase of the DMADV approach there are specific tools, which seek to foster the intended outcome. Given the vast array of tools mentioned in the literature (Kwak, Wetter, and Anbari 2006), we draw on Ginn and Varner's (2004) Six Sigma roadmap, which concentrates on the DMADV phases of the DFSS process. Table 2.5 depicts the methods and tools proposed by the authors for each phase.

Table 2.5 Methods and tools for each phase of DMADV (Ginn and Varner 2004)

Phase	Methods and tools
Define	Market analysis tools (Market forecasting tools, Customer value analysis, Technology forecasting and visioning); Process analysis tools (Control charts, Pareto charts); Traditional project planning tools (Work breakdown structures, Program Evaluation and Review Technique (PERT) charts, Gantt charts, Activity network diagrams); DMADV specific tools (Project charter, In-scope/out-scope tool, Organizational change plan, Risk management plans, Tollgate review forms).
Measure	Customer segmentation tree; Data collection plan; Customer research tools (Interviews, Contextual inquiry, Focus groups, Surveys); VOC table; Affinity diagrams; Kano model; Performance benchmarking; QFD matrix; CTQ risk matrix; Multistage plan; Tollgate review forms.
Analyze	QDF matrix; Creativity tools (Brainstorming, Analogies, Assumption busting, Morphological box); Pugh matrix; Tollgate review forms.
Design	QDF matrix; Simulation; Prototyping; Design scorecard; FMEA; Planning tools; Process management chart; Tollgate review forms.
Verify	Planning tools; Process analysis tools (Control charts, Pareto charts); Standardization tools (Flowcharts, Checklists); Process management charts.

IDOV

For Yang and El-Haik (2003), DFSS comprises four phases, known as IDOV or ICOV:

- **I**dentify requirements: Draft project charter; Identify customer and business requirements;
- **C**haracterize the **D**esign: Translate customer requirements to product/process functional requirements; Generate and evaluate design alternatives;
- **O**ptimize the design: Optimized design entity with all functional requirements released at the Six Sigma performance level;
- **V**erify the design: Pilot testing and refining; Validation and process control; Full commercial rollout and handover to new process owner.

As with the DMADV methodology, several authors have enumerated the various tools for each of the IDOV approach. Table 2.6 summarizes our findings based on Creveling, Slutsky and Antis (2003), Yang and El-Haik (2003), Woodford (2010) despite the slight variances found in the definition of each phase.

Table 2.6 Methods and tools for each phase of IDOV

Phase	Methods and tools
Identify	Developing team charter; Gathering the VOC (Market/customer research and Affinity diagrams); Develop CTQs; QFD; Kano model; Risk Analysis; Benchmarking; Target costing; FMEA; SIPOC (Supplier, Input, Product, Output, Customer map); IPDS (Integrated Product Delivery System).
Characterize the Design	Concept generation and Design for X methods; Pugh concept evaluation and selection process; QFD; TRIZ; Axiomatic design; Robust design; DFMEA and PFMEA; Design review; CAD/CAE; Simulation; Process management; Materials selection; DOE (Design of Experiments); Systems engineering.
Optimize	Design/simulation tools; Transfer functions; DOE; Taguchi method for robust design, parameter design, tolerance design; Reliability-based design; Robustness assessment; Response surface methods; Optimization methods.
Verify	Process capability modeling; DOE; FMEA; Reliability testing; Poka-yoke, errorproofing; Confidence analysis; Statistical process control (Process control plan); Training; Disciplined new product introduction.

The tools and best practices associated with DFSS and the specific approaches mentioned above are what actually deliver results. Given that practices vary, and that Kwak, Wetter and Anbari (2006) have uncovered over 400 tools and techniques for Six Sigma, where only two thirds of which are in fact unique tools and not duplications with different names, it is feasible for us to state that Six Sigma in general, and DFSS in particular is rather complex in nature and perhaps seemingly rather disjointed given that its practical roots lay in the industry and the fact that most literature is based on *best practice* studies (Linderman et al. 2003).

Product Development Practices: Final Thoughts

PD practices vary according to different perspectives. Although the modern PD process is anything but linear and structured, in its majority PD *best practices* are still put forth as a set of procedures that must be followed and specific tools to use. Based on concrete practices identified in various types of organizations and different types of projects, most literature proposes a prescriptive, more structured approach to implementing what is perceived to be *best practices* to provide a successful PDP, where specific recipes can be applied. The idea being, if it has worked before, it can be reapplied. Perhaps, this is so as the focus is still very much on the process itself. Others, such as Smith (2007), propose tools for a flexible approach, considering the unique nature of the PD process and the fact that it is people centered. This idea is concurrent with the “one size does not fit all” defended by Krubasik (1988) and Otto and Wood (2001). Indeed, without questioning the prescriptive literature, we propose these *best practices* should always be adapted to each particular situation. By customizing procedures and tools and avoiding a direct and mechanistic implementation, we can foster a flexible PDP that supports uncertainty and adapts to changes which is a reality in today’s world.

2.1.4 Product Development Frameworks

As mentioned previously, research on product development is diverse and fragmented, making it extremely difficult to understand, systematize and organize. Various authors have attempted to address this problem, among them Brown and Eisenhardt (1995) and Krishnan and Ulrich (2001), each within a different perspective. This section depicts the authors’ key research findings, as their synthesis is an important development and useful contribution to an in-depth understanding of PD.

Gericke and Blessing (2011) state:

> "A key weakness of design process models is their difficult application to real design problems. Most process models are too general to help project planning and to guide daily decisions. While most models of designing integrate an iterative component or the evaluation of the results they do not describe how to achieve fitness for purpose of the product".

Nevertheless, this important field of study already provided a set of principles that we can consider as the PD theoretical basis for our research. Several reviews organize research into frameworks. Brown and Eisenhardt (1995), for example, organize PD research depending on its methodological approach. They aggregate previous empirical findings into a framework of factors, which affect the success of PD projects (see Figure 2.12).

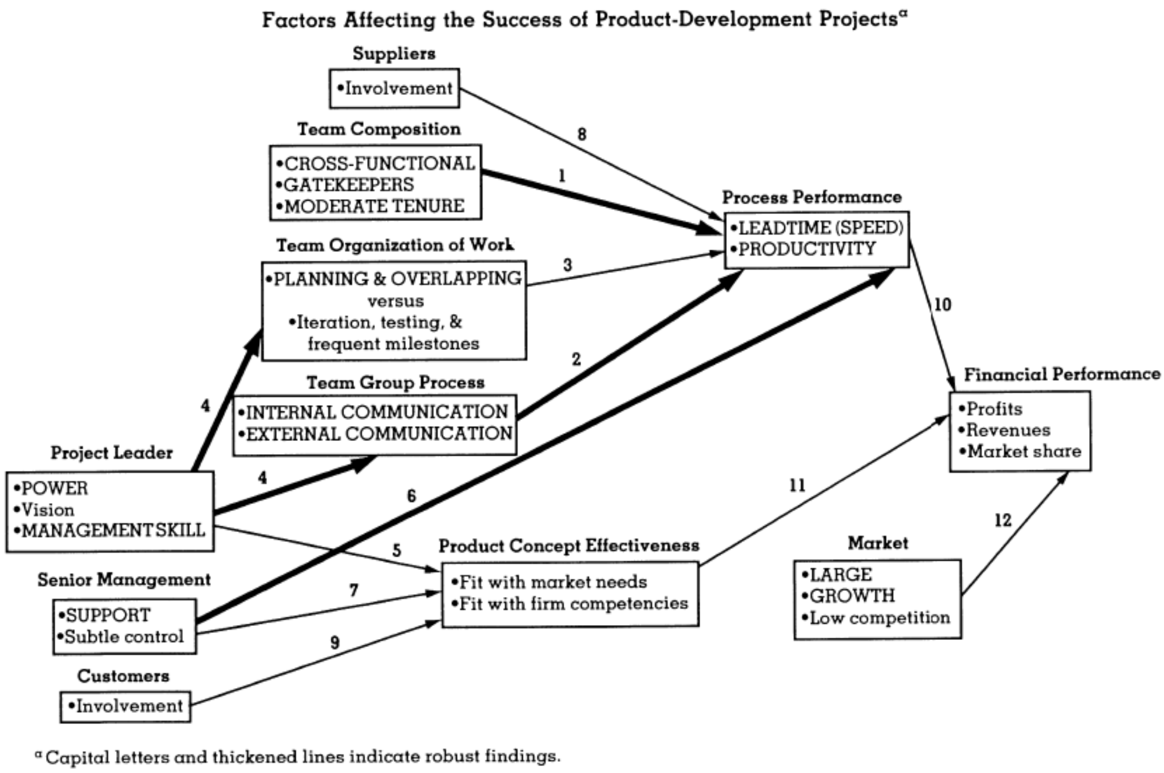


Figure 2.12 The Brown and Eisenhardt (1995) framework

An important observation of Brown and Eisenhardt is that:

> "… there are two relevant problem-solving models for organizing PD. One focuses on factors such as planning and overlap that are relevant for more stable products in mature settings, and the other focuses on experiential product design that is relevant for less predictable products in uncertain settings".

Finally, the key construct behind the framework is that product financial performance is influenced by the actions of multiple players (that perform roles in the PD process). The authors argue that the project team, leader, senior management and suppliers affect process performance; the project leader, customers and senior management affect product effectiveness; and the combination of an efficient process, effective product and attractive market determines the financial success of the product.

The PDP success factors synthesized by Brown and Eisenhardt are consistent with the principles and related practices defended by LPD, as explained in Section 2.1.3.

This perspective clearly suggests that any PD process model should emphasize the roles involved in the process in parallel to the tasks and decisions. The model should enable a view of who is responsible for what and how they interact. As the next section will illustrate, most of the PD modeling approaches neglect this facet of the PD process concentrating almost exclusively on tasks. In real projects the "what to do" is translated in "how to do" by the roles involved in the PD process. We intend to understand this translation.

Krishnan and Ulrich (2001) use a different approach. By combining different perspectives and disciplines, they identify two broad categories within the literature: one focusing on decisions that are made prior to the development project (which consider both strategic and organizational decisions); and a second category where the decisions are made within a development project (which include all the major phases in the development process). The authors classify research in clusters, which establish three essential enablers in PD decisions: product features (market and design), architecture-related issues (also encompassing organizational issues), and portfolio-selection decisions that attend to the strategic development aspects. Figure 2.13 illustrates their findings.

Once more the referred model includes issues related with the tasks required to develop the product and, to a lesser extent, the roles involved in the development process (the "who"). The authors state:

> "Product planning decisions and development metrics seem particularly ad hoc in industrial practice. (…) Insights on customizing product development practices to diverse environments such as small entrepreneurial firms and varied industries should also help increase the relevance and applicability of the development literature" (Krishnan and Ulrich 2001).

The above quote is one of the motivations for the research presented in this thesis.

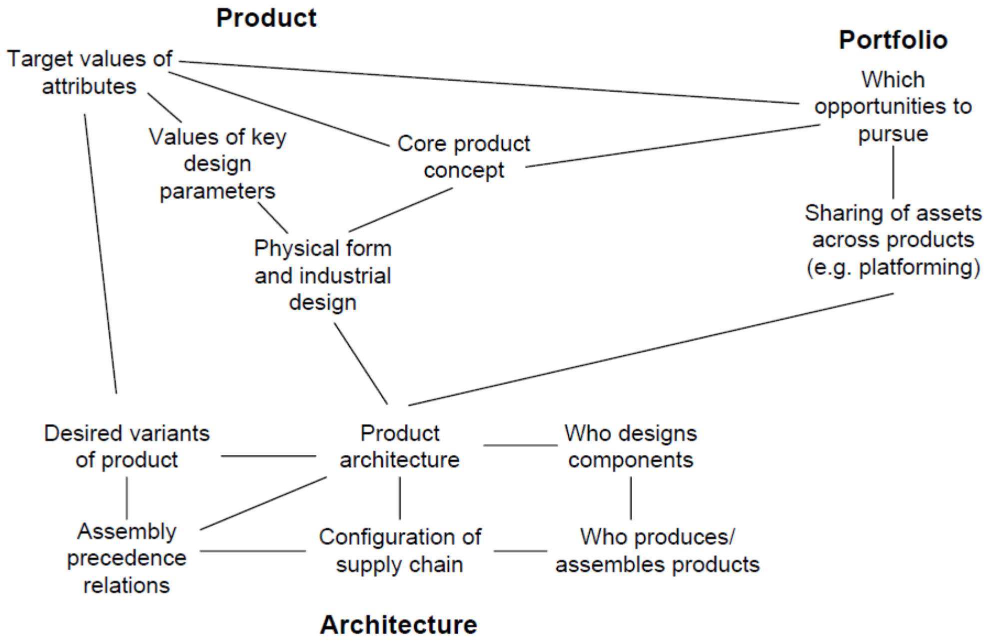


Figure 2.13 The Krishnan and Ulrich (2001) classification

Product Development Frameworks: Final Thoughts

Brown and Eisenhardt's review on PD, as well as that of Krishnan and Ulrich, provide an in-depth perspective of PD success factor. Brown and Eisenhardt's analysis suggests successful PD process models need to draw attention to the roles or, as Smith (2007) advocates, greater importance must be given to the people factors in parallel to the tasks and decisions. Furthermore, the authors concluded that in PD projects with higher levels of uncertainty and thus higher risks associated to decision processes, experiential approaches benefit process performance. Iterations, testing and frequent milestones promote learning and significant knowledge gains, which directly influence lead-time and productivity. This is in line with Smith's flexible approach to PD, where delaying decisions until the last responsible moment is regarded as an essential practice for successful PD. As the author states, "the last responsible moment is different than typical procrastination. It involves identifying and collecting information now that will help you make a better decision".

As we will see in the next section, in practice, most PD modeling approaches continue to overlook these references in the literature. It is thus our intention, with the present study, to delve into these aspects as they clearly represent a research gap.

2.2 Product Development Process Modeling

Having considered the recommended, prescriptive models in the PD literature in Section 2.1.2, our focus now shifts to descriptive models as these allow us to perceive what is actually being done at the PDP level. In order to obtain these descriptive models, the PDP has to be modeled.

Browning, Fricke and Negele (2006) identify a model to be "an abstract representation of reality that is built, verified, analyzed, and manipulated to increase understanding of that reality". The authors draw on Box (1979), admitting, "all models are wrong, but some are useful". As Ould (2005) explains, a "model is right, if it helps". The usefulness of a model resides in the fact that it can be helpful for prediction making and hypotheses-testing, through the pertinent insights it can provide. Becker, Rosemann, and Von Uthmann (2000) posit a helpful model should acknowledge the *Guidelines for Modeling*, identified as follows:

- Correctness: the model should be correct in terms of arrangement order;
- Relevance: only the relevant aspects are represented in the model;
- Economic efficiency: the relation between cost and benefit of modeling;
- Clarity: to ensure understandability;
- Comparability: the consistent use of naming conventions and modeling schemes to enable comparisons;
- Systematic design: the clear separation of different views.

2.2.1 Business Process Modeling

Business process management and, consequently, business process modeling emerged with the book *Reengineering the Corporation*, written by Hammer and Champy in 1993. Although the authors at the time proposed a traditional, restrictive input–output view of the business processes (see Section 2.1 for a clearer definition of business process), its criticism led to what is currently denominated as Business Process Management (BPM).

BPM can be defined as "using methods, techniques, and tools to support the design, enactment, control, and analysis of operational business processes that involves humans, organizations, applications, documents and other sources of information" (van der Aalst, ter Hofstede, and Weske 2003; van der Aalst 2004). The ultimate goal is thus to improve and enhance the organization's business processes.

Among the methods, techniques and tools proposed, is the process description, which entails modeling the business processes, also known as business process modeling. Business process models are “an important knowledge source for managerial decision making” (Dalal et al. 2004).

Aldin and de Cesare (2009) summarize the elements that are commonly and generally accepted by the business modeling community as characterizing a business process as follows:

- “Process: A set of activities, events, and so on that together and cohesively deliver a service and/or a product.
- Activity: Specific behavior carried out in an organization.
- Service and Product: The observable outcome of value of a process.
- Role: The types of actors or agents that take part in processes.
- Goal: The aim of a process.
- Event: An occurrence that takes place at a specific point in time and that is capable of inducing some observable behavior (activity or process).
- Rule: A constraint defined for any part of the organization and its processes”.

The authors posit business process modeling is an activity, which seeks to represent all, or part of the abovementioned elements. In their comparative analysis of the different modeling approaches within BPM, Aldin and de Cesare (2009) cite Kettinger et al. (1997) who identified a total of 72 techniques and 102 tools that can be applied, depending on the intention and focus. The authors summarize the findings in the literature, drawing on Luo and Tung (1999), Eriksson and Penker (2000), and Caetano et al. (2005), concluding that the main purposes for business process modeling consist of:

1. Sharing the understanding of the process through common process representations, fostering human understanding and communication.
2. Providing reuse as the basic input requirement definition.
3. Creating business support systems, through a descriptive model for learning.
4. Supporting process improvement and enhancement through business process analysis.
5. Supporting decisions during process execution, and control.

Despite the plethora of process modeling techniques that proliferate in the literature, some of the most recognized business process modeling techniques, in general, include:

Business Process Model and Notation (BPMN), Extended Business Modeling Language (xBML), ICAM Definition (IDEF0) and Unified Modeling Language (UML).

BPMN

Deriving from BPM, the Business Process Model and Notation (BPMN) is widely used in business processes. BPMN was established by the Business Process Management Initiative[5] (BPMI) in 2004 and is currently a set standard for business process modeling. This standard provides a direct link between the graphics of the notation and the underlying constructs of execution languages, particularly Business Process Execution Language (BPEL).

BPMN is a specialized flowchart technique for business processes (Havey 2005). The modeling elements of BPMN are categorized into flow objects, connecting objects, swimlanes and artifacts (see Figure 2.14). Given the wide range of elements pertaining to the flow and sequences, BPMN is said to be easy to use (White 2004; White and Miers 2008; Aldin and de Cesare 2009; Kreimeyer 2009). Despite its complexity, it is not necessary to know all of the specialized notation in order to create a complete and useful BPMN diagram (Aldin and de Cesare 2009). Hence its primary focus is an intuitive understanding of complex models (Kreimeyer 2009).

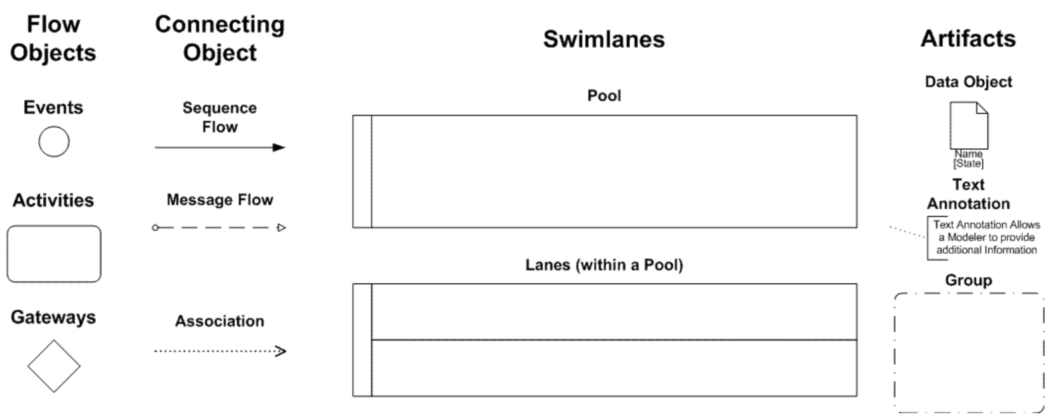


Figure 2.14 Core set of BPMN elements (Source: http://www.omg.org/bpmn/Samples/Elements/Core_BPMN_Elements.htm)

Aldin and de Cesare (2009) advocate BPMN is semantically richer than other modeling techniques. Indeed, specific descriptions of the different types of elements are available for multiple domains. In general, activities may be modeled as tasks or multiple instances of a task. Furthermore, BPMN allows sequence and message flows, as well as conditions to be modeled. Pools and lanes may be used to represent agents or applications. Text annotations can also be attached to the model to provide stakeholders with additional

[5] http://bmi.omg.org/

information. Gateways are used to control flows, represent decisions or even concurrent activities (White and Miers 2008; Kreimeyer 2009).

As BPMN was developed in order to facilitate the task of translating the real process to a computer program, it is tailored to model repetitive processes (which are the vast majority of the processes of an organization). It also focuses heavily on activities rather than on the roles performing the activities, hindering the task of modeling interactions, collaboration and concurrency between roles. On this, Ammann (2009) as well as Turetken (2007) concede BPMN lacks knowledge-related constructs and does not adequately consider the human role in business processes.

Despite being considered an established standard in business process modeling, as far as we are aware of, the use of BPMN in PDP is very limited. Our research found only Kalpic and Bernus (2002) who have approached PDP from a BPM perspective. The authors considered BPM not only as a tool for process engineering, but also as an approach enabling knowledge management. We will look at the most relevant modeling techniques for PD in the remaining section.

2.2.2 The Uniqueness of Modeling the Product Development Process

Having determined that PD is a process (see Section 2.1.1), and recognizing the importance of modeling processes, it is important to understand the uniqueness, which underpins PDP, the focus of our study.

Browning et al. (2006) acknowledge the literature on process modeling is extensive, admitting that only a relatively small subset of this literature addresses PDP specifically. Indeed, most literature concentrates on business and manufacturing processes, which, as these authors contend, differ significantly from PDP.

Different authors focus on different distinct characteristics of the PDP. Huang and Gu (2006a), for example, argue PDP is a dynamic, uncertain system with feedback, closely resembling a “network (process net), where processes are highly interconnected, including feedback loops and interactions at various hierarchical levels”. The same authors, in another publication (Huang and Gu 2006b) emphasize the need to integrate product models and process models, as their focus is twofold: the product and the intrinsic managerial activities within the dynamic realm of the PDP. The authors claim:

> “The product development process modeling consists of two interrelated aspects: product model and process model. The coupling of these two

> aspects is very important to integrated product and process development, which not only avails to manage and control the whole process efficiently, but also avails to organize a multifunctional team to develop product concurrently and cooperatively".

On this duality, Whitney (1990) had already posited that *design* is both a "technical process to be accomplished" and an "organization process to be managed". Indeed, the author acknowledged not only the relevance of the product and the sequential representation of the tasks, but also that of the people involved and how they interact. Identically, Eppinger et al. (1994) contended that to be helpful, a PDP model must include not only the sequence of the tasks but also the many technical and informational relationships among the tasks.

Browning, Fricke, and Negele (2006), within a more holistic approach to modeling the PDP, enumerate a series of distinctive features in PDP. The authors' perspective concurs with that of Vajna (2005), mentioned in Section 2.1.1. These features can be summarized as follows:

1. PD seeks to do something new, once.
2. The outputs of many PD activities cannot be verified until much later.
3. PD is multidisciplinary, with many interdependencies among activities.
4. PD processes tend to be parallel (see Section 2.1.3).
5. Unclear dependencies as a number of assumptions and interactions tend to be undocumented, and there is greater ambiguity in the required actions and interactions. PD processes need to be more flexible and agile as creativity and innovation are not linear.

In sum, the authors characterize PD as *creative and innovative; dynamic, interdisciplinary, interrelated, parallel and iterative; and uncertain, ambiguous and risky*. These characteristics are, in fact, corroborated by other prominent authors in PD such as Fricke et al. (1998) and have important implications on the modeling approach, as most (business) process modeling techniques are not able to incorporate these (Park and Cutkosky 1999; Browning, Fricke, and Negele 2006; Jun and Suh 2008). Thus, PD processes are more difficult to model when compared to others such as manufacturing and business process.

Having carried out extensive work on the issue of modeling the PDP (Browning, Fricke, and Negele 2006; Browning and Ramasesh 2007; Browning 2009; Lévárdy and Browning 2009;

Browning 2010), Browning and colleagues summarize the fundamental propositions that form the basis of PD process modeling theory (Browning, Fricke, and Negele 2006):

- "The process of invention/innovation cannot be fully mechanized.
- Nevertheless, the PD process has some repeatable structure.
- Project management is facilitated by a structured approach.
- Processes can be regarded and treated as systems that should be engineered purposefully and intelligently.
- In many aspects, complex process behaviors can be better understood by examining their relatively simpler, constituent parts (actions) and those parts' endogenous and exogenous relationships (interactions). We refer to this as the decomposition paradigm in process modeling.
- There is always a gap between the real system and a model of it.
- Process models are built for a purpose".

In an attempt to overcome the aforementioned difficulties, which derive from the uniqueness of PD, various modeling techniques specifically for PDP have been proposed, while other implemented techniques derive from BPM. Smith and Morrow (1999) reviewed some of the PD process modeling methodologies and evaluated them. The authors acknowledged the importance rigorous, tractable, and applicable modeling techniques, admitting that despite some existing rigor, if the techniques are not easy to use, their application will be non-existent. Finally, the authors concede PDP modeling is in an earlier stage of development when compared to, for example, management.

2.2.3 Analytical Approaches and Focuses

Each modeling approach provides a different perspective of the process structure. Thus, there are modeling approaches that are best suited depending on the intention and focus. The variety inherent to the different needs and focuses is perhaps the reason for the plethora of PD modeling approaches in the literature. Recker (2006) stated a PhD student's count of the process modeling techniques in use stopped at 3,000. The question then remains, how to best approach PDP modeling.

Given that purpose drives the question of a suitable modeling technique (Recker 2006), Browning and Ramasesh (2007) provide a taxonomy of purposes for process modeling specifically in PD, reproduced in Table 2.7.

Table 2.7 Four categories of purposes for PD process modeling (Browning and Ramasesh 2007)

Category	Purpose
1. PD project visualization	a. Actions, interactions, and commitments b. Customized "views"
2. PD project planning	a. Making commitments b. Choosing activities c. Structuring the process d. Estimating, optimizing, and improving key variables (time, cost, etc.) e. Allocating resources
3. PD project execution and control	a. Monitoring commitments b. Assessing progress c. Re-directing d. Re-planning
4. PD project development	a. Continuous improvement b. Organizational learning and knowledge management c. Training d. Compliance

Coming from a different approach and in order to propose a modeling framework for PDP considering its characteristics, Jun and Suh (2008) compare the most prominent modeling techniques referred in the literature and systematize them into two broad groups, graph-based techniques and matrix-based techniques. Graph-based modeling approaches include *Petri nets* and its variants, *IDEF* and its variants, *GERT*, among others. Within the matrix-based modeling approach, the leading technique is the task-based *Design Structure Matrix*, also known as *DSM*.

The IPO paradigm

Underlying most modeling approaches, both in business, management and in development processes, is the simple input-process-output (IPO) advocated by Hammer and Champy (1993) (see Section 2.1.1). The logic is that in modeling, engineers, for example, describe what they are doing (P) by describing relevant tasks and activities; what they need to accomplish this (I), such as documents and data files; and what they produce (O). The output of a process may be then used as input by other processes. This output-input relation embodies process interaction. Within this paradigm, the structure of the development process is in conflict with the structure of the information flow (Gartz 1997).

Most modeling techniques have in their genesis this IPO paradigm (see, for example, Fricke et al. 2000; Browning 2002; Browning and Ramasesh 2007, among others).

We will now provide an overview of the most prominent modeling techniques in PD. Drawing on Jun and Suh's (2008) work, we group the techniques into graph-based modeling approaches, where we will focus on *IDEF* and *Petri nets*; and within the matrix-based modeling approaches, we will focus on *DSM* and its variants.

Graph-based modeling approaches

IDEF

The IDEF (stands for *Integrated Definition*) methodology comprises a group of modeling methods. It was originally created by the United States Air Force and is currently being developed by Knowledge Based Systems[6]. It was originally developed for the manufacturing environment, but since then, the more than fourteen methods (from IDEF0 to IDEF14) have been adapted for wider use. These methods are descendants of data flow diagrams with a functional, structured approach (Melão and Pidd 2001). Melão and Pidd claim IDEF0's modeling constructs: *inputs*, *activities*, *outputs*, *mechanisms* and *controls* (see Figure 2.15) reveal its mechanistic perspective.

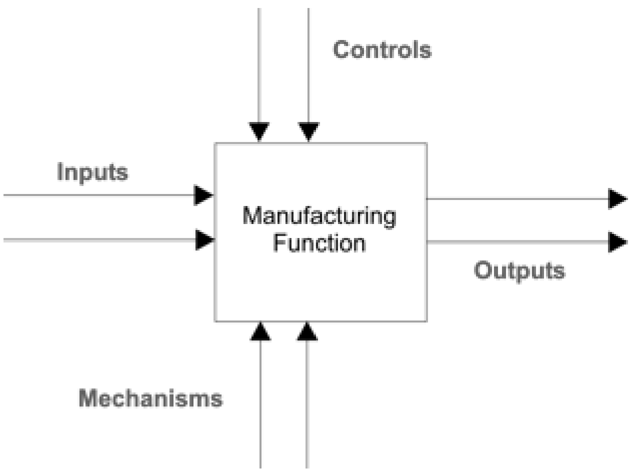


Figure 2.15 IDEF0 box and arrow graphics (Source: http://www.idef.com)

A closer look at IDEF3 (*Integrated Definition for Process Description Capture Method*) reveals that it complements IDEF0, as the former notation, which describes process flows, is capable of modeling the relationships between actions as well as the specific states a

[6] see Knowledge Based Systems, Inc. homepage at: http://www.idef.com.

process undergoes (Kreimeyer 2009), thus capturing behavioral aspects (Knowledge Based Systems 2010).

Although IDEF enables the view of organizational knowledge from multiple perspectives, the focus on roles/agents is weak and the prominence is on the sequential representation of activities (Turetken 2007; Knowledge Based Systems 2010).

Recent studies using IDEF in PD advocate this technique alone is not adequate for complex processes (Chin et al. 2006) and should be conjugated with other techniques, such as colored Petri nets (see Petri nets, below). The authors state IDEF can give a clear description about input and output information, resources and constraints pertaining to the development process. They defend the approach can help streamline the overall process but only to a certain degree as IDEF0 is “static and qualitative and lacks mathematical rigor”.

Other authors, such as, Kusiak and Belhe (1992), Zhang, Chen and Xiong (1999), and Fairlie-Clarke and Muller (2003) have also advocated the use of IDEF or IDEF-based methods (input-output) to model the PD process, as a rigorous approach capable of identifying a complete set of activities for any PD process.

Petri Nets

Carl Adam Petri invented *Petri nets* in 1962 as part of his Doctoral Thesis. Since then, Petri nets have been used to model and analyze processes, including protocols, hardware, and embedded systems to flexible manufacturing systems, user interaction, and business processes (van der Aalst 1998). This approach combines “visual representation using standard notation with an underlying mathematical representation” (Vergidis, Tiwari, and Majeed 2008), which makes this modeling approach unique (Peterson 1981).

Petri nets use graphical and mathematical notations to represent a process. Activity flow is represented with place nodes and transition nodes, whereas arcs connect places with transitions (see Figure 2.16).

Concepts such as *service*, *goal* and *role* are not explicitly supported. Aldin and Cesare (2009) claim Petri Nets have limited explicit expressivity given the reduced number of modeling elements. However, the authors believe it is an appropriate method for modeling systems with concurrency.

A numbers of extensions have been introduced to the classical Petri nets in terms of color (for literature on colored Petri nets see Jensen 1996), time (see for example Berthomieu and Diaz 1991) and hierarchy to solve some of the detected problems (van der Aalst 1998). Nonetheless, Aldin and de Cesare (2009) considered this modeling approach to be a non user-oriented technique, which is difficult to use without experience. Curiously, on this point, van der Aalst (1999) states Petri nets are “intuitive and easy to learn”.

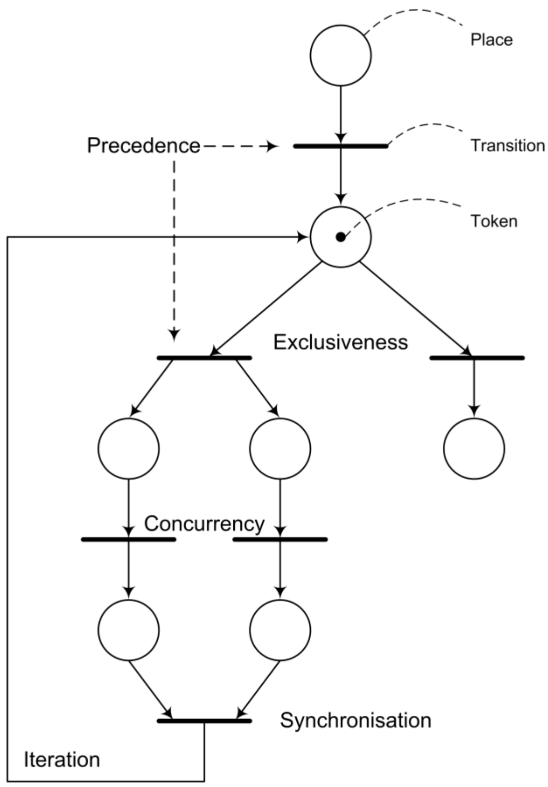


Figure 2.16 Petri nets graphical notation

The use of Petri nets method has had some discussion in PD literature. The review of the literature by Chin et al. (2006), among others, allow us a glimpse of the most recent work in the area. Liu et al. (2002) applied workflow colored Petri nets to the PD workflow. Given the time factor in the PDP, Belhe and Kusiak (1993), Lin and Qu (2004), and Chin et al. (2006) mixed the Petri net extensions, introducing timed colored Petri nets in PDP modeling in order to analyze workflow time performance. Furthermore, authors such as Zu and Huang (2004) and Ha and Suh (2008) have also proposed the use of hierarchical timed colored Petri nets in PDP modeling and performance analysis of collaborative design.

Matrix-based modeling approaches

DSM

One of the most important matrix-based modeling approaches in PDP is that based on the Design Structure Matrix (DSM). This modeling approach was originally developed in order to analyze parametric descriptions of designs by Steward in 1981. Since then, a whole community has developed around this (see, among others Kusiak and Wang 1993; Eppinger et al. 1994; Smith and Eppinger 1997; Browning 2001; Cho and Eppinger 2001; Yassine and Braha 2003; Batallas and Yassine 2006; Huang and Gu 2006a). Recently Lindemann, Maurer, and Braun (2009) presented a compendium of a multitude of matrix-based approaches for managing complex data in product design.

Underlying the basis of the DSM is the assumption that a design task is a predicable information-processing task with identifiable inputs and outputs and, as such, can be modeled using and creating information (Smith and Morrow 1999). As Smith and Morrow explain, the output information from one task then becomes the input information for another task. The relationships amongst the inputs and outputs may comprise cycles, which indicate the need for iteration. The DSM represents these relationships and dependencies (see Figure 2.17). DSM thus enables the modeling and analysis of complex processes, where entities and relations are known. However, drawing on Lewis and Cangshan (1997), Smith and Morrow concede DSM is relatively difficult to understand, especially in the beginning. Furthermore, the modeling approach, as originally proposed, is lacking in terms of sequencing and scheduling design tasks within iterative groups. Given the identified shortcomings, newer variations have since been proposed.

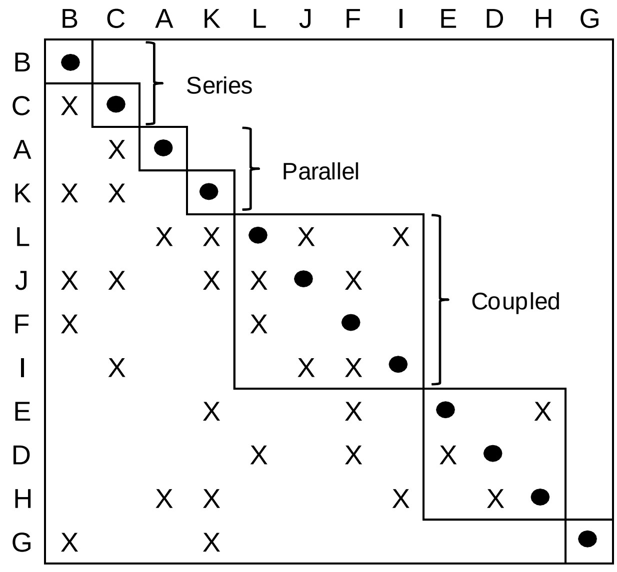


Figure 2.17 Design Structure Matrix (Smith and Morrow 1999)

So as to propose a modeling framework for PD, Jun and Suh (2008) summarized the evolution of DSM. Since its development, Smith and Eppinger (1998) for example, proposed a variation of DSM, which draws on the strength of the dependencies and adds the execution time of each activity with diagonal elements. Kusiak et al. (1995) presented a matrix capable of representing the precedence relation between activities. In turn, Cho and Eppinger (2001) proposed a PDP modeling and analysis technique with the DSM and advanced simulation, considering the iterations that occur among sequential, parallel, and overlapped tasks. Huang and Gu (2006a), by drawing on PD as a dynamic process, developed a DSM in order to capture the interaction and feedback of design information.

More recently, Danilovic and Browning (2007) proposed the evolution of DSM to domain mapping matrices, so as to allow the inclusion of more than one domain. Maurer (2007) took this approach further in order to model processes comprising multiple domains, each with multiple elements, connected by different types of relationships and dependencies, using a Multiple Domain Matrix (MDM). The underlying basis in all abovementioned extensions is the DSM, with just more details and different foci.

2.2.4 Limitations of the Modeling Techniques

From our analysis above, we can state that, except for the DSM, business process modeling techniques focus the business processes in general, which significantly differs from the PDP. Consequently, despite the attempts to incorporate the various BPM modeling techniques in PDP, these fail to capture the overall essence of PD.

Graph-base models are focused on the static control flow of the process, and thus fail to capture feedback loops and dynamic information exchange. They can, however, serve as basis for analyzing structural characteristics.

Matrix-based approach DSM, on the other hand, has been developed specifically within the realm of PD. Although they are able to provide “simple and powerful manipulations of the PD process management” (Jun and Suh 2008), they too fail to capture various PD specific characteristics. Furthermore, they are difficult to comprehend, restraining understandability and usability, especially at the beginning (Browning 2001; Jarratt, Eckert, and Clarkson 2004).

Although DSM is suitable to identify the entities and relations from any process, in practice, however, these types of models are often not as definite as they seem (Kreimeyer 2009), as modeling a PDP is, in essence a consolidation process of the different perspectives on an actual “as is” project. Additionally, most possess an activity-centric view, emphasizing vertical, hierarchical relationships, while neglecting the various horizontal relationships, drivers of the deliverable flows that induce to the emergent behaviors of the overall process (Browning and Ramasesh 2007). DSM modeling approaches are not able to represent interactions across functional boundaries. Difficulties are encountered when attempting to represent relationships with three or more elements, or when dynamic relationships emerge (Crawley and Colson 2007). Finally, it is difficult to make a DSM at the conceptual design stage or for a new product that has never been designed before (Tang, Zhang, and Dai 2009).

Indeed, the previous modeling approaches seem to fail to capture the overall uniqueness of the PDP. As Jun and Suh (2008) claim, modeling techniques have limitations in capturing PDP's iterative, evolutionary, cooperative and uncertain characteristics.

Given the limitations of the different modeling methods expressed in the literature, there is a clear demand for a modeling method that can represent typical PD characteristics holistically. This instigated our curiosity and our search that led us to the Riva Method, described below.

2.2.5 A Different Approach to Process Modeling: the Riva Method

Given the specificities of PDP, and the shift from sequential, activity-focus process to people, dynamism and interactivity preached by the most recent methodological approaches to PD such as CE and LPD, perhaps a radical change is also needed in business process modeling.

A shift in paradigm: from IPO models to a Role-modeling Approach

The IPO process modeling paradigm, as mentioned above, focuses on activities and the flow of information and control across these. As we've seen, one of the problems with traditional IPO-based process models is they do not seem to capture interaction between human actors very well. Indeed, although these types of models seem to be compatible with and useful for procedure-based, production-oriented processes, they are not particularly adequate for less structured business processes such is the case of product development (Center and Henry 1993; Carlsen 1997). Furthermore, in processes primarily viewed as the transformation of input into output, stakeholders and their communications tend to be weakly represented (Ilgen et al. 2005). Therefore, to better represent business processes, especially development processes, it is crucial to include a richer description of the group dynamics involved, as well as the possible or intended human communication and interaction (Carlsen 1997).

Although IPO paradigm predominates in BPM, there are other modeling paradigms. Carlsen (1996) identified five main classes of process modeling languages, namely Input-Process-Output models (see above for a description); Conversation-based approaches; Role-modeling approaches; Systems thinking and system dynamics; Constraints–based representations.

We will focus on role-modeling paradigm, more specifically RAD - Role Activity Diagrams (Ould 1995, 2005) since we intend to surpass the mechanistic thinking of activity-oriented approaches and refocus on the responsibilities involved in PDP.

The Riva Method

Central to understanding the Riva Method is the notion that a business process is about people (see Section 2.1.1). It is about how people do business, how they think they do business, how they are supposed to do it, how they might improve it, and so on (Ould 2005). The author states a process:

- Contains purposeful activity;
- Is carried out collaboratively by a group;
- Often crosses functional boundaries, and;
- Is invariably driven by outside agents or customers.

Ould (2005) argues: “It’s what people do, not what they do it to, that counts. A process is mainly about doing, deciding and cooperating, not data or things”. In Ould’s view, the social context perspective of an organization prevails.

In order to incorporate these notions, and in a clear attempt to distance himself from the IPO paradigm, Ould (1995) developed the *Riva Method*, an extension of the formerly known STRIM (Systematic Technique for Role and Interaction Modeling), a modeling approach that explicitly integrates the process, organization and goal elements.

Riva is based on the following basic and central concepts:

- “A *process* is a coherent set of actions carried out by a collaborating set of roles to achieve a goal.
- A *role* is a responsibility within a process.
- An *actor* carries out a role.
- A role carries out *actions* following business rules.
- A role has *props* which it uses to carry out its responsibility.

- Roles have *interactions* in order to collaborate.
- A process has *goals* and *outcomes*” [emphasis in original] (Ould 2005).

Riva uses two languages to represent processes:

- Process Architecture Diagrams (PAD) are used to describe the arrangement of the organizational activity into individual processes; PADs may represent several or all of the business processes within an organization, and how these are interrelated.
- Role Activity Diagrams (RAD) are used to describe an individual process.

> “A RAD shows the roles that play a part in the process, and their component actions and interactions, together with external events and the logic that determines which actions are carried out when. So, it shows the activity of roles in the process and how they collaborate” (Ould 2005).

Given our interest in modeling the PDP, we will address RADs specifically as these allow business process to be diagrammatically modeled through the representation of roles, goals, activities, interactions and business rules (Melão and Pidd 2001). Furthermore, this technique is considered by some to be the most complete as it is able to represent the most relevant features of a process, namely goals, roles and decisions (Miers 1994).

As mentioned above, the main concept in Riva is the *role*. A role is an area of responsibility. The concept may refer to concrete things such as organizational posts, functional units and job titles, as well as abstractions, such as Customers, for example. Everything that happens (whether activities or decisions) in a process happens in a role. An activity carried out by a role on its own is an action. Any collaborative act involving two or more roles is an interaction. Separate threads of activity within the same role represent concurrent activity. RADs illustrate the roles and their threads of activities, decisions and interactions; as well as triggers and goals or outcomes – also identified as intended *states* (Ould 1997). Figure 2.18 summarizes the notation for RADs.

The gray, labeled box indicates the activities carried out by a role. On the top of the box, in one or more of the roles, the arrow describes the event that triggers the process. The RAD can then be read by following the vertical lines that derive from that event. A vertical line is a state the role can be in. A circle in the vertical line describes a state. A circle at the end of the thread indicates a process goal. The darker-shaded box corresponds to an activity carried out by a role. A question depicts decisions, followed by alternative paths, each led by an inverted triangle. Whenever a role initiates a number of concurrent paths, the threads derive from a connected set of triangles. Role collaboration (such as information exchange) is depicted with a horizontal line, which connects two or more white boxes, corresponding to interacting roles. An interaction synchronizes the states of all the participant roles.

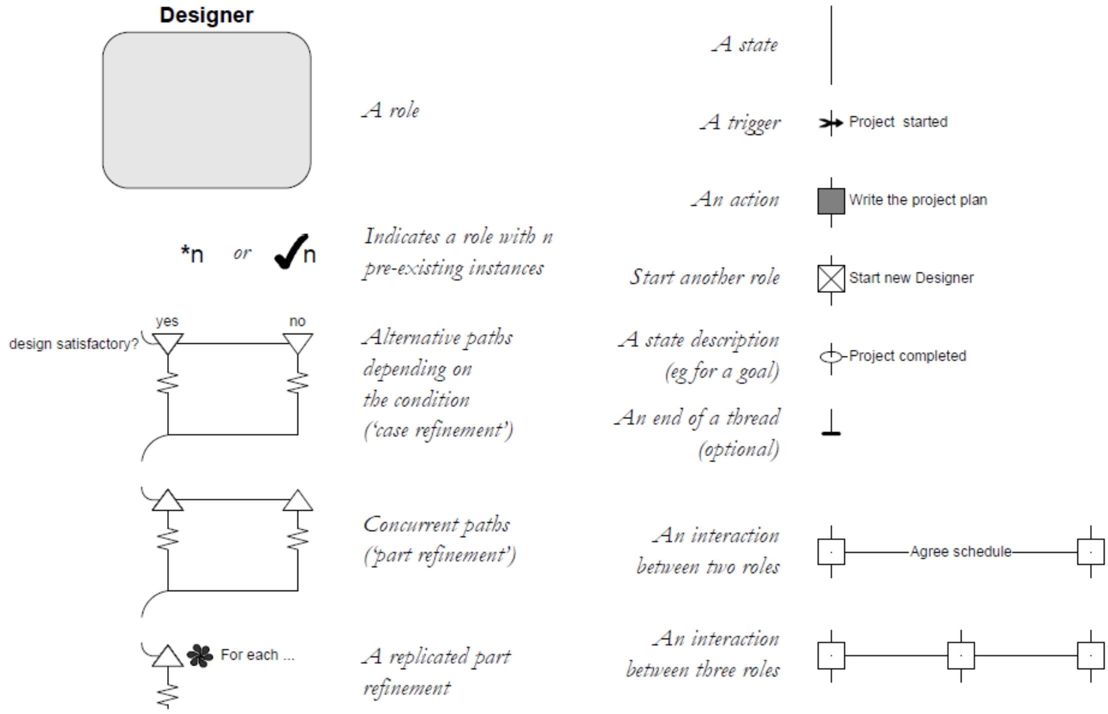


Figure 2.18 The RAD notation (Ould 2005)

To recapitulate we can say that the process seeks to achieve goals; activities are designed to achieve these goals; in turn, activities are divided among the different roles; these activities need people within the groups to interact collaboratively in order to achieve the desired goals or outcomes. Underlying Riva is the clear notion of interconnected networks of processes, rather than a hierarchy.

In terms of graphical representation, processes are not sequentially broken down into smaller sub-processes, but are rather represented as a whole. Current studies reveal (see Fady and El Aziz 2012 for example) RAD notation is, as a result, useful in showing how different activities are taking place simultaneously. By following each thread, it is possible to depict the sequence of activities within the same thread. Different threads indicate they are concurrent. As the RAD represents the process as a whole, the different threads show how the project is managed at different stages by different roles throughout the entire process.

Some authors (Turetken 2007), however, claim this may be a disadvantage for larger and more complex processes, while others (Aldin and de Cesare 2009; who draw on Cordes 2008) claim that its simplicity and ease of understanding make this method especially useful for large systems with many participants.

As a BPM method, Ould posits, Riva is “designed to provide the process designer with a rich set of real-world analogues through the concepts it supports and through its notation”. The author emphasizes the notions of role, activity, decision, thread and interaction, as these undeniably reflect concrete experiences. Thus, Riva intends to provide the process designer with a “simple heuristic approach” (Ould 1997).

Recent work using Riva Method includes El Aziz and Fady (2012) work on modeling the ATM business process architecture in Egypt through the use of PADs; Green, Beeson, and Kamm (2013) compare the process architecture of two higher education institutions by applying Riva and Fady and El Aziz (2012) who model a single commercial process using RAD.

Based on their experience these authors endorse the Riva Method stating:

> “Riva can identify a dynamic rather than a static view of the organizational business processes and their interactions with the roles involved in each process. Riva method provides a clear business process model for the entire organization with suggested improvements for the flow of work, without which improvement in the organizations were almost impossible” (Fady and El Aziz 2012).

Although relevant, these examples are not in the area of PD. In sum, it is feasible for us to say that given its inherent *creative and innovative; dynamic, interdisciplinary, interrelated, parallel and iterative; and uncertain, ambiguous and risky* nature, which derives not only, but also from the human involvement in the process, PD is, indeed unique and thus difficult to model. Nonetheless, given the shift in focus, can the Riva Method, more specifically the RAD notation, be used to effectively model the PDP?

2.3 Materials and Technology Selection

As previously stated, in order to face the changing demands of today’s market, organizations must optimize the PDP and the inherent operations to avoid becoming obsolete in comparison to competitors. From a PDP perspective, this has implications on decision-making throughout the entire process.

Indeed, innovation (whether in terms of materials or technologies) and its embrace depend on their benefits and require changes in thinking and behavior, both internally and externally. Therefore, highly innovative products have a high degree of uncertainty and risk (Trott 2012). Considering that most organizations are risk adverse and change resistant, one may expect decisions regarding material and technology to be less than optimal.

This section explores the material and technology adoption decision process in order to obtain a clearer understanding of the interconnect net of decisions and some of the existing selection strategies that influence the search for value-added alternatives, while disregarding other, less seemingly profitable solutions. Our focus is thus on new technology adoption, namely technology that is unfamiliar to the various intervenients in the PDP as opposed to established and validated technology, familiar to the company or to at least one of the intervenients.

2.3.1 Materials and Technology Selection in Product Development

In order to contextualize the importance of material and technology selection and adoption in PD, it is necessary to first understand that engineering design comprehends a “set of decision-making processes and activities used to determine the *form* of an object given the *functions* desired by the customer” [our emphasis] (Eggert 2005). The function of a product is what it is expected to do. On the contrary, form[7] is what it looks like, the materials that constitute it and how it is made. Form and function are interrelated. A product’s form, and thus material, depends on its function. However, the form will also influence a product’s function. It is amidst these interdependencies that we must view the selection methods and procedures (Dieter 1997; Ashby 2005; Dieter and Schmidt 2009). As Ashby states, “the interactions are two-way: specification of shape restricts the choice of material and process; but equally the specification of process limits the materials you can use and the shapes they can take”. These interactions are represented in Figure 2.19.

The PDP, as explained in Section 2.1.2, has many varying forms, as it is company specific. Nonetheless, all processes encompass three basic stages (put forth by Pahl and Beitz in the 1970’s). Generically we may consider the first stage as the initial approach to the project. Thus, we can state it incorporates the concept of the product, market research to determine current and future customer demands, and the review and selection of all the design and engineering alternatives (coined as Concept Design). It is therefore at this stage that materials selection *usually* occurs and costs are estimated. Stage two pursues the

[7] Also referred to in the literature as shape or geometry.

refinement of the selected concept and inherent processes (Embodiment Design). Stage three (or Detail Design) incorporates detailed definition of the product, which will then be manufactured.

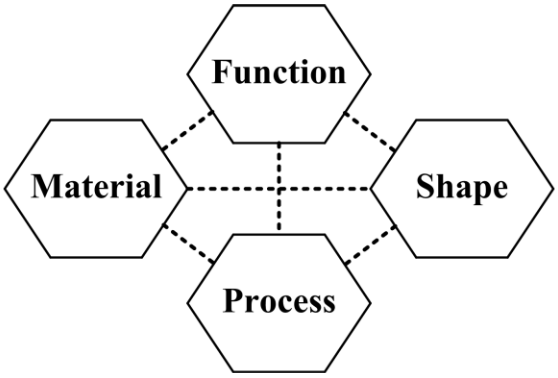


Figure 2.19 The central problem of materials selection: the interaction between function, material, shape and process (Ashby 2005)

It is during the early stages that key product specifications are defined, such as form, features and performance. Downstream detailed design and prototyping activities are based on these specifications. As changes have costly repercussions in downstream activities, it is often recommended that product specifications be determined and set early in the development process (Cooper 2001). However, PDP is dynamic and uncertain and cannot be merely defined by the stages stated above. Nonetheless, this clear-cut approach allows us to understand and situate the complex decision-making process involving the choice of materials and technologies (also referred to as processes[8]), given that this selection heavily influences the product's success factors.

Ashby et al. (2004) advocate materials and processes information is necessary not just during the early stages of the PDP, but at every stage. Approximate data for material and processes is needed at the beginning of each project while more precise and detailed data for one or more materials and processes towards the later stages of the PDP. Given the iterative nature of the PDP, corrections, modifications and re-specifications might imply the repetition of the selection process downstream.

Furthermore, the authors also clarify that the type of data needed for effective materials and processes selection assumes various forms, which range from structured data to unstructured data.

By structured, Ashby and his colleagues include specific, numeric attributes for standard properties (such as density and thermal conductivity), and less specific, non-numeric

[8] See Ashby (2005), for example.

attributes (such as resistance to corrosion). This information can be easily manipulated and is currently widespread, in the form of Materials Handbooks, for example.

Unstructured data, albeit equally important, is very often neglected and thus excluded from these databases. This type of data includes the accumulated experience of use of the material (such as analyses of failures caused by incorrect use) and infrastructure needed to support its use (such as optimization tools).

Materials and processes are interconnected in such a way that Charles, Crane and Furness (1997) include technology selection as an integral part of material selection. They state the following: "the selection of materials is about an awareness and understanding of: (1) what materials are available; (2) what processes for shaping these materials are available and how this affects their properties; (3) the cost of the materials in relation to each other, their processing and their properties". Nonetheless, decision makers must consider both in their entirety to refrain from adopting a convenient "but we've always done it this way" approach.

Mindful of this fact, but in an attempt to be clear, the subsections that follow discuss material selection and technology selection separately.

2.3.2 Materials Selection

Materials selection "involves seeking the best match between the property-profiles of the materials and that required by the design" (Ashby 2005). Materials are at the heart of every decision throughout the PDP and should be an integral part of the design process (Charles, Crane, and Furness 1997). As stated above, the features of the various materials determine the selection criteria and vice versa. In practice, as materials are by and large considered as the attributes of a product, the selection process occurs only after the physical structure has been established. In other words, materials are often selected after the conceptual design stage and consequently, designers must find materials with specific properties to meet the established requirements (Deng and Edwards 2007). However, the closer a product is to production, the greater the cost of making any change (Charles, Crane, and Furness 1997).

While in the past materials selection was based primarily on raw material availability and technological skills of the intervenients in the PDP, today that is not the case as new materials are emerging, which implies changes to the pattern of materials usage (Charles, Crane, and Furness 1997), and as current environmental issues demand further company acknowledgements (Costa and Fernandes 2012). While there are many books, which focus on finding a match between material properties and the technical requirements of a design, as well as well-developed methods, such as material properties charts (Ashby 2005) and decision-making matrices (Pugh 1991; Pahl et al. 2007), often supported by decision support tools (software), these “databases” are not exhaustive and tend to be based on the more technical and thus structured aspects of design (Ashby 2005).

We believe the answer to material and technology selection does not lie merely in these databases, but rather in the implementation of a systematic approach to selection through well-defined strategies.

Several authors have addressed the issue of selection strategies making it widespread and diversified, an example is Ljungberg and Edwards’s approach (2003), which proposes an Integrated Product Materials Selection Model (IPMS). This model analyses both physical and metaphysical properties of the products, incorporating factors such as fashion, market trends, cultural aspects, aesthetics and recycling, as well as the target group. Ljungberg and Edwards’ material selection approach clearly derives from a Marketing perspective.

Another example is the Life Cycle Engineering (LCE) methodology. Ribeiro et al. (2008) draw on Jeswiet (2003) who defines LCE as “the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the environment and conserving resources, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimizing the product life cycle and minimizing pollution and waste”. LCE is an integrated methodology that seeks to foster informed decisions within a life cycle perspective, which incorporates three performance dimensions: functional or technical; economic cost; and environmental dimension (Peças et al. 2013).

Given that, in order to implement the LCE methodology a profound engineering knowledge encompassing all the material and the related technological options is needed, Peças et al. (2013) proposed a modified approach to this methodology to support material selection decision making, denominated Materials Selection Engine (MSE).

The MSE funnels potential candidates based on a structured step-by-step, sequential analysis, namely:

- 1st step: Initial materials screening;
- 2nd step: Mapping engineering requirements with product specifications and material properties;
- 3rd step: Product “design” for each material;

- 4th step: Building a process-based cost modeling;
- 5th step: Life cycle analysis models;
- 6th step: Integrated comparison of economic and environmental life cycle performance.

This method, besides aiding in selecting the most appropriate material based on requirements, considers total life cycle environmental impacts as well as costs, which are then mapped on a matrix. The visualization facilitates the design team's final decision by providing them with an integrated comparison of fitness-to-purpose materials throughout the product life cycle.

Most state-of-the-art literature on material and technology selection draws, directly or indirectly, on Ashby and his various publications although the shift in focus is notorious. Thus, Ashby's contribution to our thesis is also pivotal.

Dieter's overview of the materials selection process (1997), for example, draws on Ashby's work and that of Dixon and Poli (1995). Dieter summarizes Dixon and Poli's material selection strategy as a four-level approach, explained as follows:

- Level I: Decisions on whether the product (or component) should be made from metal, plastic, ceramic or composite based on critical properties.
- Level II: Decisions on whether metal parts will be produced by deformation or casting; and if plastics will be thermoplastic or thermosetting polymers.
- Level III: Narrow options to a category of materials: metals and plastics can be subdivided into specific categories, such as stainless steel (for metals) and polycarbonates (for plastics).
- Level IV: Selection of a specific material according to grade or specification.

Dixon and Poli's four-level approach is funnel like, in the sense that the selection process is progressively narrowed down to a specific solution. They suggest the use of a guided iterative strategy to evaluate materials and technologies throughout the design process, in the form of a formalized handbook, which draws on charts and tables. Dixon and Poli (1995), similarly to Ashby (2005), defend a higher number of possible candidates increases design and manufacturing flexibility; an idea referred to as *least commitment* (a concept also present in SBCE, see Section 2.1.3).

Towards a comprehensive approach of the implications and interconnections in material selection, Ashby (2005) states thinking about materials information is required at each stage of the design process although the nature of that information differs greatly in terms of precision and depth. Drawing on Pahl and Beitz's PDP model (see Section 2.1.2), the author clarifies:

- In the first stage (Concept design) all options are open, thus there is a need for breadth and ease of access. At this time the designer should consider all the possibilities without restrains, both technical and aesthetic. Although the designer's choice of concept will have repercussions on the overall configuration of the design, most decisions regarding material and form are left unanswered.
- In the second stage (Embodiment design) a higher level of precision and detail is needed. It is at this stage that each potential concept is developed. Operations are analyzed and alternative choices in material and process are explored.
- In the third stage (Detail design) a higher level of precision and detail is needed but for one or very few materials.

The final step is a prototype to ensure design meets technical and aesthetic expectations. On this, Verganti (1998) posits early prototyping encourages uncertain information to be gathered in the early phases, without entering into detail design. This process for material selection does not end at this point, as failures in production or service should be analyzed and relevant information needs to be gathered and documented for future situations.

Similarly to Dixon and Poli, Ashby proposes a refinement throughout the PD process, without implying that a decision has to be made at a specific stage. Figure 2.20 depicts Ashby's thinking process about materials information.

Within this thinking framework, Ashby et al. (2004) posit three main selection strategies. For the purpose of our study, we will explain these three strategies and then will focus on the free searching based on quantitative analysis method (referred to as selection by analysis in Ashby and Johnson 2002), as it involves a systematic procedure to material selection. Ashby bases his well-known book *Materials Selection in Mechanical Design* (2005) on this selection method.

Free searching, based on quantitative analysis: This selection method is based on a quantitative analysis strategy that objectively and efficiently provides the requested information, if the inputs were precise, detailed and in a form that can be analyzed by standard engineering methods. In sum, this method requires the selection of a material from a database based on the expressed function, constraints and objectives. Each combination of these three aspects leads to performance metric(s) containing a group of material properties or material index. These can then be compared.

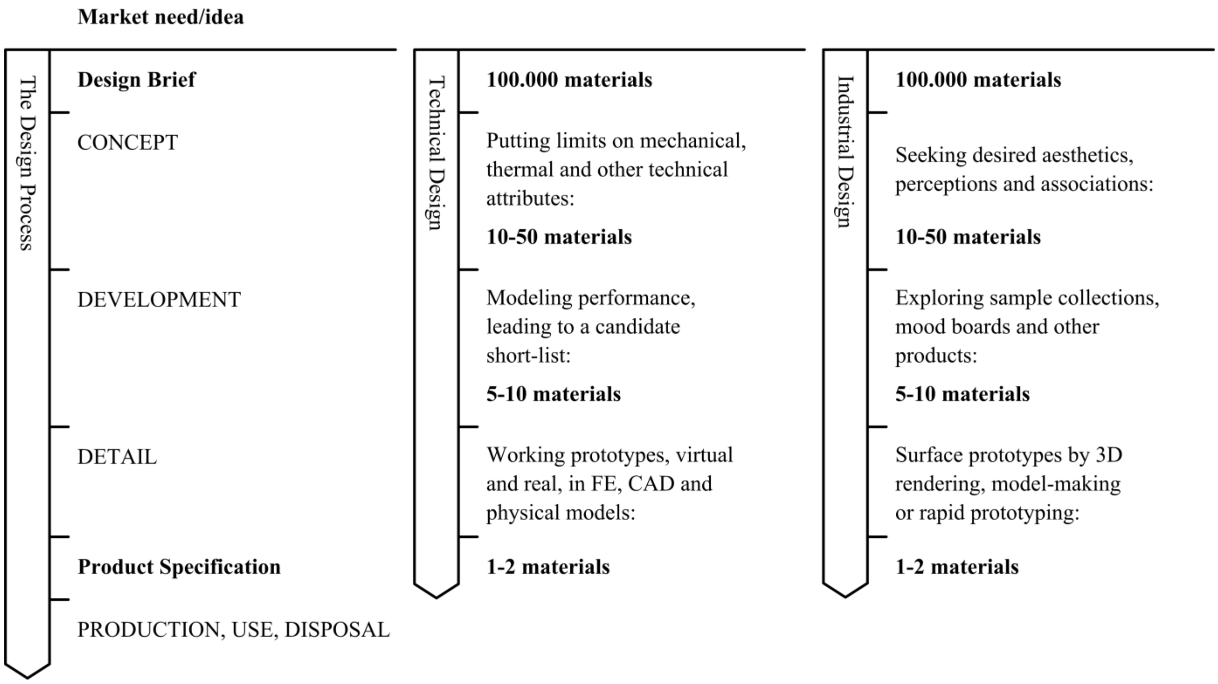


Figure 2.20 Materials in the design process (Ashby and Johnson 2002)

Questionnaire strategy, based on expertise capture: Through the use of questionnaires, the user is able to be guided through a set of decisions previously constructed by documenting experts' answers to a comprehensive set of specific questions and the subsequent questions until an unqualified answer is reached. This poses several problems, namely in terms of construction of the questionnaires as this implies time and patience. Furthermore, this selection strategy does not innovate, as it is not able to consider something the expert does not know, which might be the case of a new material or process.

Inductive reasoning and analogy (involving past cases): This strategy has its roots on past cases, previous experiences, which need to be analyzed and documented. Requirements are expressed as the features of a problem. How this problem was solved is exploited, and knowledge is compared and tested for its ability to suit the requirements. In practice this means databases are searched for cases with similar features as the ones at hand. The analysis of the information retrieved is then adapted or combined in the new product. The main problem identified in this strategy is on how to structure and index the unstructured knowledge obtained from the various cases.

Ashby enumerates various problems with the last two strategies and seems to be more in favor of the *Free searching, based on quantitative analysis* method, stating that it is currently well developed and has been successfully applied. The author classifies it as fast, efficient, systematic and with potential for innovation. Aware of the advantages of this strategy, Ashby developed it further, and within this *Analysis* method, Ashby (2005) proposes a systematic procedure for materials selection which incorporates four main steps: translation, screening, ranking and supporting information (see Figure 2.21). Underlying this procedure is the basic principle that all materials should be considered as potential candidates for any application.

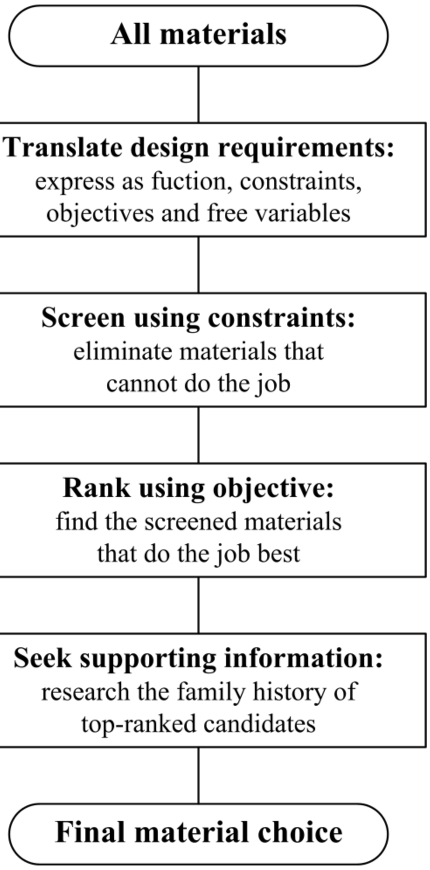


Figure 2.21 Four-step materials selection procedure: translation, screening, ranking, and supporting information (Ashby 2005)

The first step consists in translating, or examining the requirements in order to identify the constraints that these entail on the choice of material. This first step is a statement of product (or component) functions, constraints, objective and free variables allowed. After, and considering that all materials are candidates until proven otherwise, the screening process begins. This is where material choices are eliminated if the attributes cannot meet the constraints. Having limited the material choices, it is then necessary to rank the candidates by their ability to maximize performance, i.e. according to how well they can fulfill the objective. Finally, having arrived at a ranked short-list, it is then necessary to search for a detailed profile of each candidate. This information may be descriptive, graphical or even pictorial. The final choice may occur at the detail design stage.

Although it may seem like a very straightforward procedure, there are issues threatening the task, namely:

- difficulty in tracking all the candidate materials,
- difficulty in translating the requirements into material properties,
- the tendency to benchmark similar products or applications and “copy” the material in order to reduce risk, and
- the tendency to select the materials in early design stages to facilitate the remaining tasks.

This four-step procedure for material selection proposed by Ashby is carried out throughout the PD process, beginning at the concept stage and concluded at the detail design stage. However, as also highlighted by the author and discussed in Section 2.1.1, PDP is complex and iterative, thus the various stages are interconnected and are revisited throughout the process.

Identically, the material selection procedure may be triggered in any of the stages, depending on the material and the product component or subsystem in question. Thus, this procedure may be looked upon as a cyclical selection process to be applied and repeated until an optimal solution is achieved. Depending on the specific situation and the depth of the design team’s knowledge, the procedure may begin in the Concept stage, or Embodiment, and the cycle itself may stretch or be curtailed depending on the nature of the inputs.

Ashby and Johnson (2002) claim there are various creative solutions for material selection in product design and, in addition to the essential requirements (an information structure and a selection method, explained above), propose complementary methods, as follows:

- Selection by analysis (deductive reasoning): uses precise specified inputs and well-established modern design methods, through materials databases (this method was referred to as the *Free searching, based on quantitative analysis* in Ashby et al. 2004).
- Selection by synthesis (inductive reasoning): is based on documented past experiences, when searching for equivalent features, intentions, perceptions or aesthetics.

- Selection by similarity: draws on the attributes of existing materials to search for equivalent materials.
- Selection by inspiration: draws on other products and materials for inspiration to suggest solutions.

Although traditional analytical methods prevail, there are complementary methods in the sense that more than one method may be deployed in order to obtain an optimal solution. For example, we posit it is possible to employ *selection by synthesis*, *selection by similarity* and *selection by inspiration* within the screening step of the *selection by analysis* method. We cannot overlook the fact that these can be valuable sources of information and solutions and thus all help, not hinder, the material selection process, as combined they become an extremely powerful tool, more so than any one used individually (Ashby and Johnson 2002).

Finally, we stress all material selection methods should be based on the premise that all materials are possible candidates, for as Ashby (2005) acknowledges, failure to start with a “full menu of material in mind (…) may mean a missed opportunity”. This means that we cannot simply rely on the extensive decision support tools available, as these may not be completely exhaustive given the constant changes, evolutions and introduction of new materials in the marketplace.

Although the material selection process begins with product requirements, the final decisions will inevitably involve cost considerations, which, in many cases, will be the dominant criterion. In this regard, the most favorable solution may sometimes have to be discarded for the best available.

Charles, Crane and Furness (1997) cite (Pick 1968) who has said: “Material (and process) selection always involves the act of compromise - the selection of a combination of properties to meet the conflicting technical, commercial and economic considerations”. This perhaps justifies the “but we've always done it this way” argument for material selection.

2.3.3 Technology Selection

In regards to technology selection specifically, the term has different interpretations in different contexts. For example, the European Institute of Technology Management (EITM)[9] considers technology selection as a Technology Management sub-process:

[9] http://www-mmd.eng.cam.ac.uk/ctm/eitm/index.html

> "Technology management addresses the effective identification, selection, acquisition, development, exploitation and protection of technologies (product, process and infrastructural) needed to maintain a market position and business performance in accordance with the company's objectives".

Thus, technology management attends to the various processes needed to deliver products and services to the market, which pertain to all aspects of integrating technological issues into decision-making.

In the view of our thesis, our focus is on material selection and the production technologies, or processes, associated. Thus, this section of our literature survey will not approach the vast technology management realm; rather we will discuss the adoption of technology depending on and parallel to the material chosen, as these two decisions are "intrinsically interwoven" (Schey 1997).

Riddle and Williams (1987) define technology selection as "the process of determining which (new or old) methods, techniques, and tools satisfy criteria reflecting a particular target community's requirements". This selection process requires:

- the ability to *identify* a set of options to be considered;
- the ability to *evaluate* the options, either comparatively or in isolation; and
- the ability to *choose* from amongst the various options, based on the evaluations.

Although material selection will condition technology adoption and vice versa, it is a challenging process as technology alternatives are increasing and becoming evermore complex. The choice of the "right" technology is able to create significant competitive advantages as it fosters the development of competitive products, effective processes, or even completely new solutions (Torkkeli and Tuominen 2002). However, technology is often considered mainly in terms of the costs of the capital and labor involved (Bruun and Mefford 1996) for an estimated annual production volume (Ashby 2005; Eggert 2005). Process choice is thus greatly influenced by the total number of parts to be produced and by the rate of production (Schey 1997). Decisions are, consequently, usually made ad hoc, heavily based on company-established processes. In practice, this means technology selection is made in accordance with the existing manufacturing system, neglecting product requirements.

Studies advocate (Kaplinsky and Posthuma 1994; Krishnan and Bhattacharya 2002) most organizations, in practice, are resistant to change as they are risk averse and therefore are more reluctant to consider unproven technology. Indeed, the selection of the most appropriate technologies is amongst the most challenging decisions.

Langley and Truax (1994) contend it is difficult to delimit technological adoption decisions, as these implicate three interacting processes: a *strategic commitment process*, a *technology choice process* and a *financial justification process*. Furthermore, the authors defend technology adoption decisions are often contextual and issue-oriented. Langley and Truax draw on the literature and propose three classes of process models to understand technology adoption:

- Sequential models draw on the work of Mintzberg and Raisinghani (1976) and are based on the notion of technology adoption as a sequential decision process, comprised of a number of phases, where a group of activities is carried out. This approach has been heavily criticized for its simplicity and rigidness as it disregards other, more ambiguous interferences, such as social aspects.
- Political models (Dean 1987) focus on how top managers are convinced to adopt new technology, through persuasion, salesmanship and negotiation. In these models personal credibility and political support are more important than financial or strategic positions.
- Finally, serendipitous models draw on Mohr's (1987) view of the non-deterministic nature of innovation processes. Mohr identifies routines, which may contribute to new technology adoption, among others, we underline: after recruitment if new employees have the knowledge; by imitation of what others are doing; for market survival; after a search; to maintain company status.

Langley and Truax recognize the need to model the technology adoption process, as there is a lack of empirical research specifically in smaller firms.

Various authors, amongst them Phaal and Muller (2009), defend that technology selection should start by considering the various functions that the product performs (or might need to perform) and the qualities (e.g. performance and reliability) that have to be achieved. Company-established processes influence the early stages of product development (product concept and product specifications), limiting options by creating an assumption that a determined technology is the only feasible solution. The focus on functions and qualities underlines user requirements, and enables broader thinking as to the possible solutions and technologies.

Phaal and Muller (2009) defend this shift in focus is possible through technology roadmaps, as these can support a range of different business aims, including product planning. The main benefit is the communication that is associated with the process and a common framework for thinking (Farrukh, Phaal, and Probert 2003).

Johnson (2012), by applying the technology roadmaps to manufacturing technology, found that roadmapping is, in fact, “an effective tool for sharing, capturing and aligning information for developing and communicating the strategic vision, and for allocating investments”. While the author found that roadmapping to be effective at a strategic level, he argues is not an appropriate method for information on the manufacturing technologies required for a particular product being developed.

We argue that perhaps the shift advocated by Phaal and Muller (2009) can also be possible using Ashby’s selection strategies.

Similarly to the material selection process, Ashby (2005) posits it is important to choose the most appropriate process-route (manufacturing technology) for a material early in the PDP so as to avoid the costs associated with rework. The process to be undertaken will depend on the material selected, its size, shape and precision, as well as the production volume. Identically to materials, processes can be characterized by attributes. Its selection implies finding the best match between its attributes and design requirements.

Ashby proposes a procedure for the selection of the most appropriate manufacturing technology parallel to that of material selection, illustrated in Figure 2.22.

Once again, the underlying premise is that all manufacturing processes should be considered as viable until proven otherwise. The first step is then to translate the defined design requirements into constraints in terms of material, size, shape, tolerance, roughness and other relevant parameters. The constraints identified will then be the basis for the screening of the processes that cannot comply. For example, some processes are not economically viable unless substantial quantities are produced; some are incapable of producing large part sizes; while others cannot produce the desired geometric complexity (Eggert 2005). Diagrams or Process Information Maps, also known as PRIMAs (see Swift and Booker 2003), or other decision support tools (software) may be extremely useful for the screening process.

The procedure then continues with the ranking of the processes by cost. On this, Ashby proposes four basic design guidelines to minimize the process cost: Keep things standard; Keep things simple; Make the parts easy to assemble; Do not specify more performance than is needed. Consenting that "cost is one of the key strategic elements of product competitiveness and an early appreciation of the relationship between major design choices and the cost of the resulting product is a vital element of effective product development" (Clark, Roth, and Field 1997), Ashby proposes two possible approaches to rank the processes based on this criteria: economic batch size and technical cost modeling. While the former seen as a short-cut approach, the latter allows for a more precise insight because all inputs (materials, capital, time, energy and information) that contribute to the cost of the product have to be considered in the equation (Clark, Roth, and Field 1997; Ashby 2005).

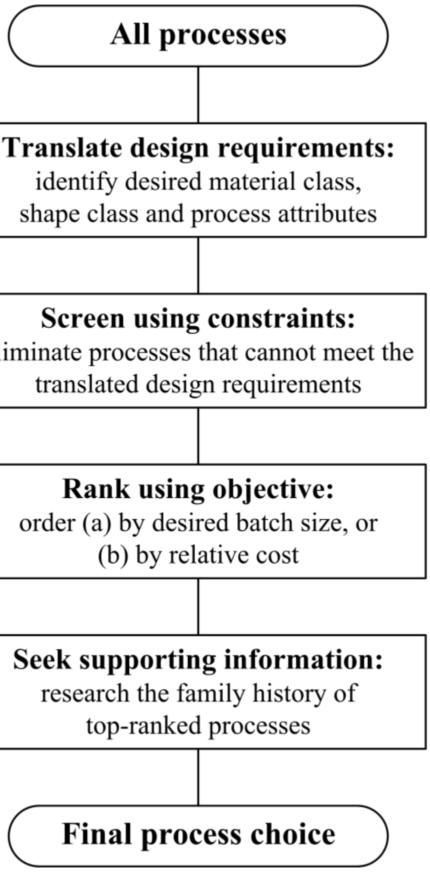


Figure 2.22 Four-step process selection procedure. It is performed in parallel with the material selection. (Ashby 2005)

Having arrived at a feasible short-list, supporting information (such as details, case studies, availability, warnings, and so on) is then needed to help the final decision.

As we've seen in the material selection process, choosing the most appropriate manufacturing technology is also complex. Nonetheless, a systematic approach instead of the mere reliance on past experience fosters better decisions.

In sum, we can state that in material and technology selection there are no correct or incorrect decisions. Both material and technology selection decisions occur simultaneously, throughout the entire PDP. As more information is collected, cost estimates can be revised, and thus, ultimately influence prior decisions. Also, due to the iterative nature of the design process, changes in features to improve functionality, for example, may imply a specific manufacturing technology or material, previously disregarded. Finally, given the extensive number of materials (Dieter 1997; Ashby 2005; Dieter and Schmidt 2009 have referred more than 100,000) and associated processes, it is therefore understandable that the selection process, albeit essential, is, in truth, complex.

2.4 Reaction Injection Molding

This section contextualizes RIM technology for the production of rigid parts by providing a technical and a business description as found in the literature. We discuss the raw materials that can be used, as well as the different features this technology enables. Finally, we review the type of possible applications, the different markets and the range of production volumes for RIM.

2.4.1 Technical Description

RIM is a thermoset process where two monomers (polyol and isocyanate) are mixed in a chamber, the injection head or mixing head, and then injected in a mold. These two liquid components chemically react to cure and form the plastic part, generally a PU (Belofsky 1995; Rosato, Rosato, and Rosato 2004). A scheme of a typical RIM process is presented in Figure 2.23.

RIM is a process to produce plastic parts from the injection of a reactive low viscosity mixture into a mold, allowing the production of parts with complex geometries. The heart of the RIM process is the intensive mixing of two monomers introduced from two opposite jets into a semi-confined mixing chamber. The resulting reacting mixture is discharged into a mold, where most polymerization takes place (Macosko 1989).

Typical RIM parameters:

- Very low viscosity (0,5 - 1,5 Pa.s);
- Low processing temperatures (30 - 45ºC);
- Low mold temperatures (30 - 45ºC);
- Low internal molding pressures (3 - 10 bar).

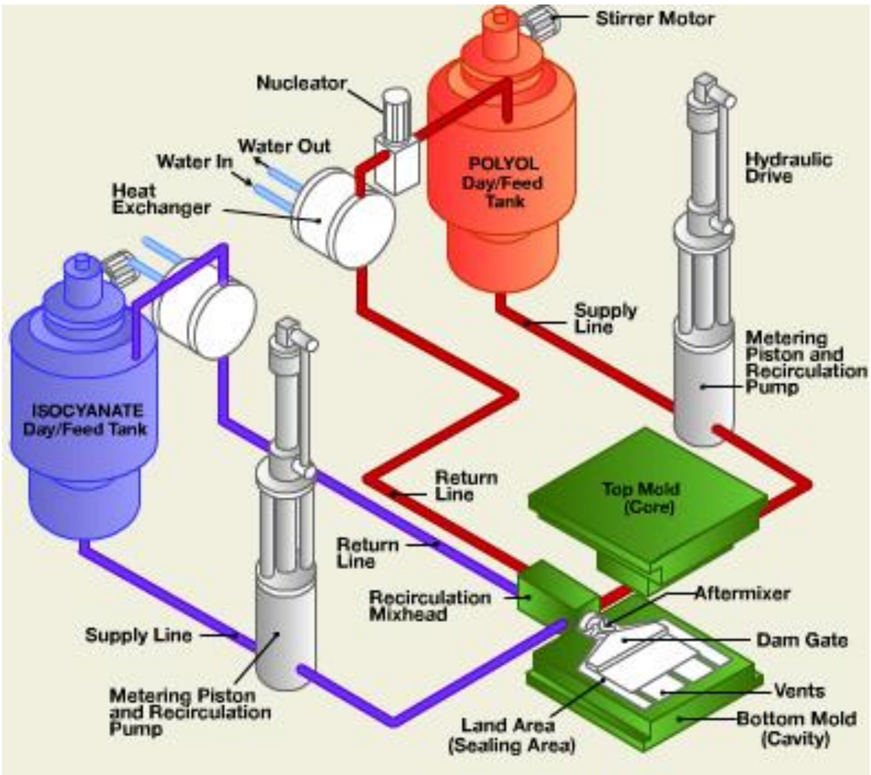
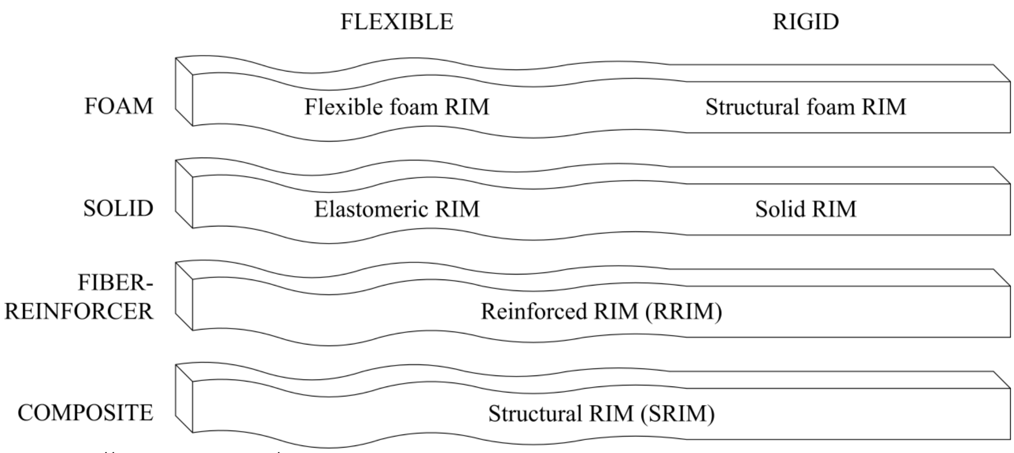


Figure 2.23 Scheme of a typical RIM process (Bayer 1995)

The materials most widely used in RIM technology are PU and PDCPD systems (Vervacke 2008), followed by polyamides and epoxies. There are differing PU systems that provide differing properties (rigidity, impact resistance, temperature resistance, insulation, etc.), see Figure 2.24. Stiffness and impact strength are enhanced by adding reinforcement in the material stream (Reinforced RIM – RRIM), or by using a molded pre-form in the mold that is encapsulated (Structural RIM – SRIM).



Source: http://www.romeorim.com/reaction-injection-molding.html

Figure 2.24 Spectrum of PU systems

Foams use blowing agents to form a sandwich of high-density rugged skin and a lower density cellular core. Solid are processed without blowing agents to form a homogeneous flexible or rigid plastic. Composite can be foamed or solid, rigid or elastomeric, but are molded with fiber reinforcements, such as glass, mica, quartz, calcium carbonate, or aluminum oxide to enhance the structural properties of the molded part.

Most common applications are in different types of enclosures and exterior panels. Figure 2.25 presents an example of a typical application in a medical device. For this blood analyzer, RIM was used to manufacture nine pieces of the assembly. It is also used in functional parts due to good insulation and impact properties.

Aiming to improve the reliability of the RIM process a new technology was developed at LSRE (Laboratory of Separation and Reaction Engineering), FEUP: RIMcop® – Reaction Injection Molding with Control of Oscillation and Pulsation, protected by USA and European patents (Lopes et al. 2005). RIMcop® allows (Teixeira 2000; Santos 2003):

- A real time control of the mixing process (not yet available in state of the art RIM);
- The inclusion of pulsations to improve the reliability of the mixing operation thus improving the final part quality;
- New geometries of the mixing chamber to facilitate operations;
- New strategies of monomers mixing for the production of new materials, like parts with optical quality or parts reinforced with nanoparticles.

Source: http://www.armstrongmold.com/pages/photo-gallery/blood-analyzer.html

Figure 2.25 Example of a typical RIM parts assembly

The RIMcop® technology controls the mixing dynamics from pressure measurements of the monomer feeding lines to the mixing chamber, which allows a real time control of the process, a feature not yet available in state of the art RIM technology. Furthermore the mixing is also ensured from a set of design changes to the mixing chamber and from the opposed jets forced pulsation (Santos et al. 2002; Santos, Teixeira, and Lopes 2005; Erkoç et al. 2007).

Developers of this technology are eager to understand of how the RIMcop® process can influence design, manufacturing and cost when compared to traditional RIM process.

2.4.2 Business Description

While we can find some technical information about RIM, as regards to market surveys or the competitive position of the companies specialized in RIM, in relation to the competing technologies not much is found in literature.

On the websites of RIM users we can find comparative analysis between this technology and others on the basis of qualitative advantages and disadvantages and the positioning of the technology in terms of processing method, capital and labor intensity, mold cost and part complexity. This information was summarized by Vervacke (2009) and is depicted in Figure 2.26.

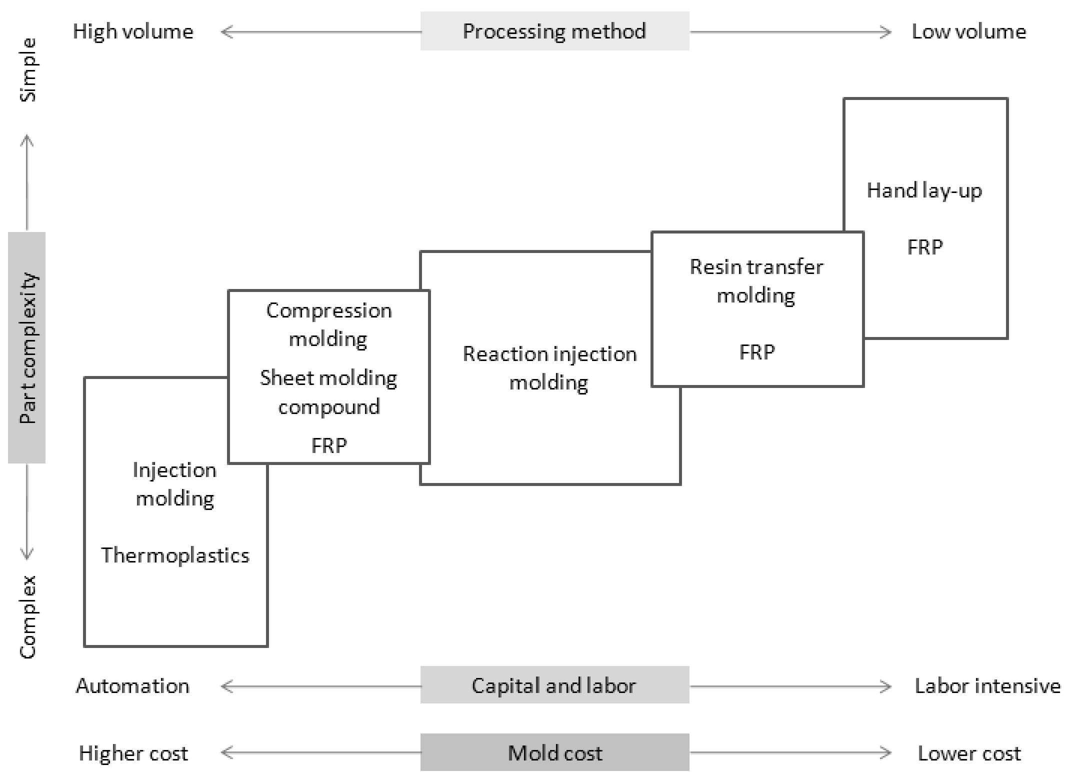


Figure 2.26 Qualitative positioning of RIM process (Vervacke 2009)

What is established, as a rule of thumb, is that this technology brings an economical benefit for large parts in small to medium series, from 1.000 to 15.000 parts per year. In terms of capital investment it is less demanding that other more automated processes, like injection molding or SMC, mainly because the RIM injection equipment (dosing and mixing machine) is much cheaper. On the other hand, RIM is faster and less labor-intensive than polyester hand lay-up or RTM, thus providing more productivity. Another advantage of RIM is the much lower tooling cost, when compared to injection molding. RIM offers freedom of design enabling the utilization of thickness variations, ribs, inserts and so on, thus complex shapes on both sides of the part are possible to manufacture.

With this we finalize the state of the art analysis about the PDP, modeling the PDP, materials and technology selection in PD and RIM technology constituting the theoretical base of this research. The next section will agglomerate the research gaps identified throughout this chapter and then formulate the research questions this thesis will strive to answer.

2.5 Research Questions

Initially this research addressed the RIMcop® technology and how to position it competitively in the production of multifunctional auto parts. Although RIMcop® has proven to be successful in controlled environments and testing, it is still not an industrial technology. Furthermore, the literature review revealed that there is very little information on the RIM industry, as well as regarding the PDP of products where RIM could be considered for the production of one or more parts. As such, before considering RIMcop® as a technological development of the RIM process, we first acknowledged the need to understand the development process of RIM parts. Only after will it be possible to identify how the RIMcop® process can influence design, manufacturing and cost. The research was therefore redesigned to address the characterization of the RIM industry in addition to the modeling and analysis of real PD projects where RIM could be considered for the production of one or several parts.

Thus, the focus of this thesis is not on RIMcop® or even on RIM technology. The focus of this thesis is on modeling and analyzing the PDP of real projects. RIM is the case study. It was chosen as the case study not only because of the interest of the LSRE research team in this technology, but also because of the appropriateness to provide sufficient empirical evidence to answer the research questions explained below.

Firstly we have to understand the current situation of the RIM industry, in particular for the production of 3D rigid parts. This study is important to deepen and systematize the knowledge about the RIM industry and technology, in order to have adequate comprehension to competently perform the case study research. The focus here is on the business description of the RIM industry in order to overcome the gap identified in literature, which seldom discusses this issue.

Furthermore we will analyze the PD process of products where a new, or rather unfamiliar, technology may be adopted as opposed to adopting a proven technology. This empirical study intends to contribute to theory about the PDP and the modeling of the PDP. Specifically, this study will try to address the following research gaps identified and justified in the previous sections of this chapter:

- Find empirical evidence of the factors that contribute to the success of PD projects. Surveys and questionnaires are interesting approaches to develop theory and establish dependency relations. However, to understand how those dependencies work in practice we need a qualitative approach based on a detailed and extensive analysis of one or more case studies. We will try to identify the constraints that inhibit the consideration and adoption of other materials and technologies in the PD process of rigid parts.
- To do this, it is important to have a clear view of the material selection process. The process used in each case study will be explained, analyzed and compared with theory. Providing a contribution to theory as the material selection literature is rich in prescriptive models and selection tools, but is missing detailed characterization of the practical implementation of the selection process in real PD projects. Documented experience modeling the technology adoption process seems to be lacking.
- The PDP must be analyzed within a decision-making process perspective, trying to identify the PD practices that facilitate better decisions in opposition to easier decisions. A good decision is the one that contributes to the success of the PD project, in terms of product effectiveness or in terms of process performance. The literature review revealed that PD practices are deeply rooted in PD methodologies, like CE or LPD. These methodologies are managed based on a set of principles. In the case studies we will map the principles and practices used and confer our findings with theory. The goal is to validate current literature with an in-depth case study and eventually find new insights to contribute to theory.
- To perform the research explained previously, it is helpful to produce a model of the PDP. A model of the process helps to communicate, understand and validate what is happening (or happened) in the real world by abstracting and synthesizing in a readable code. A model is an abstraction of reality focusing on the phenomenon we wish to study. The modeling method has to be chosen in

accordance with the purpose and the focus of the model. In this study we are particularly interested in modeling the different activities performed by the different roles involved in the process and how they interacted. The roles involved in the PDP and how they interact are vital to the proper implementation of the PD principles and practices. The modeling framework developed in this research took this into consideration, i.e. to be able to model the activities but also how the roles involved in the project interact and make decisions in the different stages of the process. The framework is based on the Riva method that is, as far as we are aware of, being used for the first time to model the PDP of real projects to add empirical evidence based on a different modeling approach to PD literature. This study will also contribute to literature by evaluating the capacity of the Riva method for modeling real PD projects.

Intending to, on the one hand, model PD projects where unproven technology could be adopted in order to contribute with experiential confirmation on successful PD factors and practices, and on the other hand, determine the suitability of a particular modeling approach within the unique realm of PD, this empirical study aims to answer the following research questions (RQ):

RQ1. What are the constraints that inhibit the consideration of other materials and technologies in the PD process of rigid parts?

RQ2. How is (and should be) the selection (decision-making) process?

RQ3. Can we develop a set of principles and practices to facilitate better decisions in opposition to easier decisions?

RQ4. Is the Riva method appropriate for modeling PD projects?

3 Research Methods and Procedure

This study is based on the framing of qualitative research methodology (Neuman 2006; Merriam 2002). The research is divided in two main stages, as synthesized in Table 3.1. The first one is dedicated to the understanding of the current situation of the RIM industry, in particular for the production of three-dimensional (3D) rigid parts. The major players are identified along the value chain, from the suppliers of raw materials, the manufacturers of the molds, the injectors of the parts, to the final assemblers and owners of the products that incorporate the parts.

Table 3.1 Characteristics of the two main research stages

	Stage 1: RIM industry analysis	**Stage 2: Case studies**
Approach	Inductive	Deductive
Type of research	Basic interpretive qualitative study	Qualitative case study
Data collection strategies	Secondary analysis Networking Non-participant observations Semi-structured interviews	Open-ended interviews Document analysis
Validity/credibility	Data triangulation Member checking	Data triangulation Member checking

In this stage the research is mainly inductive (Merriam 2002; Neuman 2006), as there was no pre-existing theoretical framing due to the lack of available information about this industry and technology. The research design for this stage of the study is a basic interpretive qualitative study that is analyzed through descriptive methods. Secondary analysis, networking, non-participant observations and semi-structured interviews were used as data collection methods.

At the end of this stage (see Section 3.1) it was possible to understand the structure of the value chain, the production processes and most of the applications where RIM has competitive advantage. Moreover, it allowed us to identify the key issue in this industry, which is the predominant role of the designer (i.e. the development team) of the product. This stage settled the context for the second stage of the research. With this stage it was possible to identify the focus of interest for this technology and consequently for this research.

The second stage of the study (see Section 3.2) is devoted to the analysis of the PD process of products where RIM could have been a strong candidate for the production of one or several parts. The consideration whether RIM is a strong candidate or not is based on the criteria developed in the previous stage. In this stage two qualitative case studies were performed, one where RIM was selected and another where RIM was not selected. Both projects were considered successful with financial performance of the resulting products in agreement with the expectations of each owning company.

Despite the fact that a case study inevitably results in new concepts and theory (which also occurred in this research, as will be explained in Chapter 5), in this stage the research is mainly deductive, because it intended to find in real projects practical evidence of the existing PD theory.

The data collection methods used was open-ended interviews and document analysis. The data collected was analyzed with a combination of methods, namely textual narrative and process modeling. Later in this chapter, the justification for the modeling framework used in this stage of the study will be discussed.

The PD process is modeled for each company, with particular attention to the concept development stage. The factors that favor a more proactive exploration of the development space are identified.

The theoretical framing developed in the previous chapter is particularly important for the execution of this stage, because the goals of this research were not only to understand the development process, but especially to add empirical evidence to theory and to validate the modeling framework used in the case studies. In both stages appropriate validation methods were employed, namely data triangulation and member checking, in order to ensure trustworthiness of the research (Kirk and Miller 1986; Denzin and Lincoln 1994; Creswell and Miller 2000).

3.1 Stage 1: RIM Industry Analysis

The analysis started with a high level picture of the plastic industry, investigating the different current applications, the most important suppliers of the raw materials and the typical supply chains for each type of application. Figure 3.1 shows the research steps performed during this stage. Participation at Polyurethanes 2009 Technical Conference, in Washington DC, with the presentation of a poster (Torcato et al. 2009) made an important contribution in this stage.

Afterwards, we focused on the investigation of the supply chain in the applications where RIM technology is used. Most of the companies were identified by web search, followed by email to confirm the main activity of the company. The email communication also proved to be a good source of information because some companies were willing to indicate their main competitors and suppliers. This step further improved the knowledge about why, where and how RIM technology is currently being used. Special attention was provided to the applications where 3D solid parts are needed, because of the interest of the research group in this type of application, as explained in the previous chapter.

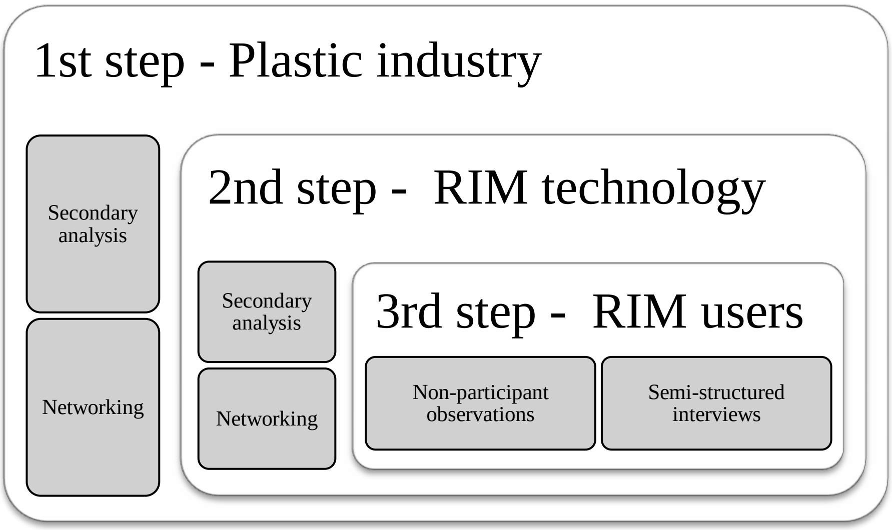


Figure 3.1 Stage 1 research scheme

Finally, three companies that are representative of the traditional RIM technology user were studied. These RIM users are specialized in the production of 3D complex shaped parts, including the injection, the finishing operations and, if demanded by the customer, some assembly operations. Table 3.2 exhibits the RIM users studied in this stage of the research.

The field research involved the permanence in each company from one day to one week, depending on the conditions offered by each company and the budget available, in order to perform the following activities:

- Deepen the understanding about the position of the company in the value chain.
- Characterize the company.
- Typify the portfolio of products and services.
- Describe the production process, including the involvement of the company in the PD process, the mold design process, the pre-injection, injection and post-injection operations and assembly.
- Identify the key success factors.
- Validate the framework of applications where RIM has competitive advantage.
- Validate the factors that inhibit the companies of achieving bigger sales and increasing the customers' base.

Table 3.2 RIM users studied in stage 1 of the research

Armstrong Mold Corp. located in New York, USA	Manufacturer of metal (aluminum and zinc) casting and plastic molding components in prototype and low-volume production quantities. RIM is mostly used for the production of PU covers for the medical sector. It represents around 30% of the business.
RIM Manufacturing LLC located in Texas, USA	Specialized in the production of custom PU parts, mainly for bezels and covers of a wide variety of products and industries. Production capabilities from injection to post-injection operations (finishing, painting), assembly of finished parts and quality control.
RIMSYS located in Portugal	A new company that started operations in the fourth trimester of 2009, located in the north of Portugal, specialized in RIM processing of DCPD for the production of exterior panels of vehicles. They have the knowledge and technology to produce and assemble enclosures for any kind of product.

The two US companies were visited during the researcher stay at MIT in the fall of 2009. They were very open and provided most of the data asked for, that allowed the development of grounded knowledge about the utilization of the technology, such as attributes of RIM, its qualitative positioning relative to other technologies, typology of applications and process flow. After the return of the researcher to Portugal close contact continued via email and telephone for feedback and further discussion.

The stay in Armstrong Mold involved non-participant observation (Patton 1980; Babbie 2013) of the facilities and the operations performed in each step of the production process, interviews with the engineering manager and the operations manager of the plastics division, interviews with the director of marketing and documental analysis. An important facet of the visit was the non-participant observation of the beginning of a new project, namely the kick-off meeting where the part to be produced was analyzed and the planning of the project was discussed.

The period spent in RIM Manufacturing allowed for a deeper analysis of the RIM process flow, including the post-injection finishing operations and some assembly operations. The visit involved interviews with the Chief Executive Officer and the Chief Operating Officer and non-participant observations of the production process.

RIMSYS was visited in 2010 for observations, interviews with the Chief Technology Officer and follow-up discussions. As this company was in the first year of operations the follow-up discussions were not as productive as expected. This is, to some extent, understandable because the Chief Technology Officer was completely absorbed with the day-to-day operations due to lack of staff, which is typical in a start-up, leaving him little time available to participate in this research. Nevertheless, this company provided valuable information about RIM processing of DCPD systems, which is a material that many companies are not capable of transforming, including the two US companies studied.

These companies were interested in the research because:

- They recognize that research work involving RIM is beneficial for their business.
- They want to understand the benefits of RIMcop®.
- They are mainly in prototyping and low volume production, thus they are highly involved in the concept development stage of the PD process. As a result, they would like to learn more about the CE philosophy and the benefits of using its principles to support the decisions involved in the concept development stage.

- They agree that the downstream processes are poorly considered in the development of product design concepts.

The first criterion for the selection of the companies was the technology: the companies had to be specialized in RIM. Followed by the type of products or components manufactured, the companies had to be specialized in the production of 3D complex shaped rigid parts. Finally, researcher accessibility to the companies was determinant to finalize the selection process.

The companies selected were the ones that showed more interest in the second step of this stage, were the ones that replied to our e-mails and eventually asked questions and contributed with suggestions. Furthermore, when invited to participate in the third step of this stage they accepted the solicitation with enthusiasm and offered their contribution for the planning and execution of the visits.

The number of companies selected was determined by the above-mentioned selection process together with the budget available to perform this step. Thus, it was possible to study two companies in the USA and one company in Portugal.

Given the objectives and characteristics of this step of the research, we consider three companies a fair sample of the population. We are confident that the collected information is representative of the reality of this industry and at least sufficient for this qualitative study. Notice that the companies are not homogeneous, they are very different in size and nature. Armstrong Mold is in the medium size of the SME with around 200 total employees and is not dedicated exclusively to RIM. RIM Manufacturing is a small size company, with less than 30 employees, specialized in the production of PU parts using RIM technology. RIMSYS is a start-up, with less than 10 employees, producing RIM manufactured PDCPD parts.

An important issue in this step is that all the companies required that any information (for example in the form of reports, papers, etc.) resulting from this particular study had to be validated by them before becoming public. One of the companies even demanded the signature of a Non-Disclosure Agreement (NDA).

Consequently, much information could not be explored in this thesis by imposition of the companies. However, we believe that this situation did not impair the quality of the thesis because the focus and scientific added-value are in the study of the PD process and its modeling, particularly the discoveries that were achieved in the two qualitative case studies explained below. We feel that, even without this contribution, we have achieved the goals of this research and demonstrated the validity of the results and the contribution to the research area.

This phase has the merit of allowing the researcher to deepen and systematize the knowledge about the RIM industry and technology, so as to have sufficient comprehension to competently perform the second stage of the research. Some of the results of this stage of the research were presented in two publications (Torcato, Santos, Dias, Roth et al. 2011; Torcato, Santos, Dias, Olivetti et al. 2011) and the feedback given by the scientific community in the conferences where the papers were presented had an important contribution to the design and execution of the remaining research.

3.2 Stage 2: Case Studies

The field research performed in this stage is a qualitative case study (Merriam 2002; Yin 2009) where the units of analysis are two companies located in Portugal with vast experience in PD. Table 3.3 exhibits the companies involved in this stage of the research. They finished a development project of a product with enclosures suitable for RIM manufacturing prior to the involvement in this research.

Table 3.3 Companies involved in stage 2 of the research

CEIIA located in Portugal	Centre for Excellence and Innovation in the Automotive Industry, a Portuguese Engineering Design Center specialized in product and process integrated development for the mobility industries.
Bosch Termotecnologia located in Portugal	A Competence Center located in Portugal specialized in products for domestic water heating that belongs to the multinational group Bosch. Responsible for the design and development of new devices and their production and marketing under the trademarks Bosch, Buderus, Junkers, Leblanc and Vulcano.

The research approach is deductive (Babbie 2013) as there is a theoretical basis about the PD process and about the modeling approach that supported the execution of this stage of the research. Data collection is based on open-ended interviews (Flick 1998) to the experts working at each company, supported by documental analysis (Clarkson 2003) of digital and physical records with supervision of those experts.

The principal purpose of this stage of the research is to model the PD process of two particular projects where RIM could be an interesting solution for the enclosures of the product or family of products. We believe that these process models will allow a deeper understanding about the dynamics of PD projects and how companies manage these highly complex, uncertain and goal oriented processes.

The focus of the modeling is on the decisions performed throughout the project; in particular the decisions related or that influence the selection of materials and technologies for the enclosures of the product. This focus in one particular subsystem of the product is justified by the technology that is under study in this research (RIM) and it's appropriateness in that particular application.

Moreover, this focus brings the benefit of facilitating the analysis, making it manageable for the researcher that, if required to analyze the decisions related with all the systems of the product, would not be able to finish the research in reasonable time.

The findings are thus not generalizable to all the decisions performed in a PD process, as in any case study (Stake 1995). In many subsystems of a product, other factors enter the equation, such as: sharing components or subassemblies with other products; buying standard components or subassemblies from other companies; or developing a proprietary technology for the component or subassembly or for the production of the component or subassembly. The findings are applicable to the subsystems where a unique design is required and there is no preexisting interest in using or developing a proprietary solution.

The projects under analysis are already completed and the products are already on the market, so there is no risk of the researcher interfering in the course of events. A drawback of this retrospective analysis is that the level of detail and personal involvement of the researcher is more limited than in an ethnographic analysis (LeCompte and Schensul 1999; Neuman 2006). However, given the objectives and the focus of the research, we think this is the best research design for the following reasons:

- The projects had to be completed and with the materials selection already performed as the interaction with the researcher, which is interested in discussing a particular technology, could alert the development team to that solution and thus influence the selection process.
- Only after the end of the project, are we able to have a higher level of certainty that RIM could have been an interesting solution to consider.

- The projects had to be considered successful by the respective companies, to qualify for this study. It was only possible to have that assessment after product launch in the market.
- Restrictions on the level of confidentiality would make the monitoring of projects in implementation phase extremely difficult, in some tasks impracticable. As was demonstrated in the visits to the RIM users.

In the CEIIA project RIM technology was selected and in the Bosch Termotecnologia project RIM technology was not selected. This does not necessarily mean that in the former case the right decision was made and in the latter case the wrong decision was made. As will be demonstrated later on in the discussion, many factors contribute to the decisions and other technologies may be considered as well as RIM.

Qualitative data was collected, synthesized and organized in order to enable the construction of the model. The process modeling procedure was performed with the support of narrative analysis (Riessman 1993; Labov and Waletzky 1997). The modeling framework will be discussed in the next chapter of this thesis.

For validity purposes, data triangulation and member checking (Denzin and Lincoln 1994; Creswell and Miller 2000) were performed during the execution of the process model. Data triangulation was mostly performed by means of documental analysis (Clarkson 2003). Member checking was fundamental not only for validation of the information but especially for the development of the model. Because it was the feedback obtained during the member checking meetings that most contributed for the detail displayed in the models.

These case studies are relevant for the overall research because:

- They provide empirical evidence of the hypothesis developed in the research. In particular, the framing where RIM technology is competitive (technical requirements and production volumes) and the difficulty of the development team in making the switch to unfamiliar materials and/or production technologies due to risk aversiveness.
- They also provide insights about the PD process adopted in these organizations, enabling the assessment of the level of implementation of CE principles and the mapping of the factors affecting the success of PD project.
- The information collected will be very helpful to draw conclusions about the factors that contribute to the selection of a particular technology by the development team. As will be noticed, these do not rely on technical issues only.

The research scheme of this stage of the study is depicted in Figure 3.2. Starting from the results of the first stage, which indicated that the research focus should be directed to the understanding of the PD process, a bibliographic research was performed in order to synthesize the existing PD theory, as presented in Chapter 2. Particular attention was devoted to the factors or principles that influence the quality of the PD process. Here, quality of the PD process means the ability of the development team to make the right decisions throughout the project, assuming compliance with lead time and budget.

The review also sought for the different approaches to model business processes and in particular PD processes. To understand a given process, we invariably need a way to describe the process; we need a model of the process. As explained in Chapter 2, the concept of model here is a representation of a real process; it is not a prescription for an intended process.

Afterwards, the modeling framework to be used in this research was developed. It is based on a modeling language, the Riva method (see Section 2.2.5), complemented by a textual narrative of the process.

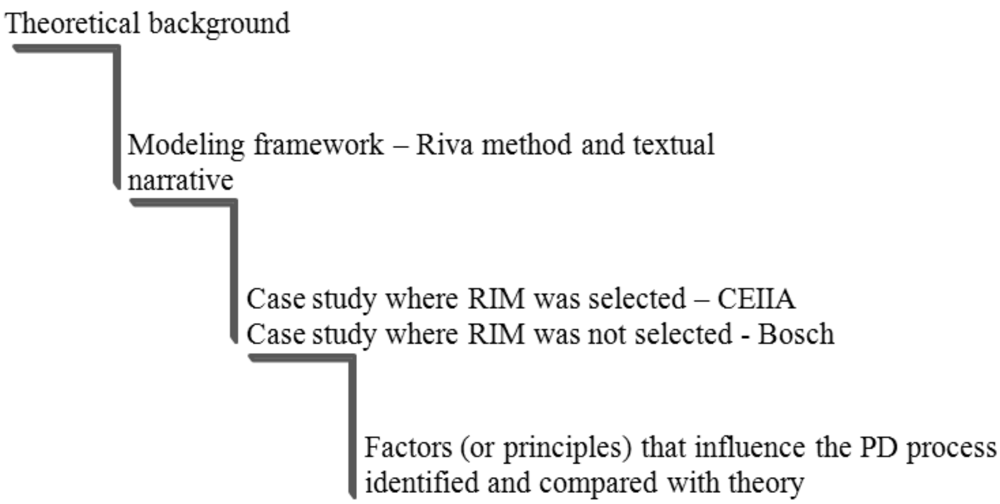


Figure 3.2 Stage 2 research scheme

The framework was tested in two distinct case studies to model the PD process:

- The CEIIA case study: To model the project for the development of a restyled version of Buddy (a Norwegian electric quadricycle vehicle).
- The Bosch Termotecnologia case study: To model the project for the development of a standalone heat pump.

The modeling framework, as well as the procedure used for the implementation of the framework, including data collection, analysis and validation will be explained in the next chapter of this thesis.

Finally the findings resulting from these case studies are discussed and compared with theory. The factors that influence the performance of the PD process are identified and compared with current literature. Attention is also paid to the modeling framework implemented in the case studies, with a discussion about the effectiveness and efficiency of the modeling procedure and about the accuracy and clarity of the resulting models, also comparing these results with literature.

4 Modeling Framework

Having completed our literature review in order to obtain a deeper understanding of the theoretical principles being discussed and the empirical research underway within the realm of PD, we developed a modeling framework to model the PDP of two real projects. Our modeling framework is based on the Riva method (see Section 2.2.5), complemented by a textual narrative of the process. This section describes the modeling framework, as well as the procedure used for the implementation of the framework, including data collection, analysis and validation.

The process modeling procedure adopted is based on Ould (2005) who proposes the following steps:

1. Decide on the objectives of the modeling.
2. Brief ourselves by getting an overall picture, no matter how coarse, from a variety of sources.
3. Run one or more interactive workshops of those involved to draw up a RAD that meets the objectives of the modeling.
4. Use other appropriate sources of information.
5. Review, revise and validate the model using other inputs.
6. Use the model.

The author stresses that these steps are not mandatory and should be tailored according to the characteristics of the process to be modeled and to the goals of the modeling. In this particular research, the intention is to model the PD process of a specific project that already happened. Thus, workshops with the roles involved in the process would be impracticable.

The workshops were replaced by interviews with the Project Manager and the Engineering Design Manager in the CEIIA case and with the Vice President (VP) for Engineering in the Bosch Termotecnologia case, complemented by documental analysis.

During the modeling procedure we noted that the Riva language could not give the necessary detail about the succession of events that are depicted in the model, particularly about the information digested by the development team and the subsequent knowledge level in each step of the project. The model is extremely useful for a rigorous presentation or description of the process, as an identity card of the process, presenting in a very intuitive way what happened during the PD project: the roles involved, the actions and interactions performed, the decisions taken and the goals of the process. However, we need a further magnified lens in order to see the insights of the process.

The same way a CAT scan is very helpful and rigorous in the diagnostic of diseases, many times doctors need to use other methods in order to determine the specific disease and why the disease emerged and developed (like for example a biopsy to determine the type of cancer or tumor that was detected in the CAT scan). To draw robust conclusions about the development process, it is fundamental to complement the model with detailed explanations for the reasons behind the events depicted.

Textual narrative is an appropriate and effective way of doing this. The narrative, like a novel, takes us to the core of events, facilitating the interpretation of the process model with a ready to read description of the what, the why and the how of the story of the project (Connelly and Clandinin 1990).

The goal of the modeling framework adopted in this research is to have a model that accurately describe the process in a A4 (210cm x 297cm), maximum A3 (297cm x 420cm), sheet of paper, accompanied by a textual description, a narrative, that explains in detail what happened in the process.

The process we are modeling is singular and the motivation to build the model is also singular. The intention with this model does not fit any of the reasons why an organization models its processes. The “four Ds and an E: discovery, definition, diagnosis, design, and enactment” (Ould 2005) are all related with a managerial perspective and framed in the context of the organization’s object of analysis. In this analysis the motivation is more comprehensive, we intended above all to contribute to the field of study. More than an analysis, we are researching and, as such, we need a different approach, a little more extensive and detailed than that which is required under strict management of the organization processes.

Although it is possible to increase the level of detail of the model, this would increase excessively its size and complexity, making it difficult to read. As demonstrated in the feedback received in academic discussions and presentations performed by the researcher, it is essential that the model is of fast reading and understanding, stressing the essentials, including *who*, *when*, and *what*. The *how* and *why*, which are critical in a qualitative research, are explained in detail in the project's textual narrative. The narrative is complementary to the model. Together they form a framework that characterizes and explains precisely and in detail the history of the project.

It should be noted that this is a retrospective analysis of projects that have already occurred, unlike an analysis of processes in real time, which is the usual situation in BPM. This difference, which looks like a detail, is extremely important because we are not looking at the process with the premise that it will be repeated. We are looking at a concrete and unrepeatable project, with the intent of describing it with the clarity and detail necessary to allow, by its analysis, to contribute with this empirical basis for strengthening the PD theory.

The modeling framework developed for the case studies research is depicted in Figure 4.1. This schematic representation synthesizes the research design explained in the previous paragraphs of this chapter.

The research is divided in three main blocks: the modeling framework, the modeling procedure and the process models.

The designed modeling framework is based on PD and process modeling theory. It is constituted by two complementary modeling approaches, the Riva method for the construction of the process model and textual narrative for telling the process story, focusing on the issue of interest (the product enclosures which are suitable for RIM manufacturing).

After defining the modeling framework, it is implemented in two case studies following a modeling procedure. These case studies are two PD projects that have been successfully completed. As referred previously, one project is from CEIIA and the other project is from Bosch Termotecnologia.

The result of this work is two process models and narratives, which describe in rigor and detail the two real projects performed by these companies. The models are analyzed and the findings provide empirical insights about the PD process of these two projects. Ultimately we seek to give a contribution to PD and process modeling theory.

The next paragraphs will explain the modeling procedure for the implementation of the framework in the case studies. A RAD of the research procedure is depicted in Figure 4.2. The modeling procedure is, itself, a process where the researcher interacts with the experts of the company in order to produce a process model and narrative of the PD project under analysis.

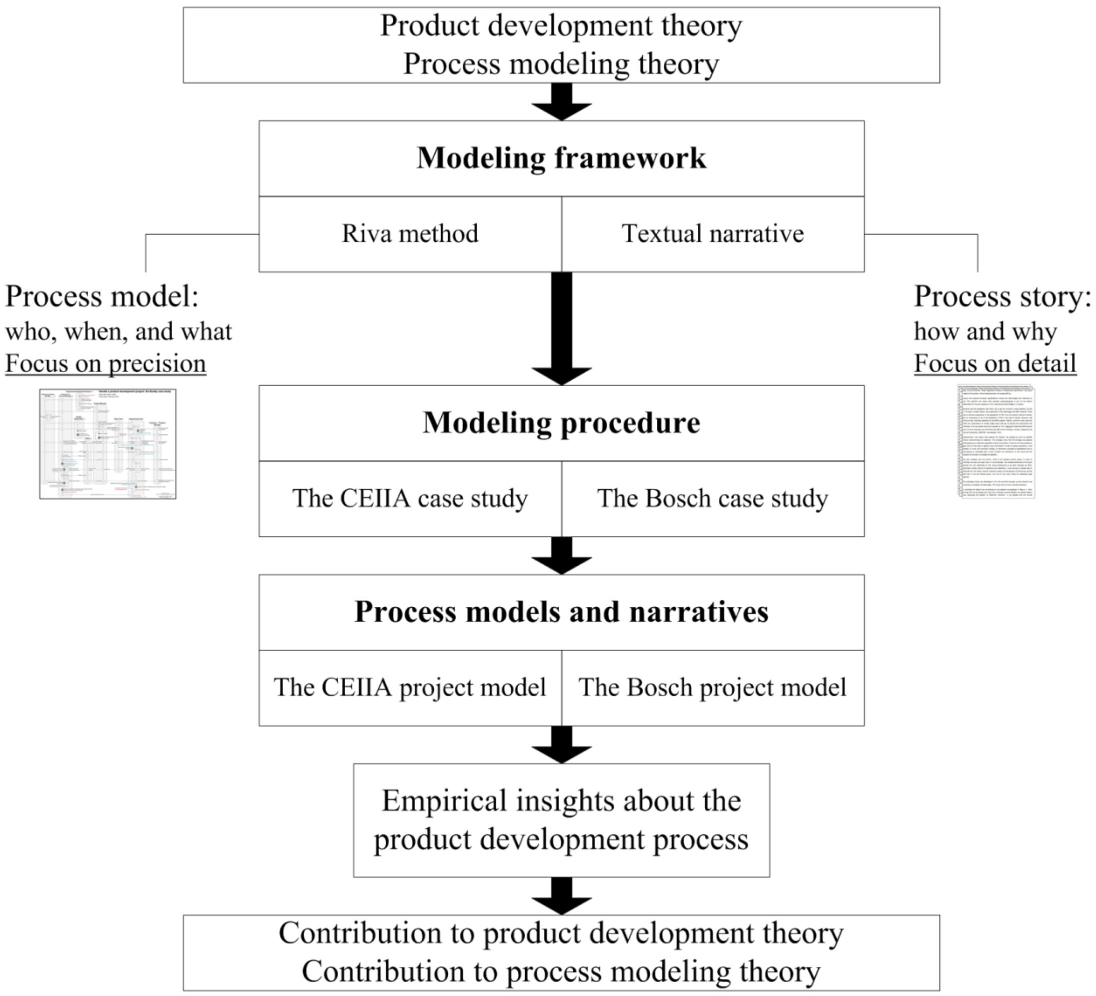


Figure 4.1 Process modeling framework

Thus, the “project case study” is the unit of work (UOW) of the researcher’s modeling procedure. Each project studied by the researcher is a case or instance of the UOW “project case study”. For simplification, one case was identified as “The CEIIA case study” and the other “The Bosch case study”. In both cases, the work performed by the researcher followed a standard set of activities, depicted in Figure 4.2 process model.

In both cases the process was activated when the researcher and the company agreed on the terms and conditions of the collaboration. This negotiation process involved the definition of the research boundary and ownership, the selection of the PD project object of analysis, confidentiality management and the company's roles that would collaborate in the modeling process.

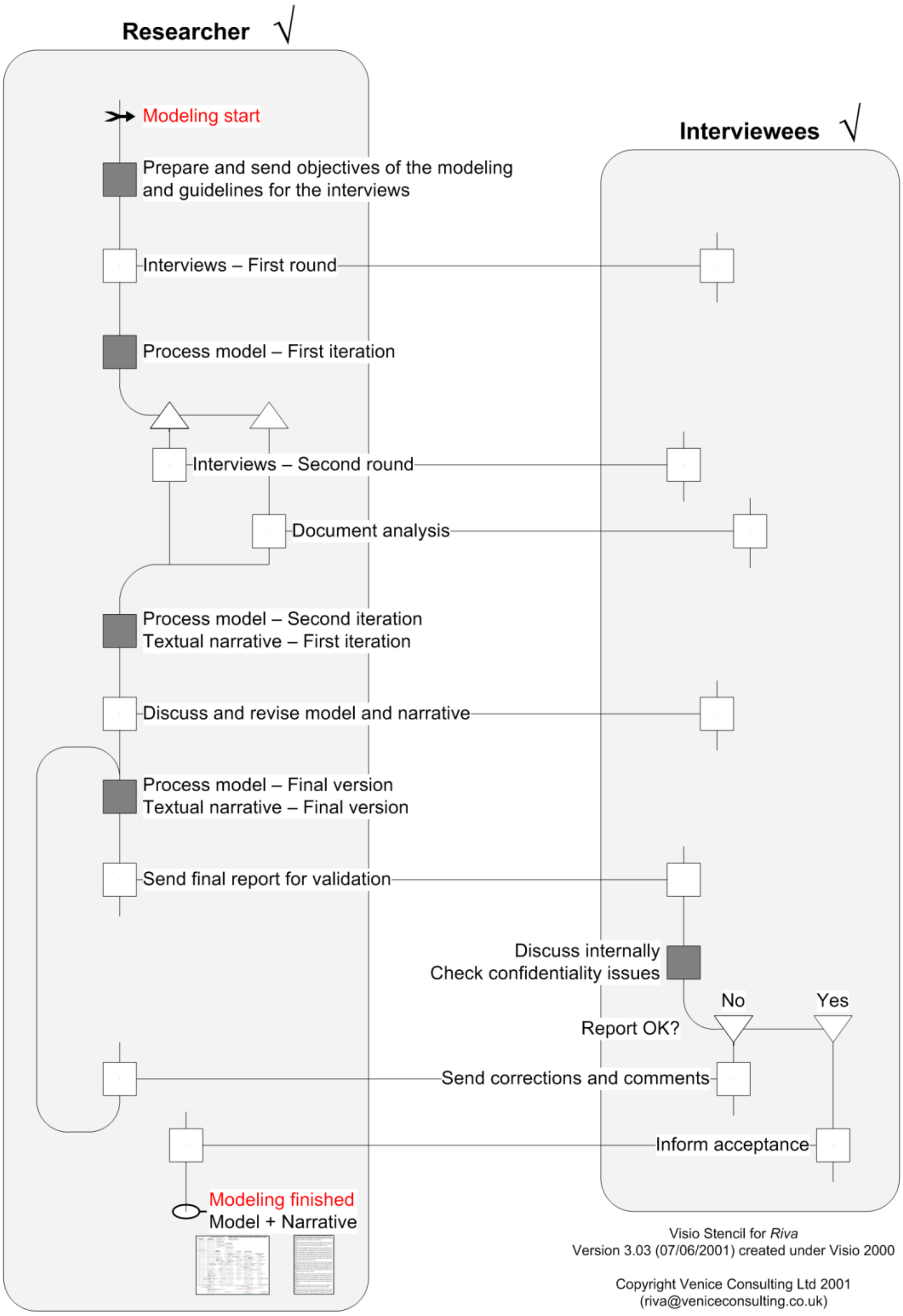


Figure 4.2 Modeling procedure for the case studies research

The collaboration is based on a succession of interviews performed by the researcher to the above-mentioned roles (described in Figure 4.2 as interviewees). The first round of interviews allowed for a coarse representation of the PD process, this is the first iteration of the process model. With this model in hand, a second round of interviews was then performed, this time accompanied by document analysis. For confidentiality reasons, the documental analysis was first reviewed by the interviewees to filter the information that could be released to the researcher.

Document analysis is necessary for two reasons: to offer the details needed to write the textual narrative of the process; for validity purposes, allowing data triangulation with the information collected in the interviews (Patton 1980; Neuman 2006). This enhances the process model, as well as improves the robustness of the findings.

Several documents related with the project under study are analyzed. Both companies have document management procedures and project dossiers organized under standardized rules, for traceability and compliance with quality management standards. The documents related with the periodic description of the project status in particular are very helpful to understand the evolution of the level of knowledge of the design team and the sequence of decisions performed on the PD process. Also, the technical documents, like 3D computer-aided design (CAD) models, bill of materials (BOM), material technical sheets, CAE analysis and others are very useful to discover the underlying justification for some of the decisions performed by the design team.

The analysis of the data collected in the second round of interviews and in the document analysis results in a significant improvement of the process model (this is the second iteration of the process model) and also enables the first iteration of the textual narrative of the process. Following this procedure, both the process model and the narrative are discussed with the company representatives.

This member checking is a fundamental contribution for the validation of the data collected and also for the development of the model. The feedback obtained during the discussion meetings represents new information, both in terms of quantity and, especially, in terms of quality, because the discussions are based on a concrete model and narrative of the project, thus facilitating the identification of gaps and misunderstandings.

Afterwards, a final version of the textual narrative and process model is proposed and integrated in a final report that is then delivered to the company for validation. This report also includes the discussion of the findings in comparison with theory and the preliminary conclusions and managerial implications.

The report is discussed internally, at the company core, without interference from the researcher. This part of the procedure is done on a deferred basis. The discussion includes the validation of the contents in the report and the screening for confidential information. This member checking may result in a series of recommendations or corrections, if the company considers the report has incorrect information or is disclosing confidential information.

If the researcher receives comments and corrections, it is then necessary to go back and rebuild the textual narrative and process model. Consequently, the final report is updated and resent to the company for validation.

The researcher performs this rework until the company roles involved in the validation of the report are satisfied with the content, both in terms of trustworthiness and confidentiality. At this point, the company informs the researcher of the acceptance and validation of the report and, with this, the process modeling procedure is concluded.

The next sections of this chapter introduce the case studies, give a synthetic explanation about the projects that were analyzed and modeled, particularly the product parts that were, or could have been RIM manufactured (the enclosures of the product), and conclude with a brief description of the specificities of the implementation of the modeling procedure in each case study.

4.1 The CEIIA Case Study

The Buddy project was developed in CEIIA between March 2008 and February 2010 with the main objective of releasing a restyled model of Buddy, the Norwegian electric quadricycle vehicle produced by Buddy Electric AS, formerly known as Elbil Norge AS (Figure 4.3). The project involved the complete vehicle development, from style definition to functional prototypes manufacturing.

This project is particularly interesting because DCPD material was selected for all exterior panels of the vehicle, which are manufactured with RIM technology. Furthermore, CEIIA and Elbil Norge had no previous experience with this material and technology. Also, the supplier of the material (Telene), despite the vast experience in the application of DCPD in the fabrication of exterior panels, was never involved in a similar experience, that of producing all body panels in the same material.

All the companies involved in the project were exploring completely new territories; nevertheless they managed to reduce the uncertainty and risk associated with the decisions using several approaches that will be described and discussed in the next chapter of this thesis.

This was a very important project for both CEIIA and Elbil Norge. It was important for the former because both the product and the activities required were right at the core business of CEIIA, it was important for the latter because it was, and still is, the sole product of the company, representing the only survival option.

Source: http://en.wikipedia.org/wiki/Buddy_%28electric_car%29
Previous Buddy model

Source: http://www.reghardware.com/2009/05/26/buddy_metro/
Restyled Buddy model

Figure 4.3 Buddy electric vehicle

The project was considered by CEIIA and Elbil Norge a success, both in terms of technological innovation and in terms of financial performance. Despite the high levels of uncertainty, the project finished on time and on budget. The product is selling according Elbil Norge's expectations.

The researcher was not allowed to record the interviews, which forced more discussion meetings in order to arrive at a satisfactory result. On the other hand, there was openness to provide technical information and some detail about the technologies studied by the development team.

Generally speaking, the process modeling procedure was adopted as described in the previous section with no relevant setbacks except the one explained in the previous paragraph. The process model and textual narrative was produced and validated by CEIIA requiring only one rework cycle.

4.2 The Bosch Termotecnologia Case Study

The water heater project was developed in Bosch Termotecnologia with the main objective of releasing the first model of a standalone heat pump (Figure 4.4). The project started in January 2010 and concluded in June 2011 when the product was launched under the trademarks Junkers, Buderus and Bosch. The first countries to receive this product were

Belgium and Poland followed by France. The project involved the complete PD, from style definition through functional prototypes manufacturing and production ramp-up.

This project is particularly interesting because EPP (expanded polypropylene) material (which is a direct concurrent of PU) was selected for the production of the enclosure of the heating module. EPP was far from being the natural choice, as will be explained in the next chapter. As in the previous project, Bosch was not familiar with this material and production technology. However, they found in their qualified suppliers' database companies with experience in EPP application on exterior panels.

Figure 4.4 Standalone heat pump.
Reproduced with permission from Bosch Termotecnologia.
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Bosch Termotecnologia is particularly interesting because it has a history of success where the introduction of new materials and technologies in their products is concerned. The company and the multinational group that the company belongs to have, deeply routed in their core values, a culture and philosophy of innovation. The PD process is tailored to manage the risk associated with the exploration of new materials and technologies. The proof of this is the project under analysis, where EPP material was adopted for the first time in the enclosure of water heaters.

Nevertheless, RIM was not considered in the selection process due to unawareness about this particular technology among the members of the design team and the qualified suppliers. This is consistent with the assumption that RIM technology is not well known in the plastics industry and in the industries that develop and assemble products that can potentially incorporate plastic components. This lack of awareness, together with deficient prospection and dissemination activities of the RIM users, limits the opportunities for the introduction of this technology in new applications.

Bosch considered the project a success, both in terms of technological innovation and in terms of financial performance, but particularly in terms of innovation, because it was the first standalone heat pump to be launched in the market by Bosch. Furthermore, it was the first to introduce the EPP material in the heating module enclosure.

The researcher was allowed to record the interviews. Thus, the interviews were recorded, transcribed and validated by the company, facilitating the downstream activities required in the modeling procedure.

On the other hand, there were some company-imposed restrictions, which limited the access to project documents and information, resulting in less detail than in the previous case study. A considerable amount of time was allocated to the discussion and revision of the model and narrative, fruit of the intense interactions needed to compile the required information.

The process modeling procedure was adopted as described in the previous section, with no relevant setbacks except the one explained in the previous paragraph. The process model and textual narrative was produced and validated by Bosch after a very intense discussion and revision process, as mentioned above.

5 Findings and Discussion

This chapter starts with the findings related with the current situation of the RIM industry, in particular for the production of 3D rigid parts. These build on the literature review carried out in Chapter 2, and add practical information regarding the technical and business description of RIM, retrieved during our interaction with the various stakeholders of the industry. The focus here is on the business description in order to overcome the gap identified in literature, which seldom discusses the issues in this area.

The three RIM companies visited by the researcher provided valuable information about the production process, the current applications and the positive and negative attributes of the technology. The value of these findings is on describing the usage of RIM technology in real companies and identifying the difficulties, both technical and managerial, that they face.

Thereafter, the findings related with the two qualitative case studies are presented. These case studies are two PD projects that have successfully completed. One project is from CEIIA and the other project is from Bosch Termotecnologia.

The findings are presented in the form of two process models and narratives, which describe in rigor and detail the two real projects performed by these companies. The models are analyzed, providing empirical insights about the PD process of these two projects. The focus is on the development of the enclosures of the products, which were, in the case of CEIIA, or could have been, in the case of Bosch Termotecnologia, RIM manufactured.

In the discussion section we seek to give a contribution to PD and process modeling theory. Brown and Eisenhardt's framework of factors that affect the success of PD projects are compared with the findings of the case studies, resulting in the proposal of a modified framework. The method used in each project to perform the materials selection is discussed and compared to the materials and processes selection strategies presented in theory, particularly Ashby's systematic procedure. The degree of implementation of CE principles and lean development system principles in each project is also discussed.

Finally, the effectiveness of the modeling framework developed for this research is discussed. The expectations created in the development of the framework are compared with the actual analysis and findings that the produced models allowed.

5.1 RIM Industry Analysis

5.1.1 Plastic Industry

Plastic industry includes all businesses that rely on the utilization of any type of plastic material to create value. It is a pyramidal industry, with a small group of companies in the extraction of the feedstocks from the natural resources, namely petroleum, and production of the different monomers that are then transformed into the commercially available plastics ready for fabrication (see Figure 5.1). This part of the industry is typically process-based with emphasis on the chemical and process engineering disciplines. These plastics are used in an immensity of products including packaging, building and construction, electrical and electronic, appliance, automotive, and practically all markets worldwide (Rosato, Rosato, and Rosato 2004). Thus, a large number of companies and value chains operate in these markets, developing products that rely on the use of plastics and related fabrication technologies.

The classification of materials into three main families is widely accepted: ceramics, metals and plastics. The family of plastics, which comprises more than 35.000 types, can be divided into two main classes: thermoplastics (TPs) and thermosets (TSs). TPs are, by large, the most widely used, with over 90wt% of all plastics.

TPs are processed by applying heat to soften the material that then is pushed through pressure or another mechanical means to form the shape of the part. They can be repeatedly softened by reheating, thus can be processed several times. TSs can be processed by applying heat and/or pressure or by the reaction of two monomers. They flow to meet the shape of the mold and, at a certain temperature, they cure, solidifying after a cross-linking chemical reaction of its molecules. In contrast with TPs, cured TSs cannot be re-softened.

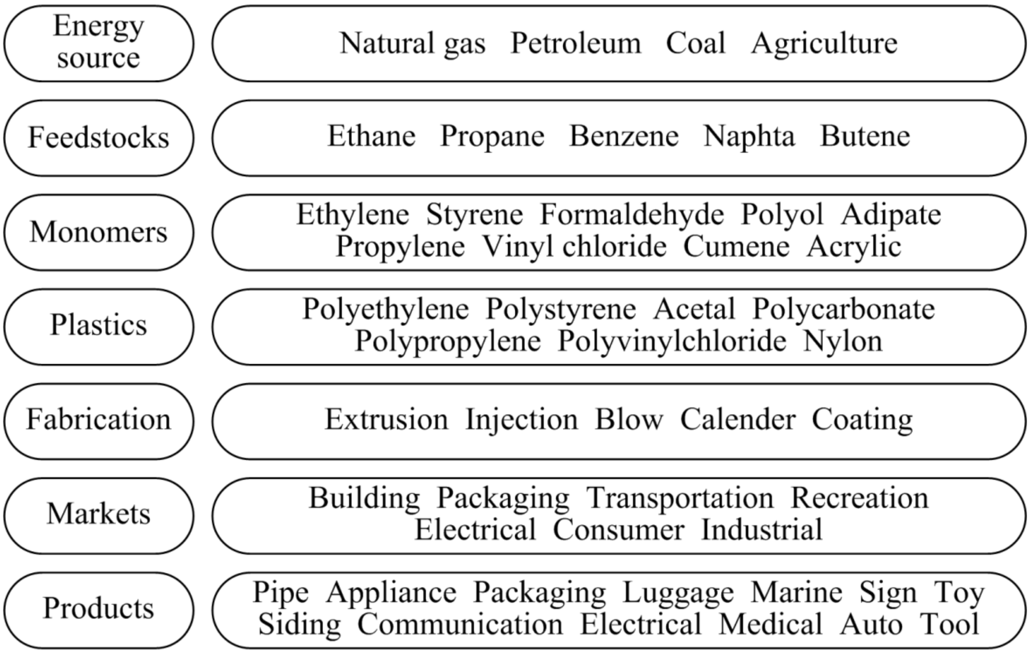

Figure 5.1 Overview of the plastic industry from source to products (Rosato, Rosato, and Rosato 2004)

As explained in Chapter 2, RIM is a manufacturing technology used to process TSs, namely PUs and PDCPDs. Compared to the major manufacturing processes (extrusion, injection molding, blow molding and so on) RIM is a relatively new manufacturing technology, consuming a marginal weight percentage of all plastics. Nevertheless, due to its versatility and capacity to produce high quality parts, we consider this as an opportunity for growth rather than a disadvantage.

5.1.2 RIM Industry

It is not an easy task to delimit and characterize the RIM industry. Actually, RIM is a manufacturing technology to produce plastic parts (see Chapter 2). It is a plastic molding process that, in theory, can be used in any industry for the production of any plastic component of a product.

With this section we intend to introduce the concept of RIM industry, which we define as the system constituted by the companies specialized in the manufacture of plastic parts using RIM technology (RIM users), their suppliers and customers. The focus is on the RIM users, i.e. the companies that use RIM technology to produce their products, which usually are components or subassemblies to incorporate in the product of the customers.

The customers are the companies that pay for the goods RIM users deliver. They can be the owners of the final product or suppliers integrated in the value chain of the final product. Thus, the number of layers between the RIM user and the owner of the final product depends on the specific industry the product is in.

In this study, it is assumed that the customer role encompasses all the layers between the RIM user and the company responsible for the design and development of the product (where the decisions related with material and technology selection are made), which is usually the owner of the product or someone hired by the owner of the product. This is an abstraction of reality that is useful for the purpose of the study. As the focus is on the RIM users, trying to analyze all the possibilities downstream the value chain would diverge attention without adding significant value to the analysis.

Beyond the processing equipment, RIM users need a mold and a plastic system (usually composed of two separate liquid monomers) to produce the plastic part. Thus, the major suppliers of these companies are the equipment manufacturers, the mold-making companies and the plastic systems developers and suppliers. A list of RIM equipment manufacturers and RIM systems suppliers is depicted in Appendix 1. Most of these companies are large or even multinational groups that are not exclusively dedicated to RIM equipment or to RIM processable materials. In fact, for most of them, RIM represents a small percentage of the business' revenue. The exceptions are the DCPD suppliers, Telene and Metton, which are exclusively dedicated to the development and distribution of their DCPD-based proprietary resins.

Appendix 1 also presents a list of RIM users, which are small and medium-size companies (SME) with technical expertise but limited commercial and marketing resources. The mold-making companies that supply the molds have similar characteristics in terms of size and know-how.

Given this, we can infer that the RIM user is the weakest link in the chain, on the one hand there are the multinational companies as suppliers, and on the other hand, there are the customers, usually much larger in size and possessing the ownership of the product.

Figure 5.2 maps the value exchanges across the industry and was developed following the value network analysis method (Allee 2008). The diagram shows an external facing value network focusing on the main deliverables between the roles identified in the previous paragraphs. The nodes depict roles that perform the transactions and the arrows with labels indicate the important transactions through which deliverables are conveyed from one role to another.

> "Transactions, or activities, originate with one participant and end with another. The arrow is a directional link that represents movement and denotes the direction of what passes between two roles. Solid lines are formal contract exchanges around product and revenue, while the dashed lines depict the intangible flows of market information and benefits" (Allee 2008).

Thus, in Figure 5.2 tangible deliverables (meaning contractual or formal deliverables) are shown with solid lines. Intangible (meaning informal or unstructured) deliverables are shown with dashed lines.

The first assessment of the value network is related with the value conversion capability of the system as a whole. This is performed by an exchange analysis that assesses the overall patterns of value exchange. Looking at the core product value chain (which is the plastic part) there is a coherent logic in the way value moves through the system, both in terms of tangible and intangible deliverables.

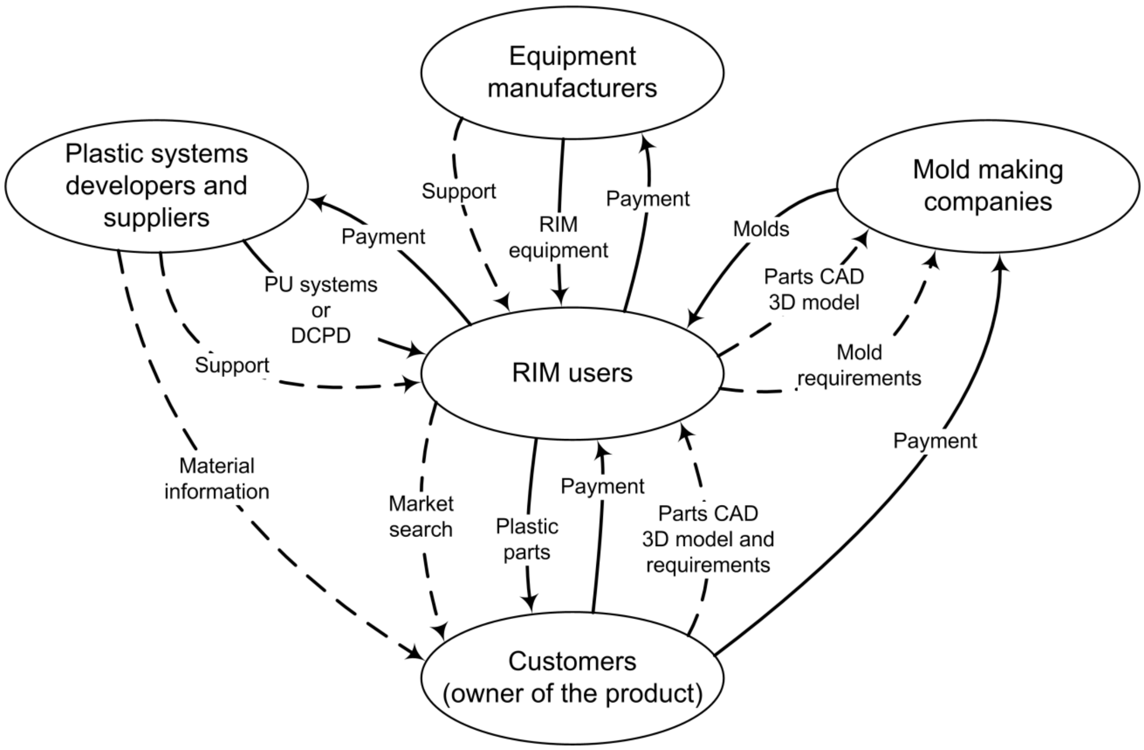

Figure 5.2 External value network of the RIM industry

However, tangible deliverables are dominant. In general, the roles do not engage in the exchange of technical know-how, collaborative design work or joint planning activities.

Intangibles are limited to the delivery of indispensible information about the plastic part by the customer, like CAD 3D models and requirements, and support activities performed by the RIM equipment and plastic systems suppliers, including material handling and processing guiding and maintenance planning of the equipment.

The RIM user is receiving and delivering tangibles in a very simple and reciprocal fashion. Each physical transaction is associated with a payment that was obviously negotiated and contracted by the roles involved. The only exception is the delivery of the mold. In this case, the usual procedure is that the mold is used by the RIM user but is property of the customer. Thus, the mold is delivered to the RIM user but is paid by the customer. In terms of cash flow this is advantageous for the RIM user but, in terms of negotiating position, this is harmful because the customer may, at any time and depending on the supply contract that was agreed upon, pick up the mold and transfer it to another company. Thereby reducing the bargaining power of the RIM users as a whole.

On the other hand, the RIM user is mostly receiving intangibles. The information delivered to the mold-making company is basically a forward of the information received by the customer with practically no value added by the RIM user. The market search activity refers to the usual commercial effort of customer retention and prospection, like participation in trade fairs, direct contact with potential customers to present the company and find business opportunities and reply to information queries. Therefore, this activity is not perceived by the customer as delivering any value.

Moreover, material information (like chemical composition, mechanical properties, typical applications, design guidelines, processing requirements, safety issues, etc.) is directly delivered by the plastic systems supplier to the customer. This deliverable is of value to the customer because it consists of fundamental information required for material selection and also for the concept development. Thus, it is an activity that benefits the RIM user because the customer improves the knowledge about the technology, increasing possibilities of selecting it. However, the RIM user depends on the marketing capabilities and strategy of the plastic systems supplier.

This industry is clearly doing *business as usual*, the physical tangibles moving in a logical and integrated way and the intangibles just supporting the business, thus, with very little added value. In particular, we found that there is lack of activity of the RIM user in regards to the collaboration and cooperation in the planning and development of the product.

In general, the customer does not involve the RIM user in the PD process. The RIM user receives information about the part that is to be manufactured when it is completely defined and is, therefore, only able to influence the design of the product when it comes to small details. Moreover, the selection of the material is already made with no influence of the RIM user and, many times, with the influence of suppliers of other better-known and well-established technologies. In this scenario, RIM technology is often out of the selection space, even in applications where RIM could be the best option, because the decision maker does not have enough information or is unaware of the technology. By choosing the wrong material and technology, the customer is losing value (because the product is less competitive) and the RIM user is also losing value (because is losing business opportunities).

Clearly, there is the need for these two roles to engage in collaborative activities in the PD process that add value due to the complementarities of skills and know-how. These activities may be intangible, provided that those involved believe they are giving as much value as what they are receiving. Or may be contracted, thus becoming tangible. The bottom line is that the RIM user needs to be involved in the development process of the product in order to increase sales and market share (see Section 2.1.3).

The former conclusion is an important argument to justify the focus of this thesis on the analysis of the PD process and the interest of including in the analysis the actions of the different roles involved in the process.

The next section will present a synthesis of the findings related with the three RIM companies visited by the researcher.

5.1.3 RIM Users

The RIM process, including design and manufacture, was studied in three different industrial environments. Differences and commonalities were identified and conclusions were made as to the positive and negative attributes of RIM (Figure 5.3); the qualitative positioning of RIM when compared to the competing processes; RIM applications; and the process flow (Figure 5.4).

The companies visited have different characteristics both in terms of size and operations. Armstrong Mold is not exclusively dedicated to RIM, the metal casting business represents 70% of the sales, from the around 200 total employees 30 are allocated to RIM operation. RIM Manufacturing is a smaller company, with less than 30 employees, specialized in the production of custom PU parts using RIM technology. RIMSYS is a start-up, with less than 10 employees, taking the first steps in a promising business with fast growing perspectives. The first business deal was very important, ensuring a long term supply of PDCPD parts RIM manufactured to a vehicle producer, providing financial and operational stability to support the company. The mission of RIMSYS is to become a reference in RIM processing of DCPD for the production of any type of part, especially enclosures and body panels.

Nevertheless, in the three companies we observed similarities concerning the practical advantages and disadvantages of the RIM process. These will be explained in the next paragraphs.

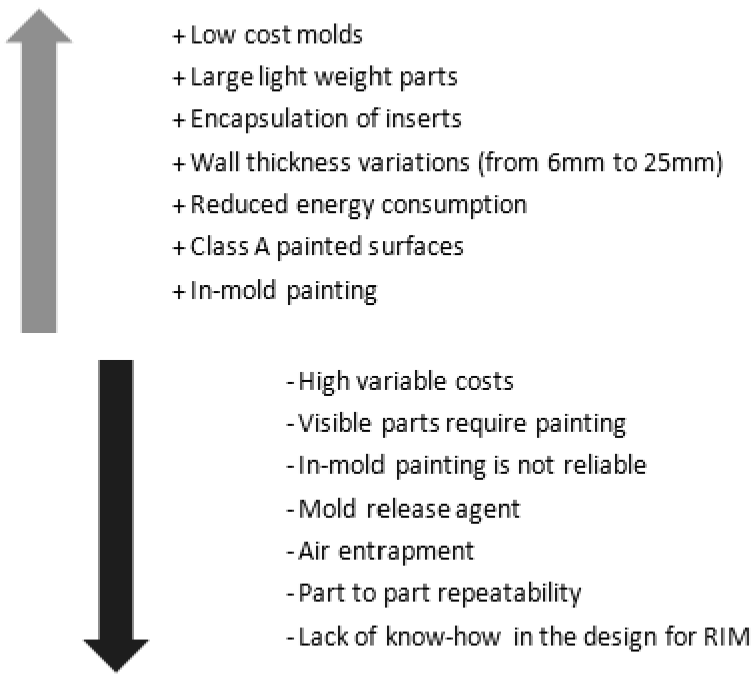

Figure 5.3 Positive and negative attributes of RIM process

As for the qualitative advantages of RIM, they will be explained next. An important attribute of this technology is that the low viscosities of the liquids that are injected in the mold result in low injection pressures to fill the part. Therefore, we can use low cost molds because the stresses that the mold has to support are very low. This same attribute of the liquids enables them to fill molds for very large parts.

As the monomers are supplied in the liquid state, there is no need to apply heat to the system. The low processing temperatures together with the low internal molding pressures enables the encapsulation of inserts, including sensitive components like electrical and electronic systems.

The low internal molding pressures and the reactive nature of the process also enable the production of parts with significant wall thickness variations (from 6mm to 25mm).

Depending on the specific formulation, it is possible to achieve thicknesses as thin as 3mm and thicker than 25mm.

Compared with the processes to manufacture TP parts, RIM consumes less energy because it requires low temperatures and low pressures.

Depending on the mold material, the surface finish of the parts enables Class A painted surfaces. Moreover, it is possible to apply in-mold painting during the injection.

RIM also has qualitative disadvantages. A very important one is that the low viscosity of the monomers causes the unavoidable appearance of flash in the parting line of the mold. Resulting in high variable costs due to post injection operations required to remove flash and finish the part. Post processing is between 20 to 40% of the total cost of the part. An increase in the complexity of the part increases injection problems (plastic leakage in the parting line, air entrapments, deformations, etc.).

Moreover, because it is not feasible to add colorants to the monomers (except black) and, especially, because the part can come out of the mold with some defects, like air bubbles, visible parts require repairing, cleaning and painting. In-mold painting could be a good solution for this problem, however it is not reliable.

The high adherence of the resulting plastic to the mold requires the application of release agent in every injection cycle, especially in PU systems and complex parts, otherwise the part will stick to the mold. This procedure is not required in DCPD systems. This is another important reason to clean the part. If the part is to be painted, it is necessary to remove the demolding agent sprayed in the mold that passes to the skin of the part.

It is common to occur air entrapment in the part because of the low viscosity of the monomers. As mentioned above, the air entrapment requires additional operations to finish the part and, if the part is visible with aesthetic requirements, to paint the part.

A final practical problem is the part-to-part repeatability of the mixing ratio. This problem is influenced by environmental factors such as humidity level and room temperature and also by the RIM system being used. There are systems that can support considerable variations in mixing ratio; there are other systems that are very sensitive to this parameter jeopardizing the quality of the part.

An important issue these companies face is the general lack of know-how of the potential customers to design parts suitable for RIM manufacture. Inappropriate part design creates many manufacturability issues. This problem was already identified in the preceding section. This underlines the importance of DFM and the advantages of stakeholders' early involvement in concept development.

There is no commercial software available for the simulation of the RIM injection process (equivalent to Moldflow for TPs). This tool would be very useful in the design of the part and the mold because the design decisions would be based on more accurate predictions.

The experience of the two US companies is that if the production volume is more than 5.000 parts per year, RIM may not be competitive and the selection usually goes to low-pressure structural foam molding or TP injection molding.

These companies already had production volumes of 1 part to 20.000 parts per year. The average and most common production volumes are between 100 and 1.000 parts per year. Likewise, the production lifetime can go from 1 single part to 15 years of production of the same part. In average, the production lifetime is 5 years.

The parts produced by these companies are integrated in their customers' products with a broad range of applications, such as medical equipment parts, automotive and truck parts, and agricultural, construction and utility machinery parts. These applications are in accordance with the general trend of the market, as explained in the literary review.

RIMSYS is exclusively producing DCPD exterior panels for the automotive industry. Armstrong Mold works for several industries, the most important one being the medical devices manufacturers, followed by the electrical and telecommunications equipment. RIM Manufacturing has a wide variety of customers in several markets, including medical devices, automotive, industrial equipment, and others.

Other technologies are in the market competing with RIM for the same applications. The most relevant ones are sheet metal, thermoforming, low pressure structural foam molding, TP injection molding, RTM, SMC/BMC, LFT, CSM and rotational molding. Customers may also select machining, if they are just making one part.

The process flow observed in these companies for the production and delivery of the RIM parts is depicted in Figure 5.4. The activities that are always performed by the RIM companies are inside the grey area. They include the manufacture of the plastic parts, the assembly of the parts (if contracted with the customer), quality checks and packaging. The assembly operation usually involves several RIM parts produced by the company and may include other parts supplied by the customer or by external suppliers.

Some companies also have the capability to design and manufacture the RIM mold, which is the case of Armstrong Mold. RIMSYS and RIM Manufacturing do not have this capability but are highly involved in the design process of the RIM mold because most of the mold shops do not have experience in the production of molds for RIM. If the RIM users leave the decisions to the mold shops, the molds are designed based on the experience of TP injection, resulting in an unnecessary increase in cost.

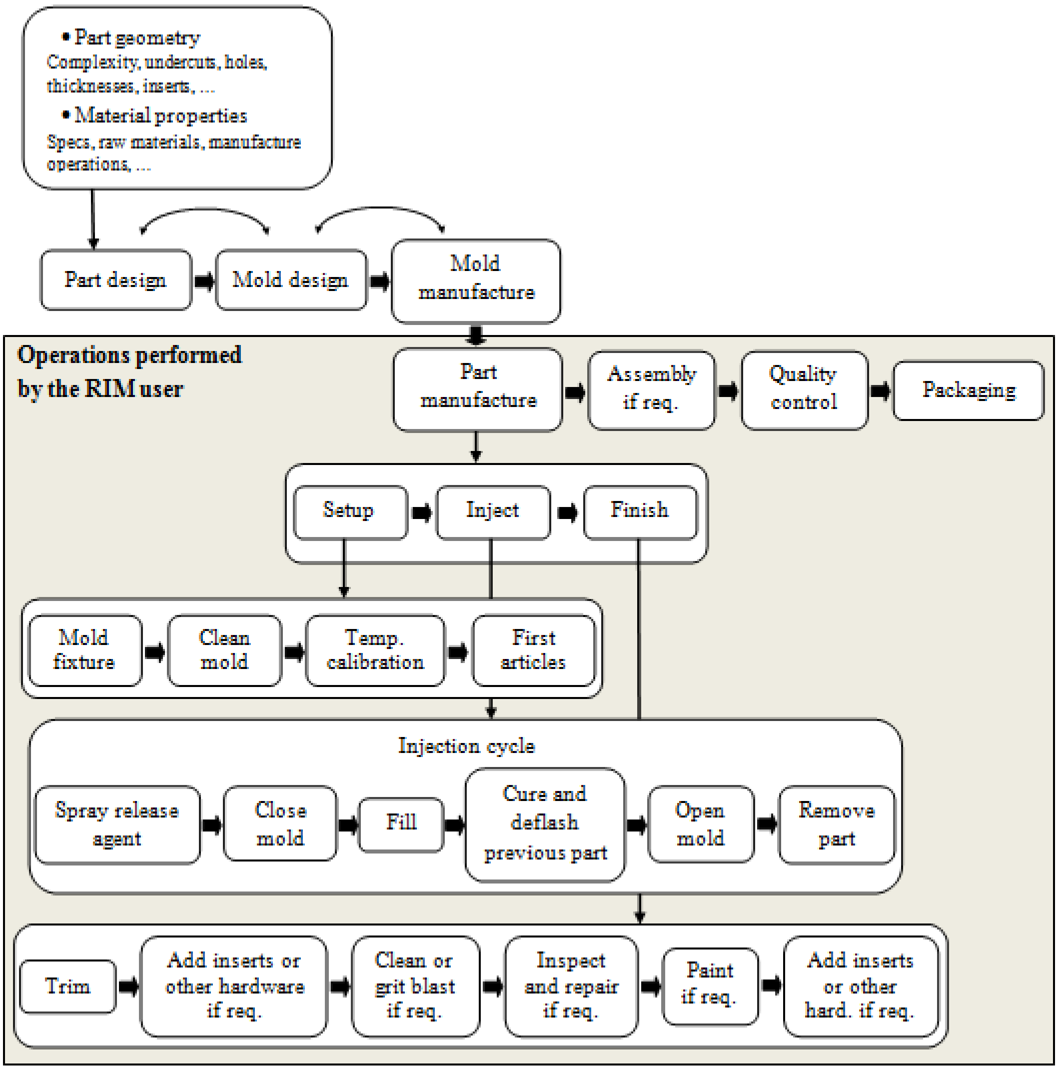

Figure 5.4 RIM process flow

An important issue in mold design that greatly influences its cost is the mold material. Unlike TP injection where steel (or aluminum for a tool life of less than 100.000 parts) molds are a must, in RIM several possibilities can be considered depending on the tool life required. Table 5.1 exemplifies the tooling options these companies consider in each project. The selection of the mold material depends on the complexity and size of the part and the number of parts the customer needs. Naturally the mold material influences the quality of the produced part. However, the finishing operations can successfully convert a poor quality part in a high quality part. Of course, better injected parts require less finishing, thus minimizing the post-injection costs.

In the development phase of the final product, a decision is made to use a RIM manufacturable material in a particular part or in a set of parts. Afterwards, the development team designs the part, together with the rest of the product, generally with no involvement of the RIM user. Thus, frequently rework in the part design is necessary to facilitate mold and part manufacture.

Table 5.1 RIM tooling options

Mold material	Part size and complexity	Maximum nr. of parts	Cost ($)
Silicone rubber	Small	<1500	<10.000
Cast epoxy	Small	<3500	<20.000
Cut Ren shape	Small	<3500	<20.000
Cast aluminum or Kirksite (zinc-aluminum alloy)	Small to big – Deep geometry	>50.000	5.000 – 35.000
Cut aluminum	Small to big	>150.000	6.000 – 70.000

The part manufacture is divided in three steps: setup, injection and finish. Setup involves the fixation of the mold in the clamping unit, cleaning the mold, calibrating the temperature of the mold and the temperature of the monomers and finally injecting the first articles until the quality of the part is at the expected level.

Then, the actual part production begins, which is basically the injection cycle. If processing a PU system release agent is sprayed, the mold is closed and the monomers are mixed and injected in the mold by the mixing head. After that, the curing starts involving the exothermic reaction of the monomers and subsequent solidification, forming the plastic part. Curing is the lengthiest stage of the injection cycle, representing between 30 and 70% of the cycle time. During this stage the operator deflashes the part injected previously. Finally, the mold is opened and the part is removed.

Finishing involves all the operations required to put the injected part in accordance with the customer's quality and functional requirements. It includes trimming, adding inserts or other hardware, cleaning, inspecting and repairing the part. Finally the part is painted, if contracted with the customer. Sometimes it is necessary to add hardware after painting.

The average reject rate in the studied companies is between 3 and 5%. As mentioned previously, part complexity increases reject rate. Most of the rejects are in the beginning of production (first parts) due to the manual adjustment of mixing parameters.

These companies only use RIM systems. Armstrong Mold and RIM Manufacturing only use PU system, mainly Bayer systems. RIMSYS only use DCPD systems provided by Telene. None of these companies formulate their own systems. Nevertheless, there are competing companies operating in the market that buy the monomers and additives and formulate their own proprietary systems. Generally, the prices of the systems go from 3,3€/Kg ($2/lb) to 6€/Kg ($3,6/lb). The very low-density systems go up to 16,7€/Kg ($10/lb).

The raw material weight required to produce a part is the part weight plus the material required for the runner, gate and flash, which is between 0,5 and 1 Kg (1-2 lb). The average scrap rate is 5% and depends on the dispensing machine being used. The scrap and the rejected parts are discarded and have no commercial value because the materials are thermosets, thus cannot be reprocessed.

The main conclusions of this stage of the research are the following:

- RIM is mostly applied in PD, prototyping and low to medium volume production;
- In markets like automotive and medical equipment;
- Where time-to-market is highly valued.

In this study we were able to acknowledge that for the production of a RIM part, the part design features are usually the dominant factor in mold design, while the mold design characteristics, in turn, dominate the process plans of mold manufacture and molding operation. As a result, most of the costs of mold-making and molding operation, as well as the quality and reliability of molds and moldings are determined in the development stage of the product that the new RIM part belongs. Therefore, there is a need for a verified design that will provide the necessary insight into metrics such as development lead time and manufacturing costs to deal with the decisions required in early stage design in order to reduce the subsequent redesigns and reworks. Based on the characterization of the industrial practice of RIM, we believe the concurrent concept development is the most suitable approach (see Section 2.1.3).

However, the concurrent development of RIM parts involves a substantial practical knowledge component (heuristic knowledge) of the relationship between part features, mold design requirements, mold-making process characteristics and the selection of production molding parameters. The designs and process plans involved are predominantly based on the experience of designers. The processes rely heavily on engineers to define their designs in detail. Extensive mathematical analysis is often not used, as analytical models with sufficient accuracy and efficiency are not available. Calculations are limited to empirical rules. Hence, the designers of parts and molds are required to have a high standard of specific knowledge and judgment. Moreover, most decisions concerning the details of the design demand knowledge regarding the mutual influences between the various quantities. Changing one quantity in order to achieve better results, for example part design features, may have a negative effect on other influencing factors, for example the mold design and mold-making process. This implies that knowledge and expertise of more than one specific area are required to have an optimum solution. The inherent complexity and intensive knowledge requirements of this concurrent development problem are crucial aspects to consider.

In synthesis, the PD process is the key for material and technology selection. If performed with proper levels of knowledge and concurrency the development team will select the optimum solution that, under certain conditions, may be PU or DCPD processed with RIM technology (see Section 2.3).

RIM users alone have no capacity to influence the decisions of the PD team, as demonstrated in the last section. The development process is what needs to be improved so that the best choices are made, and thus the RIM users are *protected* by the process, because it is also of the interest of the development team to make the best choices (i.e. meet performance requirements at the lowest possible cost).

The next section will present the findings of the two PD projects studied. One project is from CEIIA and the other project is from Bosch Termotecnologia.

5.2 Case Studies

5.2.1 The CEIIA Case Study

CEIIA typically works on PD projects. These projects can be extremely diversified, ranging from particular PD activities (like styling, CAD modeling, CAE analysis, reverse engineering and prototyping), to a complete PD service. Thus, the “project” is CEIIA’s unit of work (UOW). Each project that CEIIA is working on is a case or instance of the UOW “project”. The work performed to take care of each case of the UOW is a case process (CP), which follows a standard set of activities (depending on the type of project).

In PD projects, the work is performed following the process described in Figure 5.5. This diagram is a generic view of the process intended to illustrate the most important activities performed and the terminology used in CEIIA. Note that CEIIA does not have a formal prescriptive representation of the PD process, this diagram was developed by the researcher to facilitate communication. The activities are chunked into three phases: Concept, Feasibility[10] and Detail Design.

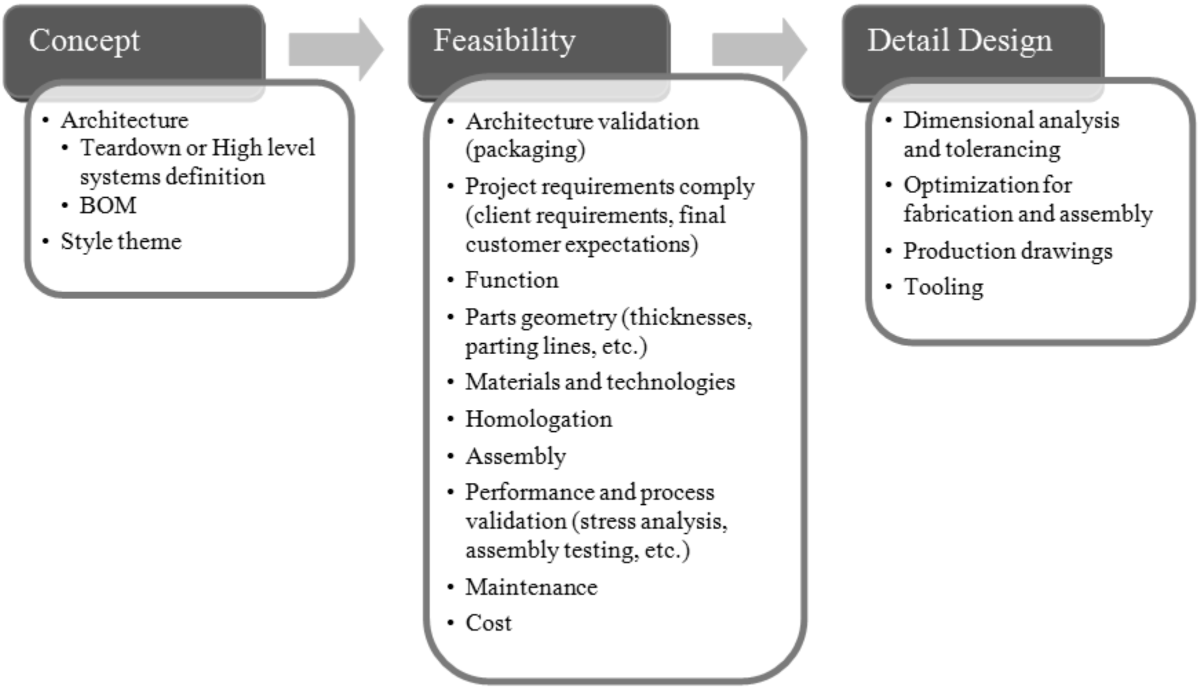

Figure 5.5 Generic product development process at CEIIA[11]

Besides a list of phases and activities, not much information can be taken from Figure 5.5. A process model must show the coherence of actions and interactions carried out and the roles that perform or participate in them. The modeling framework adopted is based on the Riva method which uses the Role Activity Diagram (RAD) to describe an individual process (Ould 2005), as explained in Chapter 4.

[10] Feasibility: part design with concept validation in relation to function, materials, manufacturing processes, assembly, maintenance, cost, perceived quality and other relevant aspects to the part.
[11] BOM (Bill of Materials): components list that is the basis for design, purchase and manufacturing processes control. It can be an excel sheet or come from a data base. The components are allocated to functional group (e.g. chassis, powertrain, exterior body, etc.) and identified with a part number. The basic properties of each part are controlled with this list (e.g. quantity, weight, material, supplier, general dimensions, versions, etc.).
Packaging: activity across the entire project in which it is defined the space occupied by each component. Generally follows a three-stage definition. The first definition is estimated with an interval of about 20mm from the final expected dimension and can be a simple geometric representation. In the final stage it has the necessary detail for the exact representation of the part.
Teardown: decomposition of the reference vehicle or concept in all its components (listed in BOM format), allocation to functional group (e.g. chassis, powertrain, exterior body, etc.). Includes images to facilitate understanding. Basic properties like quantity, weight, material and supplier are included. It is also signalized if the component is carryover or tailored for the vehicle.

The process under study is a case process that deals with one case of a complete PD project. Name of the process:

- Handle a product development project: the Buddy case study.

This case process was activated or triggered by the Business Development Director after acceptance of the proposal by the Customer (which was Elbil Norge, the manufacturer of the vehicle).

The goals of the process are the deliverables contracted with the Customer:

- Complete project dossier including 3D models (engineering deliverable);
- Ten prototype vehicles;
- Production tools (molds) for series production of exterior and interior parts;
- Production certificate issued by the homologation entity.

Roles involved in the process:

- Business Development Director;
- Project Manager;
- Prototype and Pre-series Manager;
- Engineering Design Manager;
- Engineering Team: 5 people, 1 team leader;
- Style Team: 4 people, 1 team leader;
- Quality Department;
- Customer (Program Manager);
- Telene (DCPD supplier).

The RAD for the process “Handle a product development project: the Buddy case study” is depicted in Figure 5.6. The same model is depicted in Appendix 2 in A3 format for better visualization. The pages after the model are dedicated to the textual narrative of the process, as a means to obtain a detailed understanding of the process.

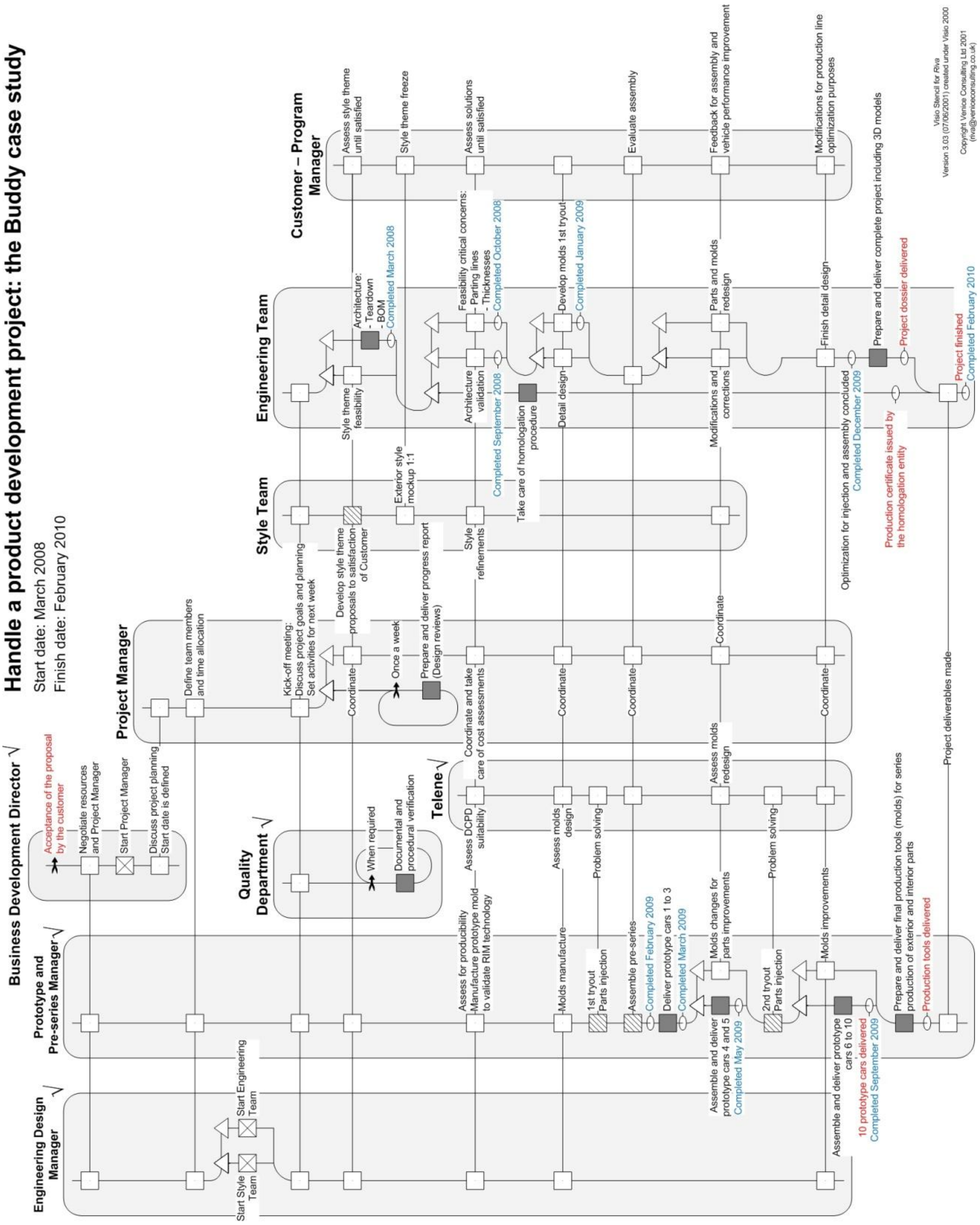

Figure 5.6 Handle a product development project: the Buddy case study

Textual narrative

After triggering the Buddy project, the Business Development Director negotiated the necessary resources to perform the project with the Prototype and Pre-series Manager and the Engineering Design Manager. This negotiation was focused on assessing the staffing requirements to attain the deliverables and lead time contracted with the Customer, thus incorporating this project in CEIIA's active portfolio of projects. The Project Manager was also selected. There was no planning nor were activities scheduled, because CEIIA does not follow a pre-determined process flow. Rather, milestones are defined to ensure focus but it is up to the team to decide what to do to accomplish those milestones.

Having completed the negotiation, the Business Development Director nominated the Project Manager, who became the primarily responsible for the project. The start date for initiating the activities was defined and a plan of the project identifying and scheduling the milestones was discussed. These milestones are, in essence, the deadlines for style theme freeze, for architecture validation, to finish feasibility, to finish detail design and to deliver the prototype vehicles.

With the information at hand, the Project Manager defined, together with the functional managers, the team members and the time allocation for the project. Given the complexity of the project, two teams were started (the Style Team with 4 members, and the Engineering Team with 5 members) by the Engineering Design Manager.

On the start date, a Kick-off meeting was promoted by the Project Manager to discuss the project goals and to determine the activities for the following week. This meeting was attended by all the internal roles involved in the project. This meeting initiates the actual PD activities, in the sense that everything done up to the meeting can be considered as planning activities. After this, and till the end of the project, the Project Manager coordinates and prepares weekly assessment and planning reports (Design reviews).

The model shows a lot of concurrency and collaboration throughout the process, especially after the Kick-off meeting[12]. During the life cycle of the project, one confidential design room was allocated exclusively to the project, so everyone involved was working in the same room. To perform the activity management required in the project, CEIIA used Excel

[12] Kick-off meeting: all roles involved in the project are at this meeting to have a common and clear understanding about the background of the project, its goals, deliverables, and so on, as well as the functions and responsibilities of each.

spreadsheets, PowerPoint presentation software, Catia 3D CAD software, MSC CAE software, and so on.

The activities performed in the concept development stage concerned the style theme definition and, in parallel, the architecture definition. The Engineering Team performed the latter and the Style Team, with deep involvement of the remaining roles, performed the former. The Engineering Team assessed feasibility of the different style theme proposals developed by the Style Team. The Project Manager coordinated this interaction and the functional managers followed the work progress. It was at this stage that the Customer was included in the PDP, with the responsibility of assessing the style theme proposals until satisfied. Thus, as everyone was involved in this interaction, the project could only move on after a style theme proposal was accepted by the Customer.

Afterwards, the Style Team constructed the exterior style mockup using a 1:1 scale for Customer validation. Changes were made in the mockup until the Customer decided to freeze the style theme. Note that the Customer had a representative (Program Manager) in the design room almost permanently during the Concept and Feasibility stages.

In parallel, the Engineering Team started three concurrent threads of activity, which mark the beginning of the Feasibility stage. They immediately started the homologation procedures that involved work till the end of the project. The other two threads started only after the style theme froze, because they involved interaction with the Style Team and the Customer, as well as the other roles. It is at this stage that Telene started its involvement in the project. In this major phase of the process, the Engineering Team validated the architecture and performed all the engineering work referred in Feasibility (see Figure 5.5) with the collaboration of many roles: the Project Manager coordinated the interaction and performed cost assessments; the Style Team was responsible for style refinements; the Prototype and Pre-series Manager assessed the producibility of the components that are not carryovers and, more specifically, manufactured the prototype mold to validate RIM technology; Telene assessed DCPD suitability for the body of the vehicle; and the Customer assessed the different solutions until satisfied.

The most relevant and difficult decision points occurred in the Concept development stage and in the Feasibility stage. These decisions were made by the Customer but with deep involvement from the other roles, namely during the assessment of the style theme proposals and during the assessment of engineering solutions.

The first decision was whether to select a unibody or an assembly solution (multi-parts body) for the skin of the vehicle. The previous version of the Buddy was based on a unibody solution produced in fiber-glass reinforced polyester (GRP). This solution is suitable for very low production volumes because tooling investment is small but requires high labor costs. As the production rate was expected to increase, preference was given to a solution based on the assembly of panels. However, the final decision was made together with the technology and material selection, already in the Feasibility stage.

The second one involved the selection of technologies and materials for the body of the vehicle and some of the larger interior components (like the vehicle seat). This selection was based on 3 criteria: functional performance (requirements fulfillment, being vehicle weight the most important one), unit cost estimation, feasibility. The criteria were analyzed for an expected production volume between 500 and 1.000 vehicles per year. In fact, the Customer was estimating a production volume of 500 vehicles for the first year and 1.000 vehicles for the second year.

Several possibilities were studied, the most important ones being: GRP unibody (previous version), GRP panels, thermoformed ABS panels or DCPD-RIM panels. The production volumes do not justify the utilization of conventional automotive technologies (like stamped steel or TP injection), due to the high cost of tooling.

In terms of performance, DCPD-RIM was clearly better than all the others: more design freedom, better repeatability, class A surface quality, very good mechanical, thermal, chemical and environmental behavior.

DCPD-RIM is very cost competitive for production rates of 500 up to 25.000 units per year and for the production of large parts or panels. Cost estimation was made for DCPD-RIM and compared with the solution implemented in the previous version of the vehicle. The cost benefit was clear to the Customer.

However, there was a critical issue to address: the minimum thickness allowed by Telene to guarantee the production and performance of the panels was 5mm, which would result in exceeding the weight requirement of 400Kg. The vehicle has to be homologated under the type L7e EC directives. These regulations impose a fundamental requirement: the empty weight of the vehicle without batteries shall not exceed 400 kg.

Usually the customer/producer specifications include the technologies and materials to use. This confirms the theory that producer conservativeness is one of the factors responsible for the poor adoption of new materials and technologies in products (see Section 2.3).

Everyone had the perception that there was a big risk involved in these decisions. No one in the team, except Telene, had experience in RIM technology and DCPD material. There was no previous experience in the application of RIM in all the exterior body of a vehicle, and no experience at all in the application of RIM in this type of vehicle. Moreover, the minimum part thickness specified by the DCPD supplier (Telene) was 5mm which would not fulfill the requirement of vehicle weight below 400 kg. To achieve this requirement the thickness of all the panels should be reduced to 3mm. We should note that GRP requires only 2-2,5mm thickness and thermoformed ABS 2-4mm thickness. In fact, the contingency plan was to keep the previous solution, the Customer already had experience with GRP and knew that, despite the inconveniences (poor repeatability, lack of design freedom and so on), the solution would work. However, despite all the risk and uncertainty, DCPD-RIM was selected, as it was considered the best option.

Postponement was clearly used because the decision was delayed as much as possible without compromising the deadline. This strategy (note that this strategy was adopted unconsciously, as a defensive approach to solve the problem, it was not a formal procedure) gave the team time to gather more information in order to reduce uncertainty. It was possible to study the production process, to benchmark examples of applications and to manufacture a prototype part (which involved the production of the mold and the injection of the part) to validate the decision.

The part selected was the bonnet, which is the smallest exterior panel, in order to minimize the cost and lead time of the prototype. The reduced dimensions of the part allowed for the machining of the mold components to be done internally at CEIIA, resulting in better control of operations and deadlines. It also allowed a reduced cost of materials for the mold. Another important reason for the selection of the bonnet was the fact that it was the flattest panel, thus one of the most critical for assessing shape stability.

The prototype mold was fabricated in PU with aluminum powder, as the intention was exclusively to validate the technology. This mold did not move to series production.

In synthesis, the factors that contributed to the decision are depicted in Table 5.2. After proving with the prototype part that 3mm thickness would be feasible, all relevant factors were balancing the decision to DCPD-RIM. Moreover, it was decided that the molds required for injecting the parts for the ten prototype cars that are part of the deliverables of the project would move to series production. This decision resulted in a reduction of cost as it was not necessary to manufacture prototype and series production molds. For each part, the same mold was used for prototype production and for series production. The material used in the molds was aluminum, which is the best choice for longer production runs. It also resulted in the reduction of development time because it was not necessary to design and manufacture two sets of molds (one for prototype production and another for series production).

Table 5.2 Factors that determined the selection of DCPD-RIM

Unibody (GRP)	Multi-parts body (DCPD-RIM)
+ Assembly: Reduced number of couplings Fast assembly cycle time	+ Assembly: Good coupling strategy to the chassis Good coupling strategy between parts
+ Style: Acceptable perceived quality due to inexistence of gaps related to thermal expansion	+ Style: Similarity to an automobile Constant gap between parts
	+ Logistics: Smaller parts Fast parts production cycle time
	+ RIM technology: Thickness control Fixation bosses embedded in the part

The project moved on to the Detail Design stage. At this stage, the Engineering Team started detailing the different subsystems of the vehicle and, regarding the DCPD-RIM panels, developed the molds for the first tryout. These activities were performed with the support of Telene, that assessed the design of the molds, and the Prototype and Pre-series Manager, who managed the manufacture of the molds. This interaction was coordinated by the Project Manager and also involved the participation of the Engineering Design Manager and the Customer.

The first tryout of the molds was performed by the Prototype and Pre-series Manager with the support of Telene. Immediately after, the first vehicles were assembled with the participation of several roles. The Customer evaluated the assembly, gaining new knowledge about problems that were not foreseen and which could endanger the series production of the vehicle. The first three prototype vehicles were delivered to the Customer for marketing purposes and also for performance testing.

The next interaction involved, once again, most of the roles. Based on the previous activities, the Customer gave feedback for assembly and vehicle performance improvement; the Engineering Team performed the required modifications and corrections in the vehicle design and simultaneously redesigned the DCPD-RIM parts and molds. Telene assessed the molds redesigns and the Prototype and Pre-series Manager implemented the changes in the molds for parts improvements, simultaneously assembled and delivered the fourth and fifth prototype vehicles.

After the first tryout it was necessary to implement improvements and corrections in the molds. Some part geometries, due to the complexity of the forms (created by the need to minimize the number of components and the total weight of the vehicle), had to be reworked to permit demolding according to the manufacturing requirements of series production. Another recurring rework was the control of air bubbles, which normally affect the total filling of the fixation bosses. Finally, there were changes derived from the evolution of engineering, improvements implemented after problems detected in the prototype vehicles. All these reworks are typical in mold manufacture for the automotive industry. No unexpected problems arose, thus we can conclude that mold development went much better than expected.

Having completed all the modifications and corrections, Telene supported a second tryout, where the parts were injected in the updated molds. These parts were used in the assembly of four more vehicles, which were then delivered to the Customer. Concurrently, the Customer proposed modifications in the project for optimization of the production line; the Engineering Team finished the Detail Design taking into account the Customer's proposals; and the Prototype and Pre-series Manager implemented the improvements developed by the Engineering Team into the molds.

After this interaction, the Engineering Team concluded the optimization for injection and assembly and the Prototype and Pre-series Manager delivered the ten prototype vehicles. Finally, the Engineering Team prepared and delivered the complete project, including 3D models. The Prototype and Pre-series Manager prepared and delivered the final production tools (molds) for series production of the exterior and interior DCPD-RIM parts. The conclusion of these two actions results in the end of the project, as all project deliverables were made.

Looking at the model, there is no doubt that CE approach was the method adopted in this PD process. Since the very beginning all relevant stakeholders were deeply involved in the process, namely the Customer and the DCPD supplier (Telene). Also, the downstream processes related to the vehicle's life cycle were considered in the early design stages. Feasibility basically aggregates all the design activities that are commonly performed in a sequential fashion. This gives the team flexibility to develop solutions for each subsystem of the vehicle at different paces and to perform as much iteration as necessary to achieve the best possible solutions. CEIIA choose not to adopt a formal prescriptive method for PD that would require heavy planning and consequently a more rigid process, which would not fit in the innovative projects they are involved in (this is consistent with Brown and Eisenhardt findings explained in Section 2.1.4). Rather they have a flexible PD process based on experimentation to gather new information, vital for succeeding in these highly uncertain projects.

5.2.2 The Bosch Termotecnologia Case Study

The Engineering Department of Bosch Termotecnologia typically works around PD projects. Thus, the "project" is the unit of work (UOW) of the Engineering Department. Each project that Bosch is working on is one case or instance of the UOW "project". The work performed to take care of each case of the UOW is a case process (CP), which follows a standard set of activities.

In PD projects, the work is performed following the process described in Figure 5.7, designated as the Time-to-Market Process. This diagram is a generic view of the process intended to illustrate the most important activities performed and the terminology used in Bosch. The activities are chunked into five phases: Product Creation Phase (PCP) Preparation; Concept Phase; Development Phase; Product Realization (Industrialization) Phase; and Zero Series Production and Ramp up. Each phase pursues a milestone that involves a quality gate assessment, respectively: Project Release; Project Confirmation; Technical Design Release; Zero Series (Production Process) Release; and Delivery Release.

Actually Figure 5.7 depicts seven phases, the Ramp up phase is separated from the Zero Series Production and the seventh phase is the Market Roll Out, where the development team evaluates project success. During the interviews we noticed that, in practice, the Ramp up activities are coupled with the Zero Series Production activities, and the milestones SOP (Standard Operating Procedure) release and delivery release are usually performed simultaneously after the quality gate assessment. We also verified that the Market Roll Out phase is not an actual working phase for the development team, as the members of the team disperse to other projects after the Delivery Release. This phase serves as a formal procedure to inform the members of the team whether or not the product attained the expected market and financial success.

This process, which is based on a Stage-Gate model, is mandatory for every PD project performed in Bosch. However, for new products, extensive planning of the activities that have to be performed in each phase of the process is not required. The model provides guidance at a macro level because the development team knows at the outset that there are milestones to attain; that they have to perform a quality assessment before closing each phase; that they have to produce and test at least four samples; and that they have to perform three FMEAs. In each milestone, the project is evaluated by the Project Steering Committee (PSC) and a decision is made on whether the project can continue to the next phase or has to revisit the previous phase. Ultimately, the project may be canceled in any of the milestones described above.

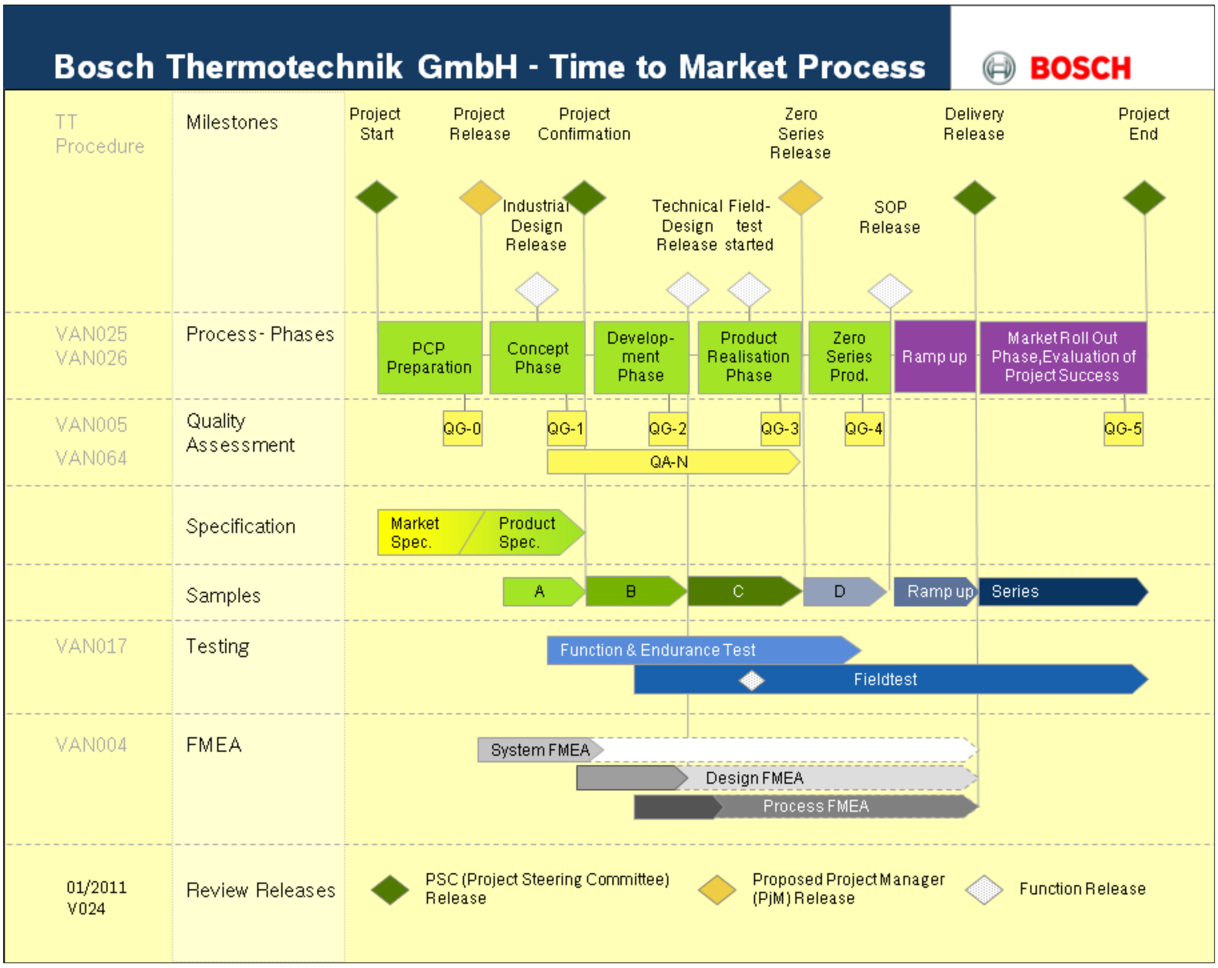

Figure 5.7 Generic product development process at Bosch Termotecnologia. Reproduced with permission from Bosch Termotecnologia. Copyright 2012 Bosch Termotecnologia.

The process under study is a case process that deals with a case of a complete PD project. Name of the process:

- Handle a product development project: the water heater case study.

This case process was activated or triggered by the PSC after the annual strategic review where one of the deliverables is the new products roadmap (a three years plan for new products introduction). The goal of the process is the series production ramp-up.

Roles involved in the process:

- Project Steering Committee (PSC);
- Project Leader;
- Product Manager – connection pivot to the Industrial Designer and the Customers;
- Development engineer;
- Process engineer;
- Purchasing engineer – connection pivot to the Suppliers;
- Quality engineer;
- Manufacturing engineer;
- Logistics expert;
- Accounting expert.

The Project Steering Committee is the management body of the company and is constituted by the President, the VP for Engineering, the VP for Manufacturing, the VP for Administration and Commercial, VP for Product Management.

The so-called Core Team is constituted by the Project Leader, Product Manager, Development engineer, Process engineer, Purchasing engineer and Quality engineer. The Project Team is the Core Team plus the Manufacturing engineer, Logistics expert and Accounting expert. All these roles represent the different functional areas of the organization and have staff working for the project under their supervision.

The RAD for the process “Handle a product development project: the water heater case study” is depicted in Figure 5.8, followed by the textual narrative of the process, once again as a means to obtain a detailed understanding of the process. The same model is depicted in Appendix 2 in A3 format for better visualization.

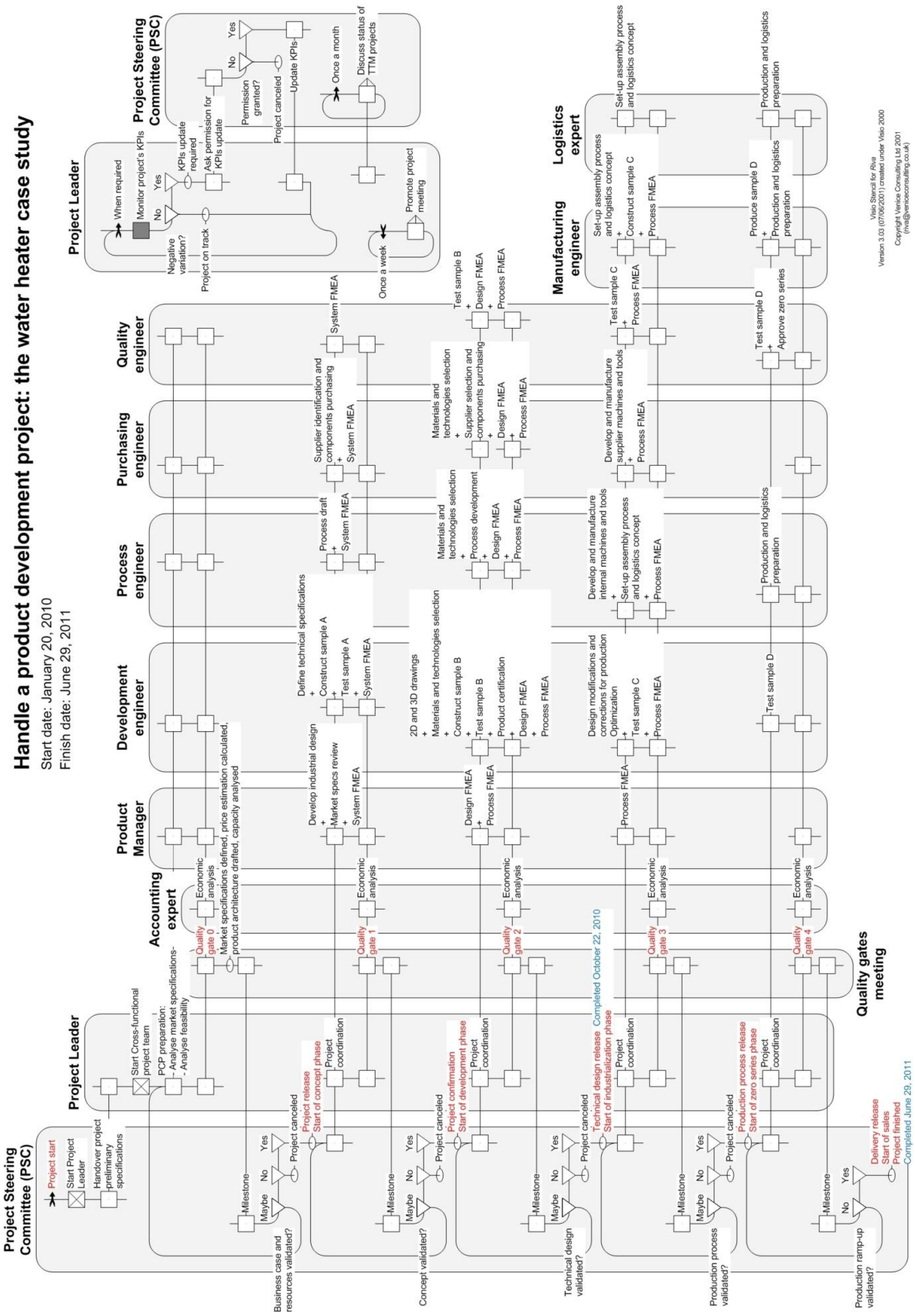

Figure 5.8 Handle a product development project: the water heater case study

Textual narrative

The project started with the appointment of the Project Leader and the release of the project preliminary specifications by the PSC. These specifications came from the new products roadmap that is a deliverable of the annual strategic review process, as referred above. They include a generic characterization of the product and the market, as well as an estimation of the project budget.

The Project Leader was responsible for the assembly of the cross-functional project team that worked together throughout the project's life cycle. The members of the Core Team were selected at this point, however the Manufacturing engineer and the Logistics expert were selected and involved in the project much later, at the industrialization phase. This reveals that the degree of downstream involvement could be bigger, if these roles were in the project team since the beginning, especially at the concept phase. Nevertheless, the Process engineer has the necessary knowledge and skills to consider the manufacturing and logistics issues in the early stages of PD. In practice, it is the Process engineer that develops the manufacturing and logistics systems that are, afterwards, materialized by the corresponding roles. During development, the Process engineer is responsible for external communication with the experts in the subject matter in order to have the necessary information to make decisions.

After the constitution of the Core Team, the PCP preparation was carried out by the Project Leader, with deep involvement of the team members. These planning activities involved several discussions related with the project's feasibility, particularly the analysis of market specifications and feasibility assessment. The Accounting expert was responsible for the economic analysis, which is performed in all the phases of the project. Finally, a Quality gates meeting (Quality gate 0) was promoted to formalize an agreement on the status and details of the project, that was then sent to the PSC for a milestone decision. This important formal meeting takes place at the end of every phase of the project to mark the point where the project freezes for a go/kill decision, a decision assumed by the PSC.

At the end of this phase the market specifications were defined, the price estimation was calculated, the product architecture was drafted and the company capacity was analyzed as well. The PSC analyzed this information that had to answer the question whether the business case and resources were validated. The project could follow three paths depending on the decision of the PSC, if the answer was "Yes" the project could proceed to the next phase, if the answer was "No" the project would be canceled and if the answer was “Maybe” the project would go back for a new iteration. As the answer was “Yes”, the PSC released the project which was then sent to the concept phase.

Bosch implements a well-defined and systematic PD process based on a set of stages and gates. In the beginning of the process a cross-functional project team is formed with representatives and experts from all the stakeholders involved in the life cycle of the product. The team does not work isolated from the outside world, in fact, each member of the team has the obligation to make the connection with his department and/or external entities. The interviewee stated:

> *“Therefore, all projects have multidisciplinary teams. Somehow ensures development in concurrent engineering with representation of the company departments and the external entities.”*

For example, the Product Manager has the responsibility to represent the Customers. Thus, he has to manage and perform the proper actions (like interviews, surveys, ethnographic studies, and others) during the project in order to ensure that the voice of the customer is properly considered in the development of the product.

The project can only start after gathering a certain amount of information, including the date to release the product in the market, the dates for the milestones (gates), project budget, production volume, product features and profitability, primary markets and commercialization trademarks.

This data is updated as new and improved information is investigated during the PCP preparation. In quality gate 0 (Project release) a formal contract is signed by Bosch Termotecnologia and the trademarks. Thus, there is a compromise assumed by the company for the cost, quality, performance, lead time and investment of the project. These are the Key Performance Indicators (KPIs) the Project Leader has to monitor during the project life cycle. Product performance is the functional specifications (power, noise, etc.). Quality is the degree of conformance with the specifications.

These KPIs can be negotiated and changed during the life cycle of the project, but the project team will be penalized for that. Any deviation from the targets negotiated and accepted by the PSC will be mentioned in the KPIs report and the project team will suffer a penalty in proportion, namely in terms of monetary bonus and the member’s individual performance evaluation. This evaluation is important for career progression and for the integration, or not, in new projects. Notice that the PSC is not evaluating the daily work and decisions performed by the project team, nor is the PSC evaluating how the work is done. Rather, the PSC is interested in monitoring the project at a macroeconomic level, particularly regarding cost, lead time and investment. Thus, the project team can perform as much iteration as they need, as long as the KPIs are not altered. The Project Leader coordinates the project and promotes weekly project meetings to enhance internal communication, verify the status of the different tasks and plan activities for the forthcoming week.

In the concept phase, the Development engineer was the driver of the process. In this phase, the members of the Core Team interact to share information and participate in the tasks required to achieve an effective product concept. The Product Manager made the connection with the Industrial Designer for the development of the industrial design and, simultaneously, reviewed the market specifications. The Development engineer was responsible for the technical specifications and for the construction and test of sample A. The Process engineer developed a draft of the process to manufacture the concept that was being developed at the same time. The Purchasing engineer was responsible for the supplier identification and for components purchasing. All the roles participated and interacted in the System FMEA. This interaction is extremely important for information sharing and to guaranty that all the roles synchronize through the harmonization of the perceptions about the reasons behind the major decisions.

The project then proceeded to the next quality gate, where the procedure was similar to the previous milestone. A Quality gates meeting (Quality gate 1) was promoted to agree on the status of the project and on the product concept. This was, then, sent to the PSC for a milestone decision. The PSC had to decide whether or not the concept was validated. Similarly to the previous decision point, the project could follow three paths depending on the decision of the PSC. The answer was “Yes”, thus the PSC confirmed the project’s continuity and the project then went on to the development phase.

In the development phase, the majority of the work was responsibility of the Development engineer, who made the 2D and 3D drawings, constructed sample B and took care of product certification. The selection of materials and technologies was performed jointly by three roles: Development engineer, Process engineer and Purchasing engineer. This demonstrates consideration of the downstream processes and suppliers’ indirect involvement. The Development engineer together with the Quality engineer tested Sample B. Simultaneously, the Process engineer developed the production process and the Purchasing engineer selected suppliers and purchasing components for the construction of sample B. Concurrently, and with the collaboration of all the roles, the Design and Process FMEA was performed.

The project then proceeded to the next quality gate, a Quality gates meeting (Quality gate 2) was promoted to agree on the status of the project and on the product details. In this milestone, the PSC had to consider whether or not the technical design was validated. Similarly to the previous decision points, the project could follow three paths depending on the decision of the PSC. The answer was "Yes", thus the PSC released the technical design and the project moved on to the industrialization phase.

In the concept phase a final selection of technologies and processes is not mandatory. The focus is on the product and its functional performance. The interviewee stated:

> *"Trying to fit in the case that brings us here, I need to say in this stage that I have here an enclosure, a housing for the product, I do not need to say at this point how it will be done. This, I would say, is very interesting because it provides complete independence between the function of the product and the processes that will be used."*

This guarantees that the solution is not pursued before defining the target thus, after defining the function, the team can search for the best possible solution. The process is heavily documented in order to force its systematic nature.

Bosch does not use a commercial project management system. Bosch uses Excel spreadsheets, Powerpoint presentation software, UG 3D CAD and CAE software, among others, as tools to perform and manage the activities required in the project. CFD (computational fluids dynamics) studies are performed by external entities. Formal rules provide the necessary guidance in the utilization of the different software (for what purpose, when, how and by whom). Bosch has a folders system associated with a systematic procedure resulting in a data-base system. The interviewee stated:

> *"We have a central folder, thus the issue of confidentiality, where all the company's projects are: TTM (Time To Market) Projects. The creation of the project automatically creates a project folder with the standardized sequence, with all deliverables and all gates"*

The most relevant and difficult decisions were the selection of the product concept and the definition of the model for the industrial process. Both decisions have great impact on lead time, initial investment and production unit cost. They constrain the future of the product in the company because they were made based on assumptions regarding production volumes and market price that, if are not met during the commercialization phase, the constructive solutions might become inadequate and the product has strong probabilities of becoming unviable.

Furthermore, this was a new product and new business for the company, which increased uncertainty and risk. The PSC was responsible for those decisions that were made after quality gate 1 and 2, respectively. However, during the concept and the development phases a lot of work is performed, mainly by the Core Team, in order to generate as much information and knowledge as possible to decrease the level of uncertainly associated with the decisions, as can be seen in the model in Figure 5.8. Throughout the project, the Project Team constructed and tested several functional prototypes (samples A, B, C and D). Product and process analysis was insured by the three FMEAs required in the Bosch PDP: System, Design, and Process FMEA. These activities, complemented by the weekly meeting to improve cross-functional communication, enhance knowledge thus reducing uncertainty and risk.

The usual procedure for PD starts with the definition of product functions (primary and secondary functions), followed by a systematic search of solutions for each function (starting with the primary functions). Thus, the budget is firstly spent on components that are related with the primary functions, the remaining budget must be enough for the other components. If the budget is not enough, a new iteration is performed and tradeoffs are made in order to comply with the budget. As many iterations as necessary are made to achieve the budget.

Concerning the selection of material and technology for the enclosure of the heating module, the expected production volumes were determinant. This was the first heat pump developed by Bosch, thus there was no previous version to rely on. The selection started with a screening of potential candidates by considering several factors, the most relevant being the following: functional requirements (like protection from the environment; thermal, noise and vibration insulation; user interface among others), industrial design, technical benchmark and knowledge of the project team and suppliers.

The final selection was based on three criteria: functional performance (requirements fulfillment); initial investment and production unit cost estimation; number of suppliers. The criteria were analyzed for an expected production volume in the order of 10.000 heat pumps per year.

Several possibilities were studied, the most important ones being: steel sheet panels, TP injected part, thermoformed panels and EPP panels (see Section 4.2). The production volumes do not justify the utilization of conventional high volume technologies (like stamped steel or TP injection), due to the high cost of tooling. RIM technology was not considered because of the project team's unfamiliarity and the inexistence of qualified suppliers with expertise in this technology. On the other hand, Bosch had qualified suppliers with experience in EPP application to exterior panels.

Cost estimation was made for the different alternatives and analyzed against the functional performance of each one.

There was a certain level of risk involved in these decisions. No one in the team had experience in EPP material. There was no previous experience in the application of EPP in the exterior body of this kind of product. Bosch's development process naturally manages this risk by building sample B during the development phase. This sample is constructed with the materials intended for the final product in order to validate that the material and geometry meet the specifications. In some cases, if the intended material was already extensively used in previous products, experience and knowledge can replace the construction of the sample.

In sum, the factors that contributed to the decision are depicted in Table 5.3. All relevant factors were balancing the decision towards EPP.

Table 5.3 Factors that determined the selection of EPP

Multi-parts body (sheet)	**Unibody (EPP)**
+ Assembly: High number of couplings Slow assembly cycle time	+ Assembly: Good coupling strategy to the tank Several parts are now merged in one
+ Style: Poor perceived quality due to existence of gaps	+ Style: Good aesthetics Constant gap between parts
	+ Logistics: Lighter parts Fast parts production cycle time
	+ EPP technology: Thickness control Fixation bosses embedded in the part

In the industrialization phase, the leading role was that of the Process engineer, who was responsible for setting-up the assembly process and logistics concept. This activity was performed in collaboration with the Manufacturing engineer and the Logistics expert. The Process engineer also developed and manufactured internal machines and tools. The Purchasing engineer involved the suppliers in the development and manufacture of the machines and tools that would most probably be purchased. Sample C was constructed by the Manufacturing engineer and tested by the Development engineer and the Quality engineer. The Development engineer was also responsible for the implementation of design modifications and corrections for production optimization. The Process FMEA that was started in the previous phase was then finalized in this phase taking in consideration the novel information collected in the meantime.

The project then proceeded to the next quality gate, a Quality gates meeting (Quality gate 3) was promoted to agree on the status of the project and on the production process. In this milestone, the PSC had to, once again, consider whether or not the production process was validated. Similarly to the previous decision points, the project could follow three paths depending on the decision of the PSC. The answer was “Yes”, thus the PSC released the production process and the project then moved on to the zero series phase.

In the zero series phase, the Process engineer together with the Manufacturing engineer and the Logistics expert were responsible for the production and logistics preparation. The Manufacturing engineer produced sample D, which was then tested by the Development engineer and the Quality engineer. The Quality engineer was also responsible for the approval of the zero series.

The project then proceeded to the next quality gate and, once again, a Quality gates meeting (Quality gate 4) was promoted to agree on the status of the project and on the production ramp-up. In this milestone, the PSC had to consider whether or not the production ramp-up was validated. In this decision point, the project could follow two paths depending on the decision of the PSC, if the answer was “Yes”, the project could proceed to the next phase and, if the answer was “No”, the project would go back for a new iteration of the zero series phase. As the answer was “Yes”, the PSC released the delivery and the project was completed, giving way to the start of sales.

5.3 Discussion

Having presented our two case studies above, we will now discuss how our empirical research may contribute to PD and process modeling theory. We begin by mapping the principles and practices implemented by CEIIA and Bosh and then compare our findings with Brown and Eisenhardt's framework. After, we explain, analyze and compare the implemented material selection process in the two case studies in order to identify the constraints that hinder the consideration of materials and technologies in the PD process of rigid parts. Finally, we discuss and analyze the modeling framework developed based on the Riva method.

Product Development Practices

As we've seen, most companies implement a company-specific PD process out of necessity, although most approaches do have a common stem, which encompasses general actions, steps or stages (Otto and Wood 2001). Therefore, although companies may work within the same business area, no PD process is the same.

CEIIA does not use any formal PD method or model, nonetheless the practices found are very much in agreement with PD theory, as we will acknowledge next. By implementing a flexible PD process (Cooper 1990), CEIIA was able to adjust to the different constraints and challenges that emerged throughout the process without jeopardizing their goals, both financially and in terms of lead time. CEIIA aggregated most of the design activities that are commonly performed in a sequential fashion into a single stage (Feasibility), providing the team with enough flexibility to develop various solutions at different paces. The activities are planned on a weekly basis however, it is the Project Manager's responsibility to keep the project on track. Figure 5.9 focuses on the part of CEIIA's model, which clearly depicts this.

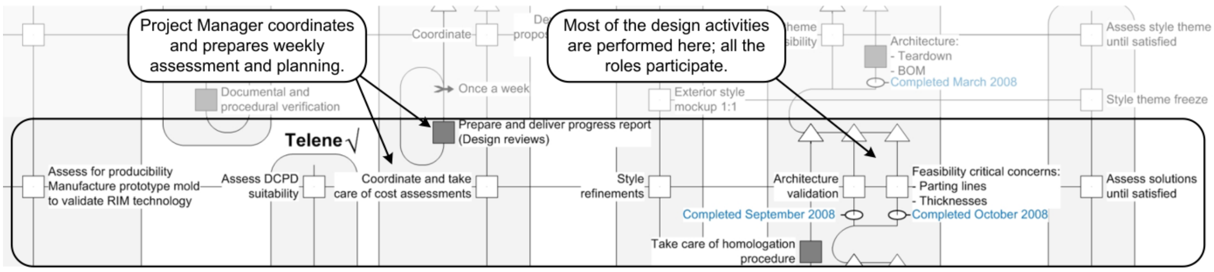

Figure 5.9 CEIIA's flexible PD process based on activities overlapping, frequent iterations, testing and short milestones

Bosch, on the other hand, follows a standardized process based on the Stage-Gate model (Cooper 1983, 1990). Its model comprises five stages and five gates, whose main purpose is to control the project, to assess quality and as "Go/Kill" check points (Cooper and Edgett 2005). The five Quality Gates Meetings formalize the gates. At each of these pre-defined moments of the project (determined at the beginning of each project), all the roles involved are obliged to participate in a meeting so as to prepare a report that is then analyzed and validated by the PSC (referred to as "Milestone" in the process model). If the PSC does not validate the report, the stage must be repeated or ultimately the project may be cancelled. This can be seen in Figure 5.10, which focuses the part of Bosch's model that represents the quality gates and the gatekeeper's go/kill decision that is carried out by the PSC.

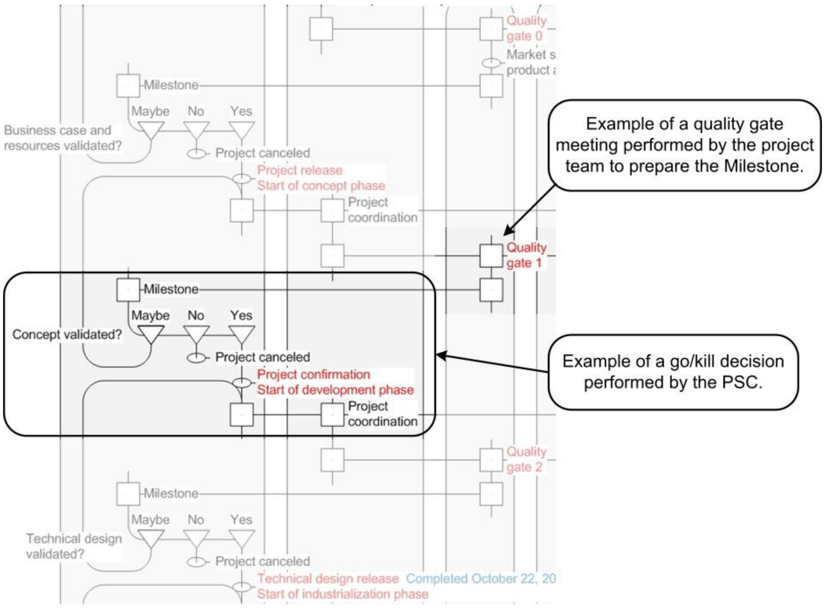

Figure 5.10 Bosch's quality gates and gatekeeper's go/kill decisions

As stated previously, although CEIIA does not use any formal PD method or model, its PDP incorporates some *best practices*, tools and routines delineated in the literature. In turn, Bosh applies a Stage-Gate model, while too incorporating *best practices* and tools for an improved PD process. Additionally, we noted CE and LPD principles and practices were applied in both projects, albeit with different models, as reiterated above.

Bosch has a well-defined PD process. Perhaps in their drive towards innovation, they perceive the implementation of systematic methods as beneficial and forge forth in the implementation of established best practices. Indeed, we can state that Bosch applies all the PD best practices detailed by Khan et al. (2012, see Section 2.1.3) except *NPD can be circumvented without management approval*. At Bosch, a project can be altered but management approval is required. Figure 5.11 depict the part of the model that indicates that any significant change must be approved by the PSC. Any change performed that negatively affects the KPIs established in the beginning of the project will also reflect negatively on the team's performance assessment.

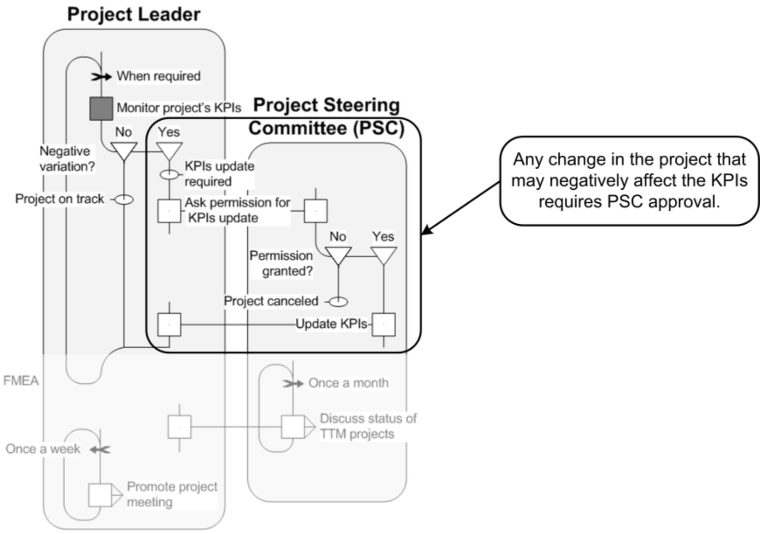

Figure 5.11 Bosch's management control of the project's KPIs

Bosch's approach is more rigid than CEIIA's. As posited in the literature, a structured process is evidently more rigid. This is evident in the clearly defined PDP stages, with established decision points. Nonetheless, we were able to confirm the use of some approaches proposed by Smith (2007) for a more flexible PD, namely:

- Front-loaded prototyping and testing techniques are an integral part of Bosch's PDP, which occurs throughout the process;
- Modular product architectures are evident in Bosch's product portfolio. They use this development strategy based on modules to foster economies of scale, resulting from the sharing of sub-assemblies between family products and to facilitate the assembly processes;

Set-based design is not implemented, as Bosch begins with a screening of the various solutions but only one moves on to Development. There is no evidence of the other approaches suggested by Smith (2007).

CEIIA is a different type of company, as mentioned in Section 3.2. Nonetheless, similar to Bosch, it too applies many of the best practices detailed by Khan et al., except the following:

- *Go/no go criteria are clear and predefined for each review gate*: At CEIIA there are no gates as can be seen in the model (see Figure 5.6).
- *The NPD process is visible and well documented*: As there is no well-defined process, the team meets weekly and defines the status and establishes the work for the upcoming week.

- *All practices within the Commercialization dimension*: CEIIA is a sub-contracted company specialized in product and process integrated development and thus, all commercialization activities pertaining to Buddy are not their responsibility, rather the responsibility lays within the company that commercializes the vehicle.

Furthermore, CEIIA's approach is concurrent with PD flexibility recommended by Smith (2007). CEIIA clearly accommodated and embraced change, as all of Smith's proposals are evident in their project, as follows:

- Modular product architectures: in line with common practice in the automotive sector, the vehicle was based on a modular architecture;
- Front-loaded prototyping and testing techniques: CEIIA endorses experimentation supported by virtual and physical prototyping;
- Set-based design to preserve options: SBCE was used, albeit unconsciously, in the development of the body of the vehicle;
- Frequent feedback from customers: the customer was deeply involved in the PDP;
- Close-knit project teams: the entire development team occupied the same room during the process;
- Collaborative decision making: as there was no formal go/kill decisive points, decisions were made throughout the process, when necessary. As explained, the client made all the major decisions, but always in collaboration with the remaining roles;
- Framing decisions and anticipating the information needed to make them: this approach was visible in the decision process regarding DCPD-RIM for the body of the vehicle;
- Rolling-wave project planning: there was no long-term planning, as plans were established on a weekly basis;

Some of these aspects, such is the case of *Development processes that maintain both quality and flexibility*, will be discussed in greater detail below, as many of the techniques, tools and approaches for change are embedded in other *best practice* perspectives as well.

Regarding CE practices, Koufteros, Vonderembse and Doll (2001) state there are three basic pillars: Concurrent workflow; Product development teams; and Early involvement of constituents. In both projects these three practices were visible.

The concurrent workflow at CEIIA is notorious, as all different roles are involved: while the Engineering Team is developing the product, the Style Team is simultaneously improving the design and the Prototype and Pre-series Manager is assessing the products' producibility and creating prototypes to validate or support decisions. At Bosch, the concurrent workflow is also present, with even more roles involved in the cross-functional team, as can be seen in the model (see Figure 5.8).

Pertaining to early involvement of the constituents, at CEIIA the customer was directly involved from the beginning of the project. At Bosch, customers were "represented" by the Product Manager (referred to as liaison roles by Swink 1998).

Besides the CE practices indicated above, we were able to verify the following methods and tools detailed by Swink (1998). In order to improve *cross-functional integration* both projects implemented meetings and used a design database and electronic communication methods. Team incentives were also present in both projects, however this was more visible at Bosch. At CEIIA, the use of collocation (a specific room assigned for the project) fostered greater cross-functional communication.

Both projects made use of functional approvals and value analysis to *improve design analysis and decision-making*. Furthermore, Bosch relied on the knowledge of its qualified suppliers throughout the project. They also implemented FMEA and design-to-cost methodology to facilitate design generation and analysis. CEIIA, on the other hand, relied on experimentation supported by virtual and physical prototyping.

When analyzing the projects from an LPD perspective, in order to identify the LPD practices implemented, we can state that the "coherent whole" advocated by Karlsson and Åhlström (1996) was not verified. Be that as it may, we observed some LPD practices in both of our case studies, although it is not feasible to talk about LPD.

Indeed, *Early supplier involvement* was a practice verified in both cases. Additionally, both projects had some type of *visual management* tool, namely CAD and Excel spreadsheets. These tools were used to manage the various activities replacing a commercial process management tool. Furthermore both CEIIA and Bosch depend on a folder system coupled with a systematic procedure to create and manage all files pertaining to the project as their *knowledge library*.

SBCE was used unconsciously in the development of the body of the vehicle at CEIIA. Several materials were considered, but the final selection was made only after validating the solution. *Standardization* is a common practice by Bosch. This is manifested in its product portfolio and architecture, which tries to maximize the economies of scale.

Finally, working with *cross-functional teams* is a generalized practice in both cases, as referred above. Also, both implement the *Chief Engineer System*. Formal coordination is the Project Manager's responsibility at CEIIA and that of the Project Leader at Bosch. At Bosch top management formally supports the PDP, which is the responsibility of the PSC. CEIIA also has management support, albeit rather informally.

Our research has also allowed us to verify that neither CEIIA nor Bosch have a formal implementation of DFSS. As such we will not consider DFSS practices and principles in our analysis as it is not applicable given that it implies formal training, certified employees (belt system) and clear company commitment in implementing DFSS philosophy (Tennant 2002).

Brown and Eisenhardt's success factors

When considering the factors that affect the success of PD projects indicated in Brown and Eisenhardt's framework (1995) specifically, our findings suggest the following:

Suppliers and customers' involvement: throughout both projects there was deep involvement including responsibility sharing and direct participation in the development tasks and decisions. In the CEIIA project, both the DCPD supplier and the customer were physically present in the design room for the activities where their involvement was needed. In the Bosch project, the Product Manager insures the liaison with the customers while the Purchasing engineer is in close contact with the suppliers. This qualitative study reinforces the mainly quantitative literature arguing that collaborative competence has a positive impact on project performance (Mishra and Shah 2009).

Team composition (cross-functional, gatekeepers and moderate tenure): looking at the PD process models we can observe that the horizontal dimension is large with many roles from different backgrounds participating in the tasks. At CEIIA, the team members (especially the style and engineering members) were a mix of moderate tenure and beginners. However, the high cross-functional composition and the deep involvement of roles, external to the organization, potentiated internal and external communication. Also, at Bosch most of the team members had already some years of experience and others were beginners. As mentioned above, at Bosch there are some roles in the project team that can be designated as gatekeepers: the Product Manager, who ensures the liaison with the customers and the Purchasing engineer, who is responsible for the liaison with the suppliers.

Team group process (internal and external communication): CEIIA's internal communication was ensured by several practices: everyone involved in the project worked in the same room; the majority of the tasks were performed through interaction (CEIIA does not have a Stage-Gate process); and responsibilities were distributed with RASIC matrices which formalizes the rule of internal communication. External communication is a natural consequence of deep supplier and costumer involvement. At Bosch, the structured process implemented potentiated internal communication. Although, it is a Stage-Gate process, all the roles of the core team have to participate in the different stages and have to meet on a weekly basis. Moreover, the reports that derive from the quality gates meetings ensure everyone participates and shares information about the status of their activities. External communication is frequent and all the members of the core team are allowed to obtain outside information during the execution of their tasks. The gatekeepers have increased responsibility in regards to external communication.

Team organization of work: the CEIIA case study shows that the problem-solving strategy adopted was based mainly on frequent iterations, testing and short milestones. Activities overlapping were also present to facilitate the iterative exploration and to maximize the utilization or resources. Weekly reviews[13] indicated the status of the project and objectives for the following weeks. The customer participated and assessed solutions in each stage of the process until satisfied. This iterative process was a constant tactic. When the level of uncertainty was too high, virtual tests or physical prototypes were produced. These experiential techniques generate information and knowledge but require time, thus decision postponement was used. At Bosch the problem-solving strategy was mainly task overlapping associated with extensive testing. These features were facilitated by the frequent iterations in order to find feasible solutions performed by the cross-functional team and by the short milestones, imposed by the PSC and the Project Leader. Despite the fact that there is a pre-established sequence of phases from concept to production ramp-up, these only represent the maturity of the project. The core team simultaneously executed the development steps, which are often performed sequentially (such as design, analysis, prototype and test - see Section 2.1.3). In each phase the product and process development tasks are performed (design); a FMEA is completed (analysis); and samples are constructed (prototype) and tested. The Quality Gates Meetings and PSC evaluations

[13] Design reviews: periodical report about the project status. Used primarily to support the meetings with the customer. Normally produced on a weekly or fortnightly basis.

are important milestones that may result in further iterations. Moreover, the weekly meeting promoted by the Project Leader may be considered a milestone, as the meetings may be used as a short-term control regarding the status of the project.

Project leader: in CEIIA's case, the model tells us that the role of Project Manager was created to coordinate the project. Although responsibilities were shared after the kick-off meeting, the Project Manager had the fundamental task of keeping the project on course. He or she was the connecting link both internally (facilitating communication and negotiating decisions within the team) and externally (mediating outside interferences and guarantying resources). Identically, in Bosch's case, the coordination of the project is centralized in the Project Leader role. He or she is responsible for planning the activities that have to be executed by the different functional departments and for managing the information exchange with the PSC. Thus, strong technical and market knowledge, proper project management and communication skills are mandatory for a successful Project Leader.

Senior management: in both cases, the analyzed projects were considered critical and with high risk, thus management was very attentive, confirming that the resources needed were there. At Bosch, the PSC performs a formal control of the project with the evaluations performed in the milestones. Also, the project's KPIs, established in the beginning of the project, are monitored. However, the project team has the autonomy to decide on the course the project should take during the execution of each phase.

Based on our discussion above, we propose that these factors, which in Brown and Eisenhardt's framework were linked exclusively to the process performance or to product effectiveness (see Section 2.1.4), should be linked to both as represented in Figure 5.12. By implementing our modeling framework (the Riva method plus the textual narrative) we were able to verify that, in practice, these seven factors affect process performance *and* product effectiveness. For instance, if CEIIA had not used cross-functional teams in the PDP, the product concept effectiveness would inevitably be affected. RIM would never have been chosen because the Engineering Team only became aware of this possibility due to the involvement of the other roles.

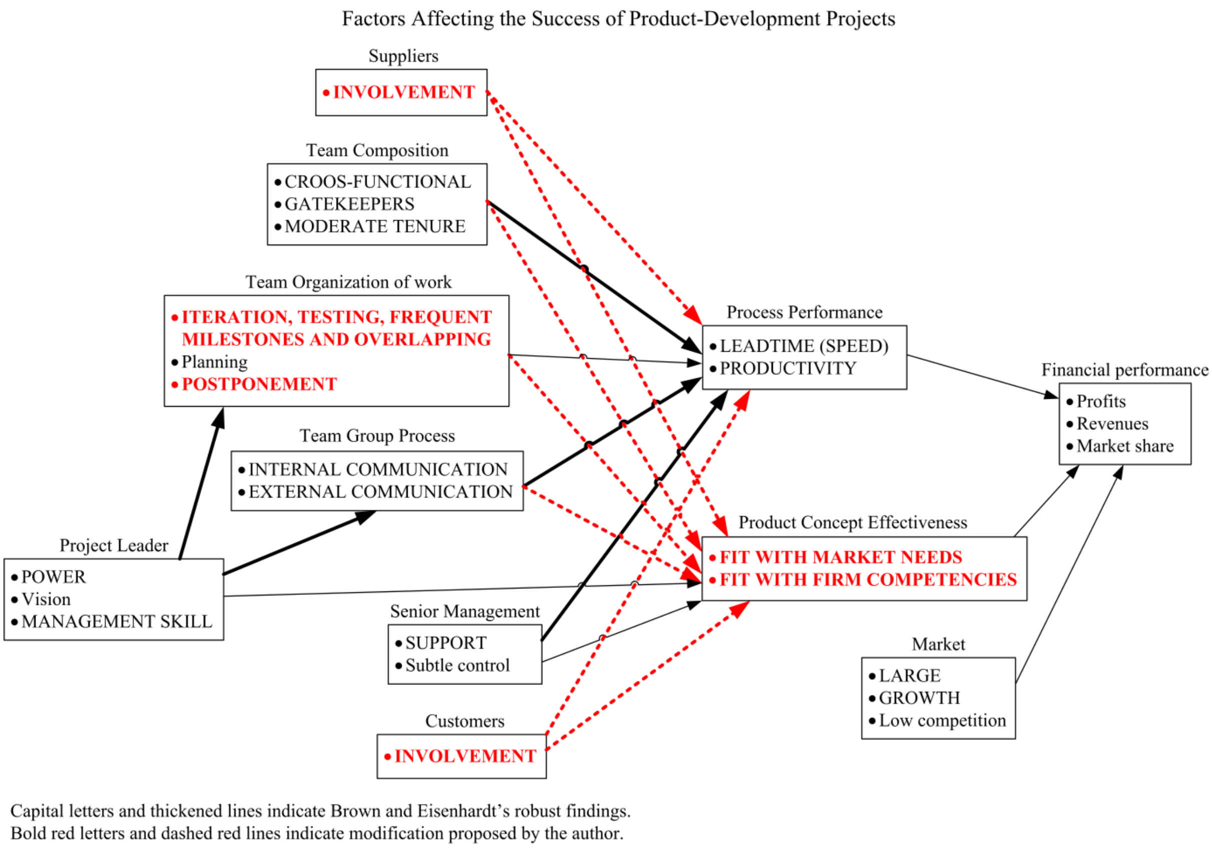

Figure 5.12 Modified Brown and Eisenhardt's framework

Materials and technology selection process

Our RIM industry analysis demonstrated that the various stakeholders in the PDP often neglect RIM technology, even where it could be the best option because the decision maker does not have sufficient information or is unaware of the technology. We then sought to understand the material and technology adoption process in these two specific case studies. In the CEIIA project RIM technology was adopted, whereas in the Bosch Termotecnologia project RIM technology was not selected.

Our modeling framework allowed us to obtain a deeper understanding of how companies manage the selection and adoption process, characterized as highly complex, uncertain and goal oriented, given the interdependencies and interactions the process relies on (Dieter 1997; Ashby 2005; Dieter and Schmidt 2009).

Neither CEIIA nor Bosch implemented a systematic procedure for material selection. Furthermore, neither CEIIA nor Bosch assumed all materials are potential candidates. This contradicts Ashby's (2005) premise that all materials should be considered as possible candidates from the beginning. However, both have what Langley (1994) identifies as a serendipitous model for technology adoption, in the sense that the company's routines may foster new technology adoption in the natural course of events. In practice, both have embedded routines which, as Mohr (1987) defends, may contribute to new technology adoption, namely, by imitation of what others are doing (benchmarking) and search (albeit, perhaps ad hoc).

Both CEIIA's and Bosch's decisions on to use and not to use RIM technology derived from past experience and benchmarking. No prior experience with RIM conditions at the outset material and technology selection. As RIM is not a widespread technology (see Section 5.1), knowledge is not widespread, and thus conditions its further spread and usage.

CEIIA's usual material and technology selection process is based mainly on benchmarking. Faced with a new project, all project members involved (from client to supplier) search for identical cases and analyze the materials used. Thus, in the Buddy case, the same procedure was carried out, based on the product's functional performance, unit cost estimation and feasibility. During this benchmarking, DCPD-RIM was identified in other vehicles such as gardening and construction machinery, produced in small to medium series. Having arrived at a short-list of three potential candidates that complied with the established criteria, CEIIA's final decision derived from a prototype part created using RIM. CEIIA had prior experience with the two other options but that was not the case with RIM. Although the DCPD-RIM attributes seemed feasible, CEIIA decided to create a prototype part for validation, because of the high level of uncertainty. Decisions were delayed until the last responsible moment (Smith 2007) in order to gather information and knowledge. This gave the team the flexibility needed to make the most appropriate decision (see SBCE, Section 2.1.3). They had to develop approaches to keep the pace of the project by working in other subsystems of the product keeping the options open for that particular subsystem.

CEIIA's material and technology selection activities are also depicted in Figure 5.9, as the process described above occurred during the Feasibility stage.

At Bosch, the usual procedure for PD starts with the definition of product functions (primary and secondary functions). Technical specifications are followed by the material and technology selection, which is based on their own prior knowledge or that of their suppliers. Bosch has a supplier database for each type of component and service that is not produced within the company, which normally implies the product's secondary functions, as is the case of the water heater enclosure. For primary functions, Bosch relies on its own R&D Department and their developments are applied directly to their products. Priority is given to components' costs that are related with the primary functions. The remaining budget is used for the other components.

Regarding the material and technology selection process for the enclosure of the heating module, the estimated production volumes were decisive. The selection process began with the screening of potential candidates in view of the functional requirements, industrial design, technical benchmark and knowledge of the project team and Bosch's suppliers.

The final selection was then based on three specific criteria: functional performance; initial investment and production unit cost estimation; and number of suppliers for the candidate material. The relation cost/functional performance is decisive at Bosch. Samples are built for material and geometry validation throughout the PD to enhance certainty.

Figure 5.13 illustrates the various intervenient roles in the material and technology selection process as well as the PD phase in which it occurs.

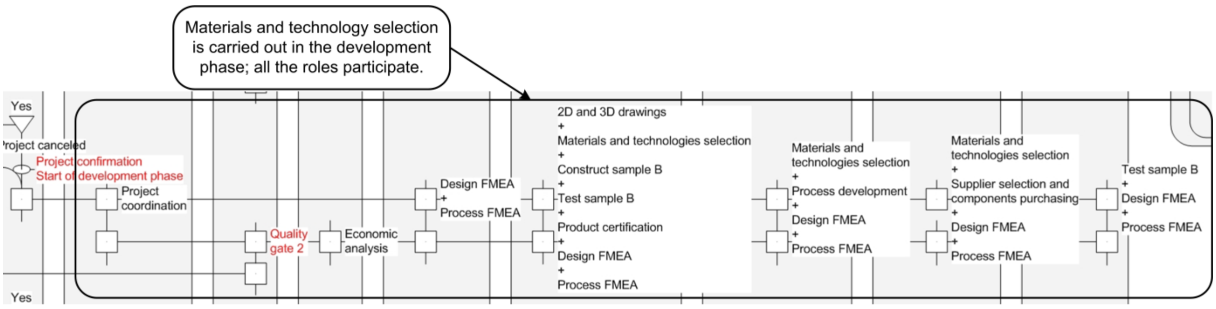

Figure 5.13 Bosch's material and technology selection activities

As the selection process at Bosch relies heavily on prior knowledge and that of its suppliers, RIM technology was not considered due to two reasons:

- the project team's unfamiliarity with this technology;
- the inexistence of qualified suppliers with expertise in this technology within Bosch's supplier database.

Our case studies confirmed that, as Cohen and Levinthal (1990) claim, outside sources of knowledge are critical to the innovation process, as it was outside knowledge that prompted new technology adoption in both cases, thus overcoming the not-invented-here (NIH) syndrome. We should however refer that the knowledge on new technology derived from benchmarking performed with the help of the customer (CEIIA) and supplier (Bosch), thus coherent with Hussinger and Wastyn's (2011) findings that internal resistance tends to be lower if knowledge emerges from suppliers or customers. Thus, accepting and adopting external knowledge means that the PDP is flexible, which in turn accommodates and embraces change (Smith 2007, Hussinger and Wastyn 2011).

Modeling Framework

Our findings and discussion draw on the modeling framework implemented, which enabled a closer look at the process, with a special focus on the roles, interactions and activities. We were able to verify the existence or not of the PD practices and principles highlighted in the literature as these principles, we argue, can be people related, interaction related and activity related.

Despite the attempt to incorporate various perspectives, most of the PD modeling approaches are predominantly activity based (such as DSM, PERT and Petri Nets) (Wynn, Eckert, and Clarkson 2007), and thus ignore the roles that enable these activities, ignore the interactions between the roles and ignore the concurrency of activities fostered by each role. They represent relationships between activities when in reality there is no such thing. People (roles) carry out the various activities and relations are established between roles.

Riva's organizational focus on roles enabled us to produce a model capable of highlighting the roles' functions and their interactions, as well as showing how different activities occur simultaneously. The Riva method allowed us to represent the concrete process in its entirety, particularly how each project is managed and the various intervening roles throughout the course of the entire project, a finding which is in line with that of Fady and El Aziz (2012) and in agreement with Ould's (2005) objective.

The Riva method by itself is able to graphically depict the complex web of interconnections of the PD; nonetheless it becomes extremely extensive and thus difficult to read. It is possible but we admit it is not practical. The method is indeed simple and easy to understand (Aldin and de Cesare 2009), but it is not appropriate for a detailed representation of larger and more complex processes.

While modeling the PDP in our two case studies we realized that the Riva language did not provide the necessary in-depth detail regarding the succession of events, particularly each member's level of knowledge throughout the project. The model is extremely useful for a rigorous presentation or description of the process, more specifically: the roles involved, as well as the actions and interactions carried out amongst the roles, the decisions, and the goals of the process. The incorporation of the textual narrative allowed us to increase the depth of detail in order to better comprehend the *how* and *why* underlying role's decisions within the PD process, which was not possible with Riva alone.

Textual narrative adds depth and detail to the graphical representation, but it is not visual. While the process model, using Riva focuses on precision, the process story using a textual narrative provides detail. Applying our modeling framework in two case studies with some degree of complexity, with many intervenients, provides us with a degree of confidence that the framework may be successfully implemented in other PD processes.

Research questions

Having discussed our most significant findings pursuant to the literature survey, the final part of this section draws on these to propose possible answers to the questions, which drove our research. Our empirical study aimed to answer four specific research questions, we will now address.

RQ1. What are the constraints that inhibit the consideration of other materials and technologies in the PD process of rigid parts?

RQ2. How is (and should be) the selection (decision-making) process?

Materials and technology selection is one of the decisions that the development team needs to perform in order to advance in the definition of the product. Many factors influence the selection process and these do not pertain only to the most appropriate match between material properties and product function.

The development team's awareness regarding a particular material and the confidence that the material will deliver the promised performance are fundamental factors. Unfortunately, our research corroborates that the development team neglects less-known materials and tend to favor the ones they, or their suppliers, already know and use. This is a shortcut that endangers the success of a given PD project.

This may also become a recurring problem: no experience or prior knowledge conditions selection, which in turn does not foster new knowledge. Unawareness will then lead to the selection of the same materials and technology. This means that not all materials are considered as potential candidates, as decision makers become enclosed in their "we've always done it this way" approach, perhaps unconsciously, bypassing new business opportunities. The "safe" approach adopted is indeed easier as new materials and technology imply a greater degree of uncertainty and risk.

Furthermore, our research found CEIIA and Bosch lack of a systematic approach to materials and technology selection. Both have established an effective process using different techniques. The involvement of the different constituents, namely client and supplier, in the development process fosters more appropriate material and technology selection decisions. Knowledge channels open and information flows, facilitating the consideration of “out-of-the-box” solutions and promoting informed decisions.

Although their established process is effective, it can nonetheless be improved. We posit a systematic approach, based on the premise that all materials are potential candidates, coupled with the early involvement of the constituents and benchmarking, for example, would improve material and technology selection strategies. This multifaceted, agglomerated strategy would conjugate the advantages brought about by a systematic and well-established method and the disperse knowledge and experience that different constituents can bring from the outside.

RQ3. Can we develop a set of principles and practices to facilitate better decisions in opposition to easier decisions?

Each PDP is unique. Each company must adopt and then adapt the process heeding their own specific situation, their necessities and their constraints. Nonetheless, there are principles and practices that have proven to be fruitful and thus can be implemented to enhance the PD process.

Our study found that the factors Brown and Eisenhardt contend affect the success of PD projects clearly contribute to both process performance and product concept effectiveness. Irrespective of the methodology implemented in the PDP, these factors and inherent practices should be present. Each of our case studies had adopted distinct methodological approaches to PD, however both also effectively implemented the success factors delineated by Brown and Eisenhardt, namely suppliers and customers involvement; team composition; team group process; team organization of work; project leader; and senior management.

RQ4. Is the Riva method appropriate for modeling PD projects?

The Riva method (through its notation RAD) was easy to learn and implement, perhaps because the method’s author provided the necessary support and clarified lingering doubts.

Modeling the PD process using the Riva method visually illustrated the existing roles, interactions and activities. We argue that the Riva method is based on a roles/activities/states framework in opposition to the popular activities/deliverables framework. The organizational focus (roles) is determinant as it is able to produce a model that highlights how decisions are made in a process as dynamic and unpredictable as the PD process, a process which revolves around people.

For a deeper understanding of the reasons behind these decisions, the textual narrative provided by the intervenients seems to be a valuable supplement. The Riva method supported by textual narrative proved to be a good modeling approach to understand decision making in these particular PD projects.

6 Conclusions

Being a human-centered process, “the NPD process is neither logical nor tidy”.
(Jerrard, Barnes, and Reid 2008)

At the end of our study, and in retrospective, we concur that PD is *creative and innovative; dynamic, interdisciplinary, interrelated, parallel and iterative; and uncertain, ambiguous and risky* in nature.

We posit PD gravitates, as Jerrard, Barnes and Reid claim, around people. Each person thinks, feels and acts differently, uniquely. Thus, human nature too is creative and innovative, dynamic and iterative, within an uncertain, ambiguous and risky world where everyone and everything is interrelated. Perhaps that is why aspects pertaining to PD proliferate in various directions, under different perspectives with a multitude of possible solutions.

This thesis is about the PD process, how it can be better understood and improved both at the strategic level by management and at the tactical level by the development team. Literature advocates many tools and techniques can help and support the process, however PD is based on people and how they interact as a means to share information, perform activities and make decisions, which steadily increases the detail of the product to be.

Indeed our literature review suggests the need to move towards more flexible, agile product development in order to incorporate the very nature of the process. This is evident in the most modern prescriptive models.

The same can be said as to the factors, practices and routines suggested by the literature and demonstrated in our case studies. Concurrent practices, knowledge exchange and informed decisions are at the core of successful PD processes. Nonetheless, in practice, uncertainty avoidance is still high, and flexibility is not the norm.

Process modeling enables a clear and precise understanding of the PDP, providing stakeholders with a valuable tool for change. Given the importance of people factors in PD, the Riva method embodies a shift in paradigm, from process to people.

In our empirical study we modeled two PD projects. Our modeling framework, using the Riva method coupled with textual narrative, by focusing on the roles and how they connect, was able to graphically display the various factors and practices that foster successful PD projects.

However, descriptive models still rely very much on the process, neglecting the essence: people. Most process models do not incorporate uncertainty, which is in fact, a human characteristic. But isn’t PD a human-centered process?

6.1 Managerial Implications

One of the most common problems with research is that what seems captivatingly straightforward on paper, often turns out to be rather complex when attempted to put into practice. Nonetheless, this section suggests how the findings and outcomes of this study can be used by PD teams and managers to enhance their process, through the implementation of established success factors, multifaceted materials and technology selection strategy and process modeling.

As we have stated elsewhere (Torcato et al. 2012) the case studies provided important insights as to the constraints that inhibit the consideration of other materials and technologies (and RIM in particular) in the PD process of rigid parts. Our proposition is as follows: to deal with uncertainty the development team should postpone the decision in order to obtain more information. To postpone decisions without jeopardizing lead time, the development team has to adopt practices and techniques that enhance flexibility, namely the ones put forth by Brown and Eisenhardt.

In this thesis we underline the concept of *postponement*, so popular in supply chain management (Van Hoek 2001), arguing that it is a fundamental factor for the success of PD projects. We define postponement in PD as delaying the decision until the risk associated is acceptable for the development team. This concept is consistent with SBCE, however in SBCE the emphasis is on the consideration of many alternatives while in postponement the emphasis is on iteration and testing.

In practice, material and technology selection decisions are somewhat ad hoc. A deeper understanding of the constraints that inhibit the consideration of some materials and technologies provides relevant guidance for PD managers. We hope that this study contributes, in general, to the theme's discussion, and, in particular, to motivating a renewed and knowable materials and technology selection practice based on a multifaceted, systematic approach with an underlying premise: all materials are potential candidates for any application.

Finally, the usefulness of the Riva method relies on the shift in paradigm where the human being is the center of interest and therefore is able to effectively describe the unique characteristics of the PD process. By focusing on people, their interactions and the activities that from them derive, PD managers are able to visually capture the process in its entirety and thus introduce deemed enhancements.

6.2 Recommendations for Future Work

Findings are not generalizable as in any case study. There are multiple factors to consider, such as: sharing components or subassemblies with other products; buying standard components or subassemblies from other companies; or developing a proprietary technology for the component or subassembly or for the production of the component or subassembly that were not taken into account in this study. We believe our findings may be applicable to the components or subsystems where a unique design is required. It would be interesting to analyze and compare studies within this realm.

The modeling framework developed in this thesis needs further case studies for a better assessment about its effectiveness. It would be interesting to test the framework in different PD projects and with different modeling objectives. In this thesis the reason for modeling the PDP was to discover the process that was adopted in specific projects. However, we can model the PDP for other reasons: define the process 'to be', diagnosis a specific issue in the process for improvement, design a new process, and so on. The framework can be tested to help in any of the former objectives.

These case studies are focused on a very specific decision-making process (materials and processes selection) however there is an array of decisions within a development project. It would be interesting to study if this modeling approach is effective in other decisions such as the ones mapped by Krishnan and Ulrich (2001).

One of the main limitations encountered in our case studies was the lack of company disclosure, with the argument that the information was confidential. We believe there is room for further empirical research in other companies with other products.

Finally, our analysis was based on past events limiting the amount and quality of information obtained. Thus, we suggest the implementation of the modeling framework during the execution of PD projects as they occur, following an ethnographic approach.

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A Appendix 1

In this section, a list of companies specialized in the manufacture of plastic parts using RIM technology (RIM users) and their major suppliers is presented.

Table A.1 presents a sample of RIM equipment manufacturers, Table A.2 presents a sample of PU systems suppliers, Table A.3 presents a sample of DCPD systems suppliers and finally Table A.4 presents a sample of RIM users.

Table A.1 Sample of RIM equipment manufacturers

Krauss Maffei Germany	Business divided in 3 technologies: Injection molding technology; Reaction process machinery; Extrusion technology. Very broad and extensive product portfolio dedicated to RIM, including machines, mixing heads, etc. They develop and supply complete production systems and have products specifically for automotive components.
FRIMO Viersen GmbH Germany	The FRIMO Group is one of the worldwide leading developers and providers of system solutions for the manufacture of high quality plastics components. One of the business units is dedicated to PU machinery and equipment.
Hennecke GmbH Germany	A Bayer company, among PU machinery and plant manufacturers, Hennecke enjoys worldwide renown as being the company with the broadest product range. Their expertise and equipment cover virtually all fields of PU application.
DESMA GmbH Germany	DESMA supplies efficient and economical production systems to footwear manufacturers worldwide. The processed materials are thermoplastics, vulcanized rubber and reactive polyurethanes. Is a leading machinery and molds supplier for PU technology.
Cannon SpA Italy	An international group supplying a wide range of industries with dedicated engineering solutions. Main fields of activity are currently Plastics Processing Technologies (for Polyurethanes, Thermoplastics, Composites and Thermoforming), equipment for Energy & Ecology, Aluminum Die-casting machines, Industrial Electronic Controls.
OMS GROUP Italy	World leading manufacturers of polyurethane foam machines and plants. OMS Group has installed plants for the production of dual hardness HR car seats, steering wheels, headrest, interior trim, external RIM and RRIM body parts, sound absorption components, carpets, etc.

SAIP srl Italy	SAIP offers high and low pressure dispensing machines as well as tailor-made equipments for the manufacturing of polyurethanes.
TECHNO PUMA srl Italy	Flexible solutions in polyurethane resin mixing and molding. Their work consists in studying, designing and producing machines and plant for polyurethane resin dosing, mixing and molding for all sectors of applications.
Graco Inc. USA	The In-Plant Polyurethane Equipment Business Unit, previously under the brand Gusmer-Decker, supplies polyurethane processing equipment, including metering machines and mixing heads.
Hi-Tech Engineering Inc. USA	Hi-Tech is committed to design and build advanced urethane machinery at the best possible price. Specialized in customizing quality reaction injection molding machines that fit in the products and process of the users.
Linden Industries Inc. USA	Manufacturer of custom-engineered and standard polyurethane processing machinery. Linden delivers all types of metering machines for the processing of urethane foam, mix heads, complete bulk and blending systems as well as innovative process controls.
ESCO USA	ESCO offers a complete range of low pressure and high-pressure polyurethane mixing and dispensing solutions, from laboratory scale prototype units to high volume production machines.

Table A.2 Sample of PU systems suppliers

Bayer MaterialScience Germany	Is the world's leading manufacturer of polyurethane raw materials and polyurethane systems for rigid, semi-rigid and flexible polyurethane foams and polyurethane elastomers. Baydur® family of integral skin foam systems are a bestseller among RIM users for the production of large complex parts.
BASF Germany	BASF is leading supplier of polyurethane solutions for systems, specialties and basic products. Provide a wide range of polyurethane systems divided into various groups according to their properties, such as hard, soft, integral or compact.
BorsodChem Hungary	Is a leading European producer of MDI and TDI base chemicals and specialty chemicals. Since February 2011 part of Wanhua Industrial Group, a growing producer and marketer of polyurethane raw materials and related products.
Dow USA	Delivers a broad range of technology-based products and solutions of specialty chemical, advanced materials, agrosciences and plastics. SPECTRIM™ Reaction Moldable Products for components molded with RIM technology for the production of compact or slightly expanded PU polymers.
Huntsman USA	Huntsman Polyurethanes is a global leader in MDI-based polyurethanes, providing a range of quality solutions to meet the needs of a broad array of applications like insulation, footwear, automotive, furniture and others.
Hapco Inc. USA	Specialized in the design, development and manufacture of thermoset polymer alloys including: high-strength urethanes and epoxy resins for parts and tooling production, potting and encapsulating compounds, liquid molding plastics and structural adhesives.

Table A.3 Sample of DCPD systems suppliers

Telene SAS France	Part of the Rimtec Corporation group, develops and distributes Telene®, a two-component DCPD resin, converted by the RIM process, and resulting in a high-performance polymer. Its process and properties allow the production of large, complex design parts, resistant to hostile environments and cost-effective for small-to medium-series.
Metton America Inc. USA	Owned by Sojitz Corporation in its specialty chemicals operations, manufactures and sales Metton® resins. As a liquid resin based on DCPD, Metton® facilitates molding of large and complex components. With its use as a new material in components for large trucks, as well as for construction and agricultural machinery, sales are expanding globally by taking full advantage of Sojitz's global network.

Table A.4 Sample of RIM users

RIMSYS Portugal	A new company that started operations in the fourth trimester of 2009, located in the north of Portugal, specialized in RIM processing of DCPD for the production of exterior panels of vehicles. They have the knowledge and technology to produce and assemble enclosures for any kind of product.
Ropico Portugal	Is an industrial company that develops its activity in the production of components for PUR-RIM and Thermoplastics, ranging from the area of consumer products to industrial technical products, and offers productive equipment of last generation, expertise and know-how up to date.
POLIRIM S.r.l. Italy	Designs and manufactures OEM's parts for the main players in the agricultural, construction and truck markets. Offers a large range of choice in plastic molding and painting application with particular expertise in RIM processing of PU and DCPD.
STR Automotive Italy	Manufactures exterior car components, self-skinning PU products and leather-covered car components. To reach its target processes several Polyurethane systems: Polyureas, Ammino, self-skinning high-and low-density systems.
THIEME GmbH Germany	Thieme has been successful in two business sectors: polyurethane and printing systems. The custom RIM parts manufactured include plastic enclosures, housings, covers, structural parts and system solutions for device manufacturers in many industries including medical, automotive, analytical, laboratory, money handling, petroleum, industrial, agricultural, commercial and heavy equipment.
RIM Manufacturing, LLC USA	Specialized in the production of custom PU parts, mainly for bezels and covers of a wide variety of products and industries. Production capabilities from injection to post-injection operations (finishing, painting), assembly of finished parts and quality control.

Armstrong Mold Corp. USA	Manufacturer of metal (aluminum and zinc) casting and plastic molding components in prototype and low-volume production quantities. RIM is mostly used for the production of PU covers for the medical sector. It represents around 30% of the business.
Romeo RIM, Inc. USA	Specializes in reaction injection molding and long fiber injection services for composite solutions.
Polyurethane Molding Inc. USA	Specializes in RIM molding and finishing high-quality, customized, cost-effective structural polyurethane components, focusing on low to medium volume urethane structural foam enclosures.
Exothermic Molding, Inc. USA	Works to help plastic designers find alternative solutions to problems of quantities, budgets, design, lead times and other critical factors. Exothermic facility includes a machine shop, multiple molding presses, painting and finishing departments.
Premold Corp. USA	Premold produces short-run, low-volume plastic parts such as covers for medical devices such as medical camera enclosures, laboratory machine covers, foot warmers and computer panels, as well as in structural applications. Many of their enclosures have received industrial design awards and acclaim.
Rimnetics, Inc. USA	RIM molder for structural parts and enclosures, cosmetics housings, encapsulation and overmolding for medical devices, lab equipment, electronics, IT, construction, marine and defense industries.
Woodbridge Sales & Engineering, Inc. USA	Manufactures plastic and rubber products for the automotive and commercial vehicle industry, using innovative urethane and bead foam technologies.
RimStar Incorporated USA	Manufacturer of superior quality RIM polyurethane products with a specialized urethane open cast molding division. RimStar is able to add color at the mixer head.

B Appendix 2

In this section, we present the process models developed in the case studies research and presented in Chapter 5 in A3 format for better visualization. The RAD for the process “Handle a product development project: the Buddy case study” is depicted in Figure B.1. The RAD for the process “Handle a product development project: the water heater case study” is depicted in Figure B.2.

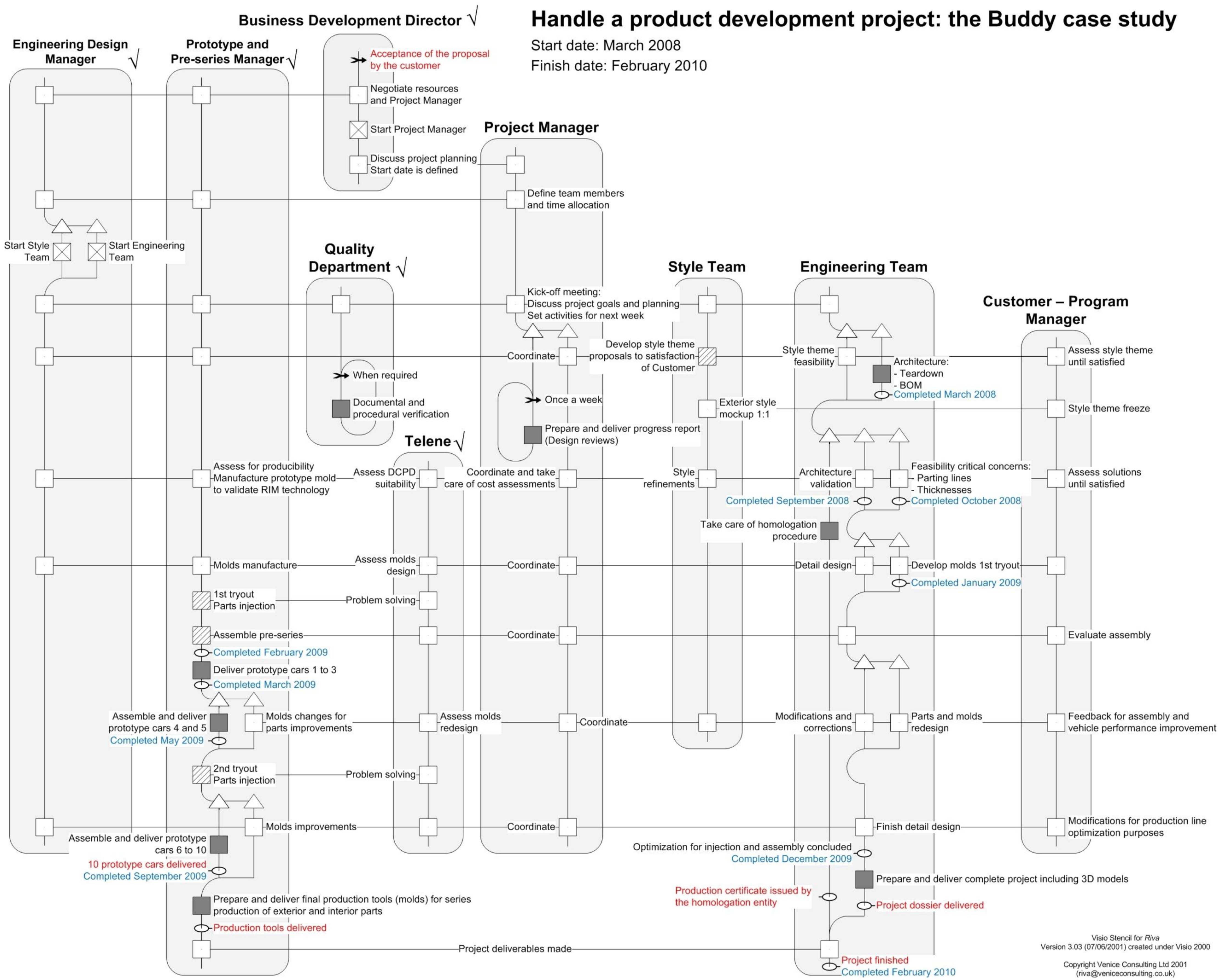

Figure B.1 Handle a product development project: the Buddy case study

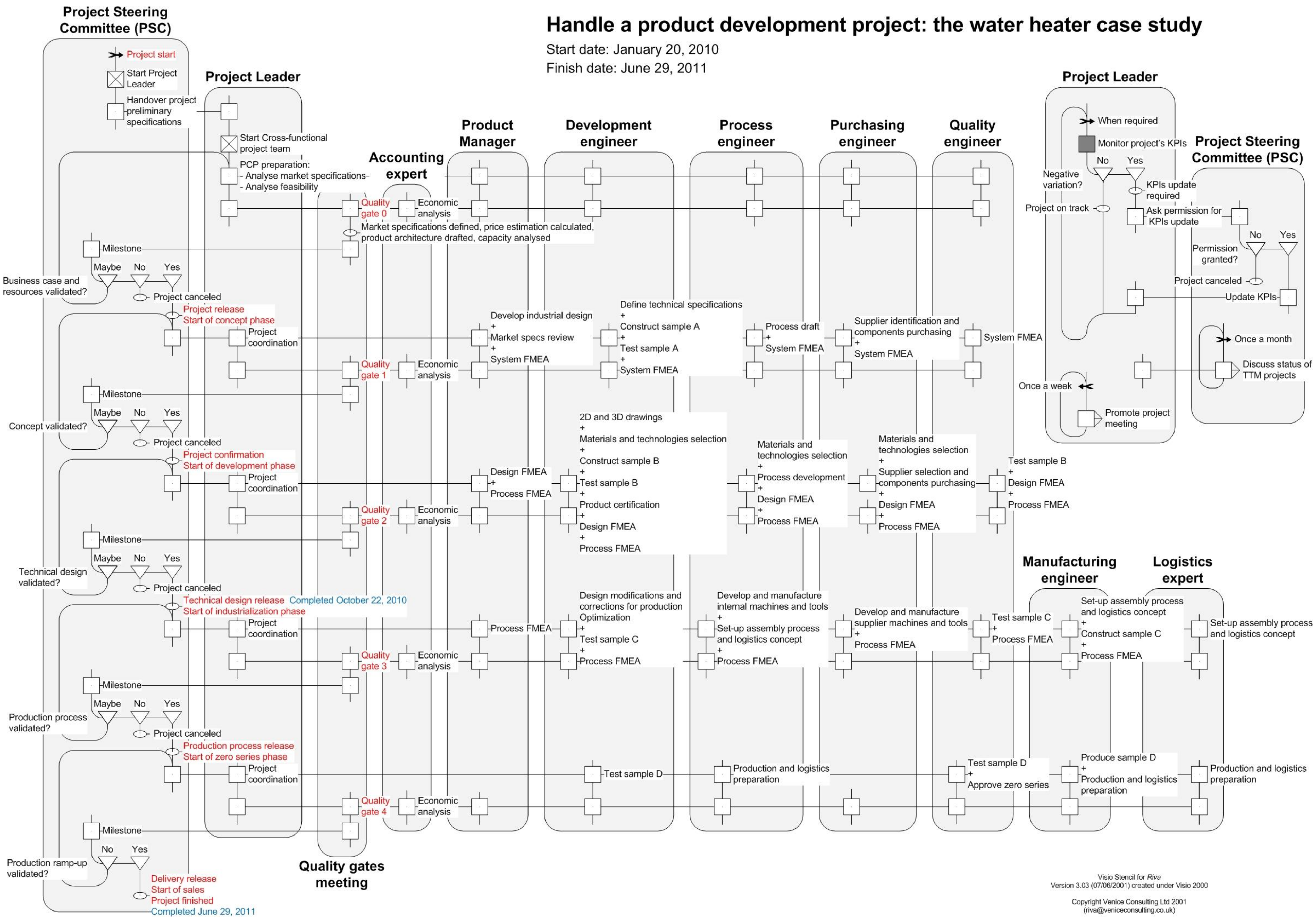

Figure B.2 Handle a product development project: the water heater case study