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When costs from being a constraint become a driver for concept generation

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Declaration

I hereby declare that, the contents and organisation of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

To my Grandparents.

I feel your presence, guiding me every day.

Thank you for all you have done for me.

"Non aver mai paura di avere coraggio"

Abstract

Managing innovation requires solving issues related to the internal development and engineering processes of a company (supply side), in addition to facing the market and competition (demand side). In this context, the product development process is crucial, as different tradeoffs and issues that require managerial attention tend to arise. The main challenges result in managers requiring practical support tools that can help them in planning and controlling the process, and of designers requiring them for supporting their design decisions. Hence, the thesis aims to focus on product costs to understand its influence on design decisions as well as on the overall management of the product development process. The core part of the thesis is based on the models and methods developed for enhancing cost analysis at the beginning of the product development process.

This investigation aims to determine the importance of cost estimation in improving the overall performance of a newly designed product. The focus on post-sales and, more generally, on the customer, has become so relevant that manufacturers have to take into account not only the most obvious aspects about the product and related services, but even consider the associated implications for customers during product use. However, implementing a product life cycle perspective is still a challenging process for companies.

From a methodological perspective, the reasons include uncertainty regarding the available approaches and ambiguity about their application. In terms of implementation, the main challenge is the long-term cost management, when one considers uncertainty in process duration, data collection, and other supply chain issues. In fact, helping designers and managers efficiently understand the strategic and operational consequences of a cost analysis implementation is still a problem, although advanced methodologies for more in-depth and timely analyses are available. And this is even more if one considers that product lifecycle represents a

critical area of investment, particularly in light of the new challenges and opportunities provided by big data analysis in the Industry 4.0 contexts.

This dissertation addresses these aspects and provides a methodological approach to assess a rigorous implementation of life-cycle cost while discussing the evidence derived from its operational and strategic impacts. The novelty lies in the way the data and information are collected, dynamically moving the focus of the investigation with regard to the data aggregation level and the product structure. The way the techniques have been combined represents a further aspect of novelty. In fact, the introduced approach contributes to a new trend in the Product Cost Estimation (PCE) literature, which suggests the integration of different techniques for product life-cycle cost analysis.

The findings obtained at the end of the process can be employed to assess the impact of platform design strategy and variety proliferations on the total life-cycle costs. By evaluating the possible mix of options, and hence offering the optimal product configuration, a more conscious way for planning the product portfolio has been provided. In this sense, a detailed operational analysis (as the cost estimation) is used to inform and drive the strategic planning of the portfolio.

Finally, the thesis discusses the future opportunities and challenges for product cost analysis, assessing how digitalisation of manufacturing operations may affect the data gathering and analysis process. In this new environment, the opportunity for a more informed, cost-driven decision-making will multiply, leading to varied opportunities in this research field.

Contents

List of Figures

List of Tables

INTRODUCTION

1.1 Background

Managing innovation requires balancing the issues related to the company's activities (supply side) and its performance in the market (demand side), as shown in Figure 1. These are the fundamental elements on which the technological paradigm is based (Dosi, 1982).

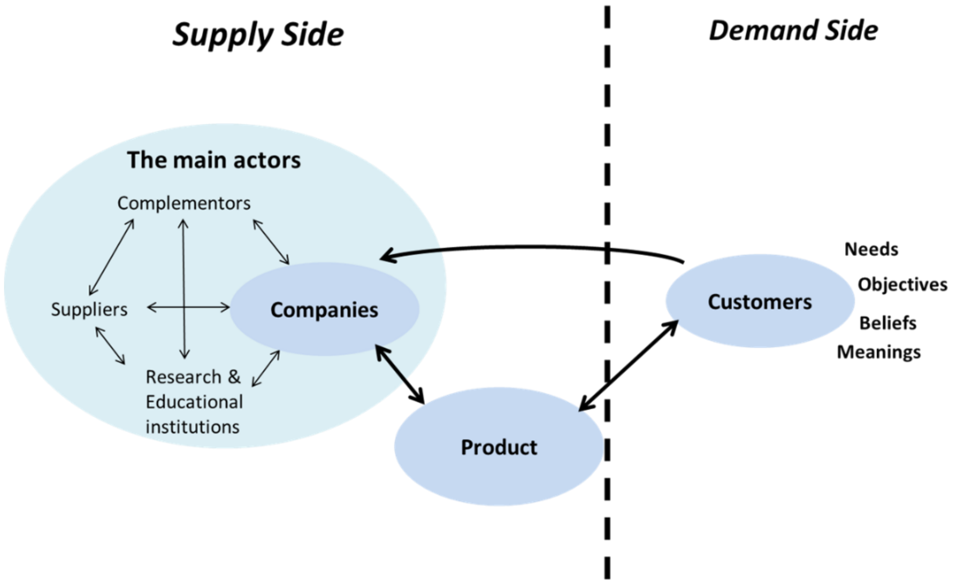


Figure 1 The element of a technological paradigm (Cantamessa & Montagna, 2016)

While producers play the main role, several other actors collaborate in the emergence of a paradigm. In particular, from the side of demand, customers represent the leading figure. From the supply side, beside suppliers, a significant part is then played by the set of actors that provides products and systems, which are complementary to the main product. These are defined as complementors in Figure 1. Universities and research centres also contribute by providing the necessary knowledge and the support.

Therefore, to satisfy the demand side, it is important that a product meets the needs and beliefs of a customer. The main challenge is the effort companies have to put in to improve the product's performance (Cohen, et al., 1996). A better-performing product can require a longer time to design, develop and deliver. Here, it may lead to the company missing out on the first mover advantage and in turn reducing the window of sales opportunity. On the other hand, rushing to the market is also similarly critical; especially in cases where the performance will be reduced will be reduced to the point where the new product will no longer be attractive to the market (Fagerberg et al., 2005).

Instead, on the supply side, innovation is strictly related to product architecture (Cantamessa & Montagna , 2016) its components and the supply chain. Ensuring the right and best organisational and management conditions to develop all these elements is one of the main challenges (Trott, 2008). As a result, managers and designers require practical support tools that can help them in planning and controlling these processes and supporting their design decisions (Montagna, 2011). In particular, decisions made in the early design phase affect the overall performance of a product and its architecture, and consequently, the integration choices within the supply chain. These decisions involve the overall sequence of the activities, and all these issues must be managed according to resource constraints, and as per the time-cost trade-offs.

The aim of my research lies in this milieu. This thesis focuses on product costs to understand their influence on design decisions as well as on the overall management of product development. The kernel of the thesis is then in the models and methods available for cost analysis at the beginning of a product development process, as other contributions in the literature suggest (Rush & Roy, 2000; Layer, et al., 2002; Newnes, et al., 2008). In particular, the research deeply investigates the peculiarities of different cost estimation techniques to understand how they can be integrated. Moreover, the research also focuses on how information can be collected and structured for cost analysis. The idea is to provide designers with a tool not only for cost analysis but also for sharing previous knowledge in the new development process. This is done through data that can be massively collected at each phase of the product development process and that must be better organised to provide actual support to the process of generating new concepts and choosing the best design alternatives.

1.2 The Product Development Process in Innovative Contexts

When one aims to manage a product development process on the supply side, different trade-offs should be taken into account. Nowadays, the rate of technology change is faster, and the life cycle of a product is shorter. Thus, the pressure on companies to reduce time-to-market and minimise the product development costs is higher. These two aspects have been widely discussed and investigated in literature and the field of Innovation Management and Engineering Design represents the main stream of research in this field.

Design choices, in fact, have a strategic worth on the one side: they are part of the product development process and can be related, for example, to the effort in providing higher product quality and performance, as well as to the level of customisation offered. The former aspects affect the duration of product development (namely, in terms of time-to-market); the latter can lead to platform-based approaches. On the other side, from an engineering point of view, design choices cope with product complexity, its architecture and the interactions among components. Besides impacting product alternatives and performance (Cohen et al., 1996), these choices once again affect the duration since product complexity is correlated to project complexity, demanding a higher effort (Smith & Reinertsen, 1992).

Both process duration and product design decisions, therefore, are closely related to costs (Ulrich & Steven, 1998), and often the main goal of the development process is to design the best product at a minimum cost to comply with the product price restrictions. In this sense, costs are unfortunately seen as a constraint to design development.

Cost considerations, however, can be differently implemented during the development process, becoming a driver for the evaluation of different design alternatives (Asiedu et al., 1998) or for exploring different product architectures and/or even in enhancing platform decisions. This is even more important if one takes into account that:

- the early design phases are the ones in which the chance to influence costs is the highest (Dowlatshahi, 1992), since the product concept is still being defined; and
- the information coming from manufacturing (e.g. number of assembling phases), from operations (maintenance programs, logistic flows, etc.), etc. can highly affect design choices. This highlights the importance of adopting a lifecycle perspective as a way to implement cost analysis (Dean & Unal, 1992).

1.3 Research Aim and Objectives

The thesis will therefore specifically address models and methods for enhancing cost analysis at the beginning of the product development phase.

The motivation behind this investigation is related to the importance of cost estimation in improving the overall performance of a product and its effect on the company's performance. Inaccuracies in cost estimation can indeed lead to mistakes in strategy and have undesirable impacts on the company business (Newnes et al., 2008). Moreover, the introduction of cost management as one of the pillars of World Class Manufacturing (WCM) also confirms the relevance of the topic in the industry.

In dealing with Product Cost Estimation, different approaches and also different techniques have been developed.Although similar to each other these techniques serve different purposes and look at the cost estimation with a different point of view (Rush & Roy, 2000).

A first example is represented by the Value Analysis (VA). VA is concerned with the analysis of a product and aims at the reduction of product or process costs (Layer, et al., 2002). VA is a technique mainly employed on existing products, or even parts or components, once new processes or assembly methods being available. Another example is represented by Value Engineering (VE), in which the relationship between product functions and costs are examined, during the early phase of Conceptual Design.VE identifies the functions that are beneficial to the customer so that the value of a product is not just perceived as a low-cost product ((Rush & Roy, 2000). Another view is then represented by the Design to Cost (DTC). Its objective is to converge the design activities in order to obtain a cost-effective product, rather than to let cost converge to Design. Applying the Design to cost perspective, the tradeoff between costs and product performance are evaluated for each of the concept alternatives, aiming at obtaining massive savings on overall cost before the start of the production (Clark & Fujimoto, 1989). Both VA/VE and DTC help to manage the risk of failing to meet the required cost targets. However, they are not focused on risk. The introduction of risk assessment and risk analysis ensures that the consequences of risks are understood and taken into account throughout the project life cycle. Risk management along with VA/VE and DTC can be better utilised by combining them into a state-of-the-art cost management framework known as target costing. Target costing (TC) is a cost management concept that is well suited for use within a concurrent engineering environment. It has mostly been used within the automotive industry with the final aim of strategically managing cost. TC provides a base in order to handle cost management issues into the forefront from the early phases of product development and can be used throughout all phases of a product lifecycle. TC combines the concepts from existing cost management and cost estimating tools (e.g. VA/VE, DTC, risk management), and bases its philosophy on the logic and benefits of activity-based costing.

Finally, the lifecycle perspective aims at providing a framework for specifying the estimated total incremental cost of developing, producing, using, and retiring a particular product (Asiedu & Gu, 1998). This thesis embraces this last view on cost estimation, in order to evaluate the consequences of decision-making associated with the entire product lifecycle and make the efforts to improve the availability of useful data for cost estimating, particularly from the in-service phase where most of the costs encountered within the lifecycle will be justifiable (Xu, et al., 2012). Moreover, among the different view that the lifecycle perspective addresses (supplier, manufacturer, customer, society), this thesis mainly focuses on the producer point of view (Asiedu & Gu, 1998). The reason is related to the importance that this methodology has for companies, and in particular for research and development-oriented organizations, for them to better address latest lifecycle phases cost issues into their product development process.

In fact, despite the wide discussion on cost estimation methodologies in specialised literature (Niazi et al., 2006), very few of them seem to consider the impact of the chosen design on the product's economic performance (Newnes, et al., 2008; Altavilla, et al., 2017). These approaches towards costing, in fact, take into consideration mainly the production phase, although the majority of costs of a manufactured product are committed for the operation/distribution phases (Korpi et al., 2008). This is because, in the last twenty years of research in this field, different methodologies and techniques have been developed, but there is still confusion regarding their use and methodological application (Altavilla et al., 2017).

Finally, the adoption of such methods appears limited in practice (Layer et al., 2002; Newnes et al., 2008). This maybe due to the challenges in actually implementing cost analysis in an organisation (Lindholm & Suomala, 2007). The need for a systematic and comprehensive data collection (Ma et al., 2014), and the way in which the generated knowledge is integrated and re-used (Hicks et al., 2002) is a matter that is always discussed, but remains unsolved. Nowadays especially, these issues are gaining more importance due to the new opportunities provided by big data analysis and Industry 4.0 environments.

1.4 Research Questions

The discussion in this paper will be based on three main research questions:

RQ1: How is it possible to operatively implement a Product Lifecycle Cost perspective (PLC) in the complexity of an innovative product development process of an organisation?

More specifically, the thesis looks not only at the operational aspect of an actual implementation of the method, but also at the methodological issues related to the creation of a PLC methodology. In fact, of the multitude of techniques and methods that have already been developed and are available in the literature, which ones are most suitable for a whole life cycle cost analysis? And, more specifically, which ones can be effectively employed? Which of those techniques can support an early cost estimation? (since it is mainly in the early phases that a finer cost evaluation is not possible)

RQ2: What are the strategic implications of the application of a Product Lifecycle Cost methodology in an organisation?

The main assumption considers the potentialities provided by the massive amount of data collected and the knowledge gained from the application of Product Cost Estimation (PCE) approaches; an enormous potential for more in-depth analyses is possible. In fact, the availability of lifecycle data from the early phases of product development can allow designers to extend their analysis to all the possible implications that their decisions can have on the overall product performance.

RQ3: Due to the new challenges and opportunities provided by the digitalisation of all the industry processes, what will be the consequences for a PLC cost analysis?

The amount of real-time data collected daily in organisations can represent a new challenge in this area of research, particularly due to the opportunities provided by the digitalised manufacturing processes in Industry 4.0 contexts. This is especially true if one considers the possible use of advanced data-driven methodologies coming from other fields, such as Information Engineering and data mining. In this thesis, the potential opportunities, advantages and disadvantages of this new stream of research will be discussed

1.5 Research Methodology

In this thesis, the Design Research Methodology DRM (introduced by Blessing and Chakrabarti (2009)) was selected as a framework for setting the entire research. As shown in Figure 2, the approach consists of four general phases, described in the following:

- Research clarification (RC), wherein the research goals will be defined and significant criteria formulated, seeking into the underlying literature. The outcome of this stage would be an initial description of the existing situation and the main problems for which the results will be evaluated.
- Descriptive study I (DS-I) in which a detailed description of the problem will be provided through a review of the literature to determine which factors should be addressed by efficiently clarifying the existing situation. However, the literature will not be the only source for understanding the problem. Hence, observing the designers at work and interviewing them could also help in better clarify the crucial factors of the problem. The definition provided at this stage will represent the baseline for developing the support (which can be a software or a tool) to address these factors.

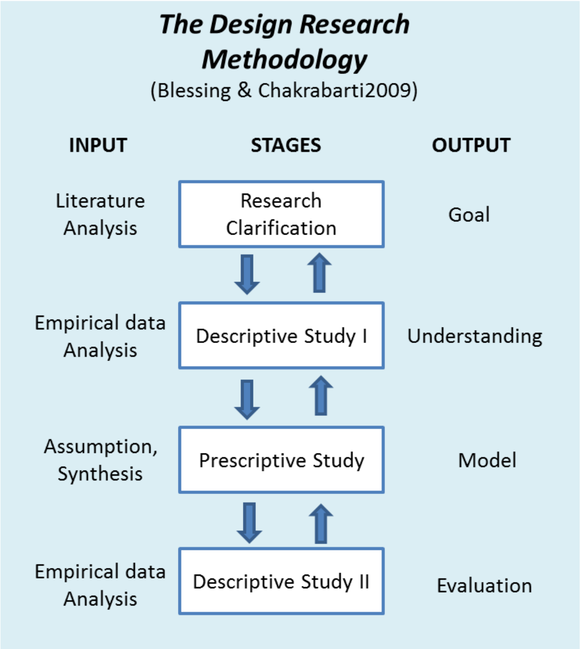


Figure 2 The Design Research Methodology framework (Blessing & Chakrabarti (2009))

- Prescriptive study (PS) in which it will be attempted to increase the quality of the existing situation, by re-elaborating the initial description of the desired situation and by developing methods and tools that convert the theories into practice. The aim is to provide a tool to shift from the AS-IS situation described in the DS-I to the TO-BE situation developed in the next stage of the Descriptive Study II.
- Descriptive study II (DS-II) in which the methods and tools will be validated against the defined criteria in order to evaluate the applicability of the support tool.

1.6 Research Structure

Following the DRM framework, and in light of the research's aim, objectives and questions, the thesis will be organised as described below and per the structure provided in Figure 3.

In Chapter 2, the research problem has been introduced at the outset through an extensive review of literature on Product Cost Estimation. In particular, the first part of the chapter focuses on the traditional model of PCE, as this is a widely studied topic in literature for decades. In this case, the main taxonomies and techniques for Product Cost Estimation have been described, highlighting the main advantages and disadvantages of each of them in terms of their methodological structure as well as their application phase and purpose. This part is mainly included in the first step of research clarification proposed by the DRM methodology. In the second part of Chapter 2, the thesis moves to the Descriptive-Study I. In this case, a review has been conducted of the methods, model and tools used for cost estimation for the last decade, with a focus on the complete product lifecycle. Here, the future trends in this stream of research, as well as the main challenges in the implementation of these methods have been highlighted. Thus, the main research questions have been recognised and extracted as a result of the literature study.

Consequently, based on the identification of the main challenges and on the research questions, in Chapter 3, a methodology for lifecycle cost analysis at the early phases of product development is introduced. In particular, in the first few sections of the chapter, the steps of the methodology have been described, which provide a methodological answer to the issue of technique integration and data collection. With this part, the Prescriptive Study starts, going on with the evaluation of the strategic implications derived from a lifecycle cost analysis, extensively described at the end of Chapter 3.

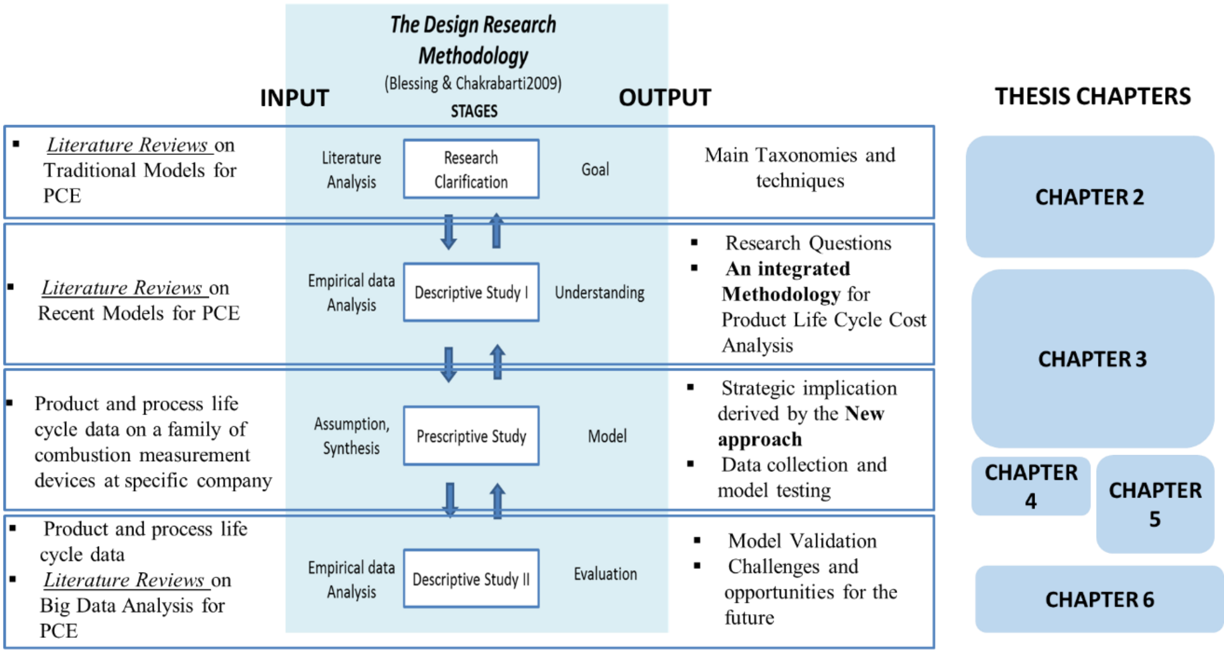


Figure 3 Research Structure based on the DRM framework

Chapter 4 and 5 aim to apply the previously introduced cost estimation methodology to an empirical case. In particular, Chapter 4 sets the boundaries of the case study and focuses on the description of the data collection and integration process within a selected automotive company that develops powertrain systems. In Chapter 5, the three steps on the integrated cost methodology are described based on the data collected on a specific family of products within the company's portfolio. The evidence gathered in these two chapters completes the prescriptive study of the DRM methodology by transforming the general methodology (Chapter 3) into a specific one. The validation of the methodology is then tackled in the last section of Chapter 5, where in-depth analyses of the consequences of product variety on the total lifecycle costs have been presented. Based on the definition of the DRM phases, this last part belongs to the Descriptive Study II, where the solutions have to be checked in terms of consistency with the main challenges and the research questions set at the beginning of the thesis.

The conclusion in Chapter 6 offers a summary of all the chapters and points out the strengths and limitations of the proposed approach. Moreover, it comprises a discussion on future opportunities and challenges for product cost analysis, and the manner in which digitalisation of manufacturing operations will affect data gathering and analysis. In this new environment, the opportunities for a more informed, cost-driven decision-making will multiply, enabling different opportunities in this research field.

CHAPTER 2

A Multilayer Taxonomy of Cost Estimation Techniques, Looking at the Whole Product Lifecycle

Product Cost Estimation has a long history and it has been investigated considering different aspects, getting specific attention in the last twenty years (Rush & Roy, 2000; Layer, et al., 2002; Newnes, et al., 2008). Actually, this theme is still a commonly debated topic in the literature (Xu, et al., 2012) and this is mainly due to its central role in affecting the performance of companies. However, despite the multitude of examples of cost estimation methods available in the literature, industry adoption seems to be limited (Korpi & Ala-Risku, 2008; Layer, et al., 2002; Newnes, et al., 2008). A possible reason is related to the multitude of approaches and techniques available that, instead of representing a guide for spreading possible implementations, actually create confusion and ambiguity on which method is better suited for a particular application.

Hence, on the last decade of contributions available in the literature, a review of the state of the art of PCE approaches has been carried out. The focus is primarily on the methods, models and tools usually suggested by academics and applied in different manufacturing industries. A more specific target of this investigation is to understand which methods can be used when the lifecycle cost estimation is required, which phases and for which purposes this analysis is usually needed, and the type of techniques consequently adopted.

The review is based on the contributions belonging to the Engineering Design and Mechanical Engineering literature, focusing on 69 highly selected papers, starting from a group of 493.

2.1 Main Classifications and Cost Estimation Methods

Nowadays, a large quantity of methods and approaches is available, covering a broad range of applications in various sectors, for several products, components, processes, and purposes. Moreover, they are applied in different phases of product development process, as well as for a single phase or simultaneously for the whole lifecycle.

In creating the methodologies, different cost estimation techniques have been used, both as standalone methods, as well as a combination of more than one approaches (Altavilla, et al., 2017). In choosing a specific technique, decisions should usually be taken into account, considering the goal of the estimation and the uncertainty characterising the development process (Curran, et al., 2004), which at their turn deeply depend on its advancement status and the amount and quality of data gathered (Cavalieri, et al., 2004).

Corresponding to a large number of available cost estimation techniques is an equally high number of their classifications. In reviewing the literature, four main distinct taxonomies emerge (Altavilla, et al., 2017). They split up the cost estimation/calculation techniques in different ways: (1) Qualitative and Quantitative methods, (2) Analogy-based Techniques, Parametric Models, and Engineering Approach, (3) Variant-Based, Generative, and Hybrid cost estimation and (4) Classical and Advanced methods. The differences among the taxonomies are in the included techniques, the format of the data used, the potentialities of their applications, the accuracy of the cost estimation, and the degree of integration proposed for the different methods.

Among these classifications, the one suggested by Niazi et al. (2006) (1) is the most well-known and widely diffused, where the techniques are hierarchically grouped between *qualitative* and *quantitative*. The qualitative methods are divided into intuitive and analogical; the quantitative techniques instead are categorised into Parametric and Analytical, as reported in Figure 4. Qualitative approaches are naturally more appropriate in the early phases of design, as they are based on the qualitative comparison of the new product with the previous ones (Rehman &

Guenov, 1998), mainly relying on expert judgements or heuristic rules. The cost estimation is achieved by making use of historical data (Poli, et al., 1988), (Lewis, 2000) or manufacturing knowledge (Gayretli & Abdalla, 1999), as well as cost engineering experts to identify information from similar products. Quantitative techniques instead aim to provide estimations that are more accurate, and their usage is often restricted to the final phases of the development process. Here, in fact, detailed information on product's features, manufacturing, and (Curran, et al., 2004) service processes are required for the estimation, as the costs are calculated using parametric (Cavalieri, et al., 2004) or analytical functions (Yang, et al., 1998), which aim to assess product and process variables as cost drivers (Li-hua & Yun-feng, 2004)

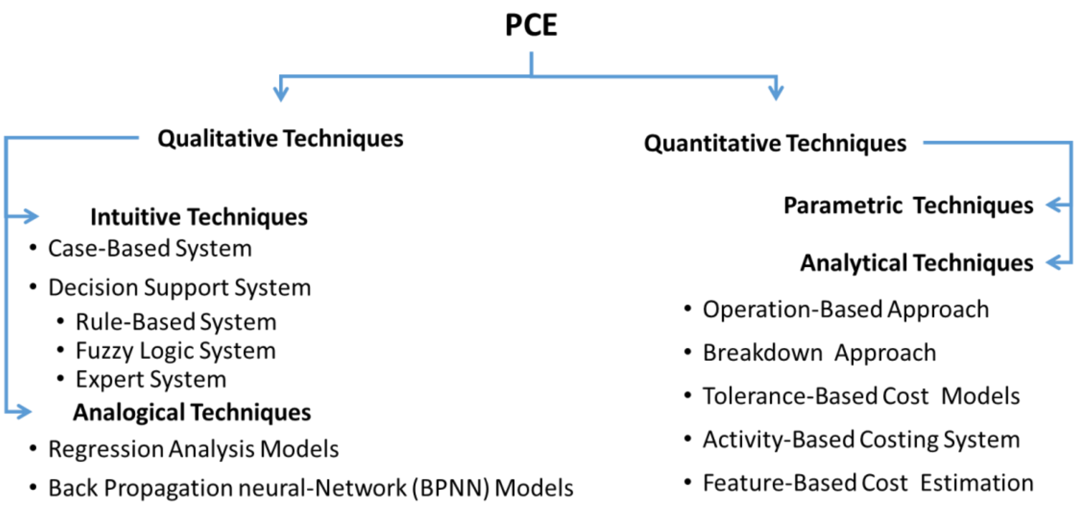


Figure 4 Classification of the PCE techniques (Niazi, et al., 2006)

The second classification (2), mainly diffused by the authors (Cavalieri, et al., 2004; Asiedu & Gu, 1998; Fabrycky & Blanchard, 1991), divides the approaches into *analogy-based techniques*, *parametric models*, and *engineering approach*. The distinction between these three categories relies on the degree of the precision in performing the estimation, which increases from the first typology to the last one. While analogy-based techniques look at the similarity between a new product and an existing one, the engineering approach requires a very detailed knowledge of the product and an accurate industrialisation analysis, as well as an expert designer for the estimation. This last approach, although the most expensive and time-consuming, gives the most accurate results. For this reason, the application is mainly related to the development of entirely new products, when information on existing similar products is not available.

The third cost modelling classification (Wierda, 1990) (3) reports a distinction based on three main approaches: *variant-based*, *generative*, and *hybrid* cost estimation (that obviously combine methods from both the two previous classes). The main difference from the previous taxonomies is that the third recognises the importance of integrating different techniques. In performing the cost estimation during the development, some parts have already detailed information available, while others can be at the beginning of the design phase. Generative methods can be used in the former case since they are based on a detailed analysis of known production processes and a further disaggregation of the total costs on a single component. Variant-based methods instead can be adapted for the ones that are still at the earliest phases, because they require collecting data from the most similar earlier manufactured product/project to adapt all the parameters to the new product to be developed.

The fourth and last classification (4) is mainly diffused by Curran et al. (2004), where the techniques are clustered in *classical* and *advanced* methods. The first class includes the conventional analogous, parametric, and the bottom-up approaches. The second class borrows approaches from other domains (e.g., fuzzy logic, neural networks, Monte Carlo analysis, data mining techniques, etc.) to promote advances in Product Cost Estimation.

Looking at the different proposed classifications, some similarities result since all of them take into account three common aspects: the nature of the estimation, the accuracy of the input information, the precision level of the resulting estimate. However, the list of techniques, as well as their interpretation and categorisation, is not the same within each classification. This shows that a clear and shared grouping of techniques has not been provided yet, and hence there is a general confusion on the available methods that can be used for PCE. Therefore, in Table 1 a list of techniques has been derived, including all the methods encountered in the various classifications, aiming at a comprehensive set of approaches available nowadays.

Table 1 Group of cost Classifications

<table>
<tr><th colspan="2" rowspan="2">List of Techniques</th><th colspan="6">Cost Classifications</th></tr>
<tr><th colspan="2">First classification (1)</th><th>Second Classification (2)</th><th colspan="2">Third Classification (3)</th><th>Fourth Classification (4)</th></tr>
<tr><td colspan="2">Case-Based Methodology</td><td rowspan="5">Intuitive Techniques</td><td rowspan="9">Qualitative Techniques</td><td rowspan="9">Analogy-Based</td><td rowspan="3">Variant-based cost estimation</td><td rowspan="15">Hybrid cost estimation</td><td>Classic Estimating Techniques</td></tr>
<tr><td rowspan="4">Decision Support System</td><td>Expert System</td><td rowspan="3">Advanced Estimating Techniques</td></tr>
<tr><td>Data Mining</td></tr>
<tr><td>Fuzzy-Logic Approach</td><td rowspan="12">Generative cost estimation</td></tr>
<tr><td>Rule-Based System</td><td rowspan="2">Classic Estimating Techniques</td></tr>
<tr><td colspan="2">Regression Analysis Models</td><td rowspan="4">Analogical Techniques</td></tr>
<tr><td colspan="2">Grey Prediction Methods</td><td rowspan="3">Advanced Estimating Techniques</td></tr>
<tr><td colspan="2">Monte Carlo Analysis</td></tr>
<tr><td colspan="2">Artificial Neural Network Models</td></tr>
<tr><td colspan="2">Parametric Method</td><td>Parametric Techniques</td><td rowspan="6">Quantitative Techniques</td><td>Parametric Models</td><td rowspan="5">Classic Estimating Techniques
Advanced Estimating Techniques</td></tr>
<tr><td colspan="2">Operation-Based Approach</td><td rowspan="5">Analytical Techniques</td><td rowspan="5">Engineering Approaches</td></tr>
<tr><td colspan="2">Breakdown Approach</td></tr>
<tr><td colspan="2">Tolerance-Based Cost Models</td></tr>
<tr><td colspan="2">Feature-Based Cost Estimation</td></tr>
<tr><td colspan="2">Activity Based Costing</td><td>Classic Estimating Techniques</td></tr>
</table>

However, for the purpose of this thesis, the classification proposed by the First taxonomy is maintained, and all the further analyses consider the techniques hierarchically as divided between Intuitive, Analogical, Parametric and Analytical. The advantages and disadvantages of each class of techniques will be discussed below, and in particular:

- *Intuitive Methods* base their estimation on the past experience, usually with minimal enquiry details (Ong, 1993). In particular, the used knowledge relies on the domain of experts and is retrieved from a database in a qualitative form, as the judgment of experts, or structured in the form of rules and decision trees (Layer, et al., 2002). Usually, since the used information is grounded on experience and memory only, without strong support of mathematical theories, this class of techniques is difficult to justify, and trade-offs among alternatives are difficult to evaluate (Ong, 1993).
- *Analogical Techniques* exploit for the purpose of the estimation the similarity between the product under consideration and previously developed and manufactured products. The analogy is usually based on the intrinsic characteristics of a product, and more, in general, it comes from functional and geometrical aspects (Layer, et al., 2002). Once the match is obtained, these techniques use the historical data to derive the cost structure usually by means of regression analysis or back propagation methods (Niazi, et al., 2006). The advantage of these methods is built upon their easy and quick use, which makes them particularly effective during the early development phases, especially for relatively standard products, although with a loss in precision (Ong, 1993). Actually, they need a significant amount of historical data, as well as a good information system to retrieve and store the information (Layer, et al., 2002).
- The *Parametric Methods* use the relationship between the product parameters and the lifecycle costs, built as an analytical function of a set of variables (as volume, weight, geometrical characteristic etc.). The mathematical model of the relationship is derived from regression analysis of historical data (Rush & Roy, 2000). Parametric estimating has been recognised as a powerful tool in cases in which data collected are accurate enough, and assumptions are clearly identified and documented (Ong, 1993). However, the estimation is meaningless if only based upon statistical assumptions, in fact, common sense and engineering knowledge should always take into account at first to generate the hypothesis, successively tested by statistical analysis (Rush & Roy, 2000). The main advantage of Parametric methods is in the low amount of information required for the analysis, although sufficient data should be collected to build the analytical function and validate the obtained relationship. However, the main problem of this approach is in the lack of robustness in cases in which nonlinear relationships between the costs and the product characteristics are present, even if they are usually assumed or bypassed in the most of the cases (Zhang, et al., 1996). Another shortcoming is represented by the inherent weakness in

providing feedback regarding possible redesign directions because they do not give any information about the influence of design decisions on cost (Agarwal, et al., 1999).

- *Analytical Techniques* consider a product as a decomposition of a series of elementary units or tasks, operations and activities (Niazi, et al., 2006). Based on this subdivision the costs are estimated as a sum of all the components, going deep to details such as, for instance, the time per operation, the labour cost, material cost and overhead costs, etc. (Rush & Roy, 2000). Due to that level of detail and precision required by this class of techniques, an understanding of the product and its main processes is necessary, consequently delegating their use to the more advanced phases of the product development process (Layer, et al., 2002). Analytical methods are the most accurate and consistent approaches for cost estimation. Moreover, they can be used in cases of changes in the product technology processes, by regenerating the model. The resulting estimate is useful mainly for detailed consideration on costs reduction, in particular when the product is already in the production phase. However, the primary weaknesses are represented by the effort in producing the estimates and the accuracy of estimation that relies significantly on the information available (Ong, 1993). Moreover, the amount of the data necessary for the analysis is enormous and sometimes difficult to achieve in particular in cases in which the knowledge and understanding of the lifecycle processes are not yet obtained (Layer, et al., 2002).

2.2 A New Taxonomy of Product Cost Estimation Techniques.

When different classifications have been proposed and several techniques employed, one can highlight a lack of framing and standardisation in the research stream (Altavilla, et al., 2017). The problem is easily mirrored in practice when practitioners are approaching cost analyses. In fact, nowadays, based on the tools and taxonomies available, the choice in selecting a specific technique is still restricted to its qualitative or quantitative nature, its analytic or descriptive purpose, etc. A more comprehensive awareness about the links between the method's features and the intended purpose of the application is indeed missing.

In fact, several reviews of the cost estimation literature have been made, but each of them looks at PCE from a different and single viewpoint or application context without providing a guide on the peculiarities of the techniques and their intended application. Questions such as "What happens when more than a single viewpoint must be taken into account for cost analysis, or, for example, the intended estimation is meant for a specific sector, and in the same time for a particular product?" "Which criteria should be adopted in the choice of a specific method?" remain without an answer.

In particular:

- Rush and Roy (2000) develop a matrix to support the choice of applying an estimating technique at different phases of the product lifecycle. However, the review was applied specifically to a concurrent engineering environment.
- Newnes et al. (2008) analyse a broad variety of industrial approaches and commercial systems, but they devoted particular attention to methods applicable to infrequent products characterised by low production volumes, in the aerospace, construction, and the injection moulding sectors.
- Layer et al. (2002) provide an overview of the qualitative and quantitative approaches available; they, however, ignored the analysis of the former group and addressed only the quantitative ones.
- Xu et al. (2012) review the research on cost engineering, looking both at the individual phases of the lifecycle (i.e., design cost, manufacturing cost, and operating cost) and at the lifecycle cost. Risk/uncertainty management and affordability engineering were addressed as well. Although this is perhaps the most comprehensive review, its focus is however on identifying the gaps in the literature, instead of analysing the adoption issues.
- Chandrasegaran et al. (2013) provide a detailed review of theories and commercial tools available for capturing the knowledge coming from earlier design, to enhance the availability of information that can be reused in the decision making of new product development. In fact, also cost can be seen as a knowledge domain that can be extracted from past development experiences.

Looking carefully at every single review it has been noticed that the proposed perspectives are not antagonistic, but if anything complementary. Hence, by combining all of them, a new framework for classifying the current literature in PCE can be proposed.

In this sense, the points of view provided by each contribution can be used as a single layer, and the new taxonomy integrates them into a multilayer framework. In this way, the new structure considers together the different natures of the available approaches (so as to extend the point of view of Layer et al. (2002)), the reuse of previous design knowledge (so as to embrace the perspective of Chandrasegaran et al. (2013)), the different engineering environments (so as to go beyond Rush and Roy (2000)), the possible lifecycle perspectives (as suggested by Xu et al. (2012)), and process and product features (so as to enlarge the point of view of Newnes et al. (2008)).
In particular, the five identified layers for a multilayer classification, as reported in Figure 5 are:

- *The nature of the technique:* This layer looks at the different methods from their specificities (such as the methodological approach, their estimation power considered alone or integrated with other techniques), grouping those that present similar features. The focus is not only on the different nature of the techniques, but also on the degree of accuracy these methods are able to provide.
- *The nature of the analysis:* This layer looks at the kind, the quality, and the granularity of input/output. This distinction is mainly based on whether or not historical data are available on previously developed products, which can influence the choice of the right technique that can be used. Consequently, the layer considers if the technique provides quantitative or qualitative findings (it depends on the input data), as well the nature of the analysis, to understand if it described a deterministic or a stochastic model (and this affects the output).
- *The product/process features:* This layer accounts for the differences in product/process characteristics, which can suggest different approaches to cost estimation. For instance, the costing activities of product architectures, as well as the ones associated with manufacturing processes, are the aspects tackled in this layer.
- *The application goal, application phase, and the owner:* This layer concerns the application purposes, as well as at the product development phases. Moreover, the actors involved might be different, and each of them looks at the cost estimation from a different perspective. As the development

progresses, the cost analysis changes; hence, different techniques can be adopted.

- *The object of the estimation:* The analysis can be performed for one specific lifecycle activity (i.e., development, manufacturing, maintenance, disposal), as well as considering all the phases simultaneously.

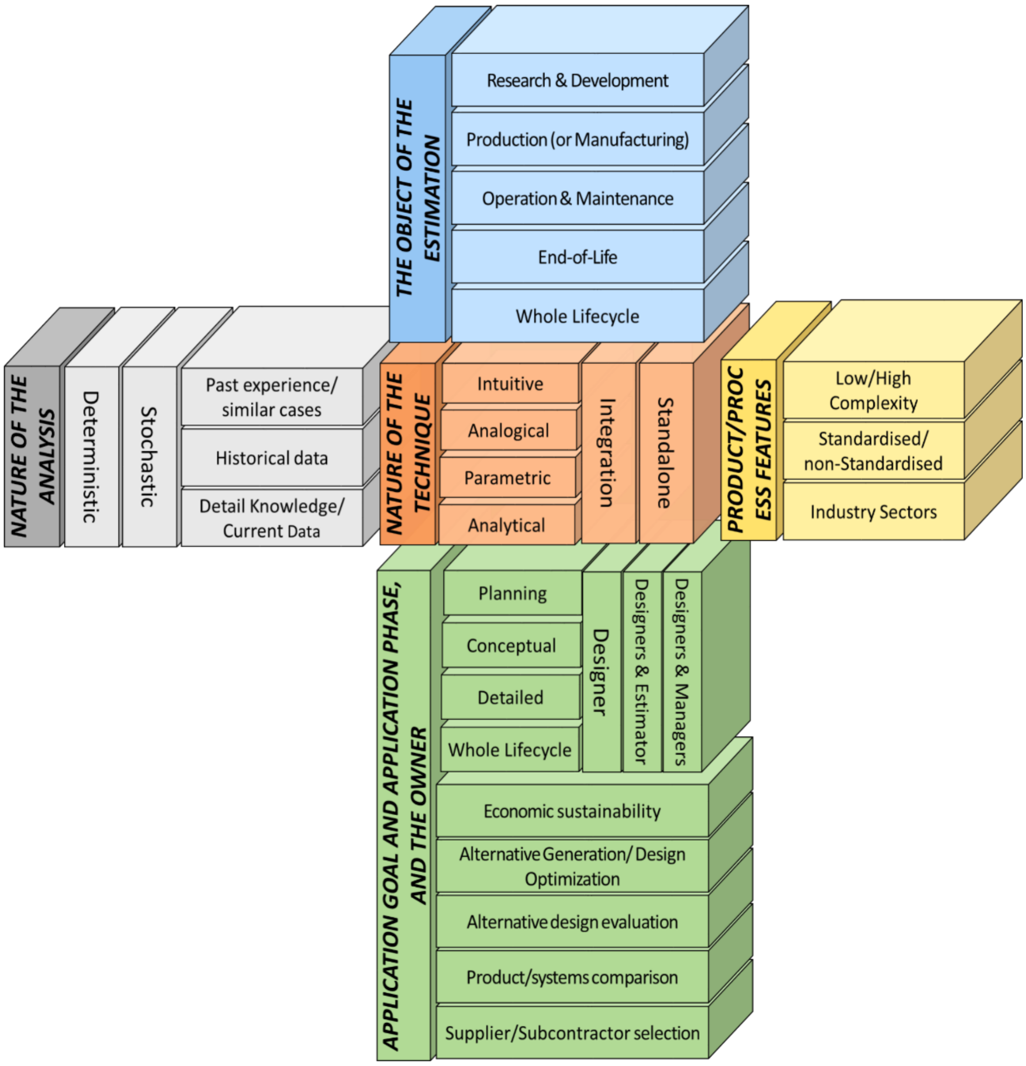


Figure 5 The multilayer framework

In this way, the choice of a particular model takes into account not only the most obvious aspects related to the methodological nature of the technique (e.g.

being qualitative or quantitative), but also other considerations, such as the typology of product or process to analyse, the amount and typology of data to collect, the intended application purpose and phase and the object of the estimation.

For practical use, then, the framework can be seen as a sort of guide in which, starting from a single layer, and by proceeding throughout the different others, one can evaluate the set of techniques that best suit the intended estimation. If, for instance, the industry sector is known, and combining it with the application goal and the phase in which the estimation is required, the new classification framework suggests the set of possible classes of techniques to adopt. Similarly, the typology, the quantity, and the detail of input data can be a starting point for cost estimation.

Finally, this multilayer framework can be used as a model in which to locate the future developed methods, and by which evaluate the new trends in the PCE literature based on the different identified layers.

For instance, by looking at the way data will be extracted, or even by acknowledging new differential integration of techniques, the structure will help in recognising changes in this stream of literature in the future.

Hence, the framework provides an operative guide for academics to identify research opportunities, and to practitioners in performing a PCE analysis, thereby fostering the adoption of these techniques in the industry.

2.3 State-of-the-art in Product Cost Estimation Techniques

From a methodological point of view, the previously introduced multilayer framework has been used to organise, interpret and summarise the relevant contributions, with the final aim of photographing the current state of the PCE literature and providing guidelines for future investigations. For this purpose, a list of explanatory variables, whose meaning directly refers to the layers previously identified can be listed, and each paper will be then analysed according to them. Table 2 lists and describes the variables according to the layers adopted.

In the next sections, each layer is described through the analysis of the literature, presenting results looking at every single viewpoint singularly. Results are then summarised and discussed in section 2.4, underlying the future trend in the PCE literature.

Table 2 List of variables divided by layers for the analysis

Layer	Variable	Description	Section
Nature of the Technique	Classification of techniques	The information, reported in the SoA section, allows understanding the interpretation of the cost classification provided by the author of the new model/methodology. In this way, the proposed contribution is situated within the current literature on PCE.	3.1
	Techniques adopted	This criterion takes into account the type of techniques used in the Product Cost Estimation . The possible integration of different techniques is also taken into account.	3.2
Nature of the Analysis	Nature of output data	The type of output is analysed to better understand the purpose of the paper if it provides quantitative or qualitative findings. Moreover, the nature of the analysis is accounted to understand if the contribution provides a deterministic or a stochastic output.	3.3
	Nature of the input data	This descriptor accounts for the type of input data required by the model/methodology proposed in the article. The distinction is made between qualitative and quantitative data, also looking if the information is related to a previously developed product.	3.3
Product-Process features	Product/Process Description	The variable takes into account the typology of product/process object of the estimation. The distinction is made based on the degree of standardisation, etc. For example, for a product, the level of production volume, and if it is a single product or part of a product family has been taken into account.	3.4
	Industry sector	The variable reports for each model/methodology analysed the industry sector in which the cost estimation is performed.	3.4
	Application case	A description of the application case is reported, looking at the degree of maturity of the developed model/methodology, to understand if either it has been applied to the single case study reported in the paper or it has been validated for more general applications.	3.4
Application goal and application phase, and the owner	Aim and nature	For each paper, the aim for the cost estimation is outlined. In general, only descriptive contributions have been included in the analysis, since they explain in detail the steps required to perform the cost estimation.	3.5
	Phase of the development process	The stage in which the model is applied during the product development process is here taken into account.	3.5
	User Description	The users of the proposed method/model are also identified within each contribution.	3.5
Object of the estimation	Lifecycle perspective	The criterion accounts for the phases of product lifecycle to which the estimation is aimed.	3.6

2.3.1 Layer 1: The Nature of the Technique

If one focuses on methodological approaches for PCE, three groups of contributions can be derived. In particular, the first group describes the application of a single (standalone) technique, considering it powerful enough in terms of estimate accuracy. The second group considers instead more valuable the integration of more than one technique, highlighting the possibility in this case of using different detailed information. All the contributions in the last group, finally, look at the application by comparing the techniques, so to result in the appropriateness of each of them to the application.

As Figure 6 shows, most of the papers belong to the first two categories (88% of the total), while only a 10% aim at comparing techniques, perhaps for the effort that is required for this last kind of analysis.

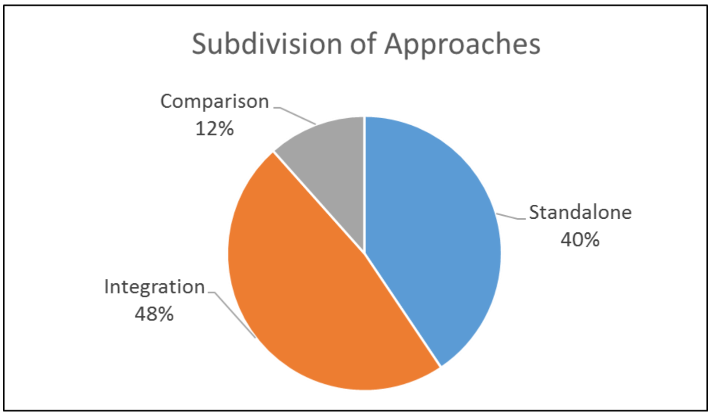


Figure 6 Subdivisions among the three groups of approaches

In the following sections, each group is discussed separately, looking at how the different techniques are employed from a methodological point of view. The list of the techniques presented is the one listed in Table 1, while the classification reported is the one related to (Niazi, et al., 2006).

2.3.1.1 The use of a single cost estimation technique: The Standalone Group

Table 3 reports how these standalone methods clustered among the previous Niazi's categories.

The majority of contributions that present standalone techniques use Analytical approaches (1). This result is sensible since analytical methods are considered the most powerful to provide already a sufficiently accurate estimation, even if used alone (Curran, et al., 2004; Layer, et al., 2002; Rush & Roy, 2000) and do not usually necessitate further integrations with other cost estimation techniques. Within this group of papers, the Breakdown Approach and the Activity Based Costing (ABC) are the most used methods. Both of them are advanced techniques, specifically focused and characterised by a high detail of the information required as input. The main difference in the group instead is the driver chosen for the estimation: the Breakdown and the Operation-Based approaches look at the cost of the activity (even if differently characterised), ABC focuses instead on the organisation cost centres, while Feature-Based techniques consider the physical parameters of the product.

Table 3 Subdivision of the Standalone models among the Techniques

<table>
<tr><th colspan="2">List of Techniques</th><th>Cost Classifications</th><th>References</th></tr>
<tr><td colspan="2">Breakdown Approach</td><td rowspan="4">(1) Analytical Techniques</td><td>(Cheung, et al., 2015; Castagne, et al., 2008; Cicconi, et al., 2014; Waghmode, 2014)</td></tr>
<tr><td colspan="2">Operation-Based Approach</td><td>(Ye, et al., 2009)</td></tr>
<tr><td colspan="2">Activity Based Costing</td><td>(Chen & Wang, 2007; Haroun, 2015; Park & Simpson, 2008; Tsai, et al., 2012)</td></tr>
<tr><td colspan="2">Feature-Based Cost Estimation</td><td>(Agyapong-Kodua, et al., 2014; Johnson & Kirchain, 2009)</td></tr>
<tr><td colspan="2">Artificial Neural Network Models</td><td rowspan="3">(2) Analogical Techniques</td><td>(Duran, et al., 2009; Ju, et al., 2010; Seo & Ahn, 2006; Wang, 2007)</td></tr>
<tr><td colspan="2">Grey Prediction Methods</td><td>(Hongzhuan, et al., 2013)</td></tr>
<tr><td colspan="2">Regression Analysis Models</td><td>(Brunoe & Nielsen, 2012; Lee, et al., 2011; Luiza, et al., 2014; Loyer & Henriques, 2014; Quintana & Ciurana, 2011; Roy, et al., 2008)</td></tr>
<tr><td colspan="2">Parametric Cost Estimation</td><td>(3) Parametric Models</td><td>(Chang, et al., 2013; Heller, et al., 2014; Folgado, et al., 2010; Newnes, et al., 2007)</td></tr>
<tr><td rowspan="2">Decision Support System</td><td>Expert System</td><td rowspan="2">(4) Intuitive Techniques</td><td>(Helbig, et al., 2014)</td></tr>
<tr><td>Rule-Based System</td><td>(Naranje, et al., 2014)</td></tr>
</table>

the lifecycle. Four papers propose this approach (Cheung, et al., 2015; Castagne, et al., 2008; Cicconi, et al., 2014; Waghmode, 2014). Castagne et al. (2008) suggest an application of the described model for the estimation of the manufacturing processes of an aircraft, although just the production phase is taken into account. Cicconi et. al. (2014) instead, in the estimation of a medium-small sized electric engine, extend the analysis after manufacturing, so to include the use cost. Waghmode (2014) and Cheung et al. (2015) finally focus on the later phases of the product lifecycle, including in the analysis the maintenance activities (Waghmode, 2014) as well as end-of-life consideration (Cheung, et al., 2015).

The Operation-based approach is used to estimate the cost of the single activity operation time (e.g. manufacturing activities) (Ye, et al., 2009). In this case, the activity duration is the driver used to which material, labour, equipment and tooling costs are related to.

The ABC technique, which is one of the most common and diffused approach in Cost Accounting literature, is proposed by four other contributions (Chen & Wang, 2007; Haroun, 2015; Park & Simpson, 2008; Tsai, et al., 2012). Here, the cost estimation is obtained by collecting information about the different units and cost centres involved, as suggested by previous reference applications (Cooper, 1988; Johnson & Kaplan, 1987). The technique appears helpful in those cases where overhead costs among different variants of the product must be identified (Chen & Wang, 2007; Park & Simpson, 2008), or even when reaching a high level of accuracy and precision is required (Haroun, 2015; Tsai, et al., 2012).

Finally, a Feature-based technique can be applied for determining the effects of physical parameters on the total product costs. In the latter case, the type of material used and the typology of the manufacturing process (e.g. among the latest contributions, Johnson & Kirchain, 2009), or the geometric detail and complexity of each of product’s component (Agyapong-Kodua, et al., 2014) are taken into account for the estimation.

Analogical Techniques (2) represent the second large group of contributions. In particular, four papers use Artifical Neural Network (ANN) Techniques (Duran, et al., 2009; Ju, et al., 2010; Seo & Ahn, 2006; Wang, 2007), six contributions ground their model on Regression Analysis (Brunoe & Nielsen, 2012; Lee, et al., 2011; Luiza, et al., 2014; Loyer & Henriques, 2014; Quintana & Ciurana, 2011;

Roy, et al., 2008), while the last one applies Grey Prediction methods (Hongzhuan, et al., 2013) to deal with the uncertainty in cases of a limited amount of historical data.

These three techniques show similarities. In particular, all of them employ historical information on products with known cost structures as a proxy to derive the cost of a new one (with similar characteristics regarding product structure and lifecycle processes). Moreover, the database is generally obtained by using different sources (past developed family of products in Brunoe and Nielsen (2012); Roy et al. (2008); Loyer and Henriques (2014); designers experiences in Seo and Ahn (2006); industry dataset in Quintana and Ciurana (2011); or simulations in Duran et al. (2009)). The main difference consists of the internal structure of the model used for the interpretation. ANN-based techniques apply Neural Network to interpret the cost information received as input by using several layers (input, hidden and output) of neurons (Duran, et al., 2009). These are trained by a learning algorithm, and the typology of the learning algorithm characterises hence the architecture of the Neural Network. In this sense, the most widely used are the Back Propagation Neural Network (Ju, et al., 2010; Seo & Ahn, 2006; Wang, 2007). The quantity of input cases (usually between the 70-80% of the total of the cases) required for training the network represents the main drawback of ANNs. Grey Prediction methods (Deng, 1982; Deng, 1985) can be helpful for this matter, as they ensure a reliable enough cost estimation also with limited and variable information (Hongzhuan, et al., 2013). Regression Techniques finally use a selected number of variables linearly related to the former product cost, using the derived regression model to predict the new cost. In general, regression techniques are widely accepted and employed in different domains, even preferred when the product complexity is high and independent variables are a lot (Brunoe & Nielsen, 2012).

This last group of techniques represent the main methodologies for cost estimation, in cases where there is high similarity between the new product to be developed and previous already developed products. However, it is common for designers to use parts already developed for designing new products. In fact, the 80% of the parts has been estimated, since they result from the modification of previous designs (Iyer, et al., 2005). Therefore, other techniques that precisely focused on 3D shape searching and retrieving of product information have been developed and successfully integrated with analogical techniques for PCE. In particular, for CAD applications, the use of these techniques help in recovering information related not only to the product architecture, but also on the manufacturing process, costs and materials (Iyer, et al., 2005).

The third group of contributions applies Parametric Models (3) (Chang, et al., 2013; Folgado, et al., 2010; Heller, et al., 2014; Newnes, et al., 2007) for the estimation. In this case, the significant variables that influence the total product cost (aka cost drivers) are identified and included in the mathematical equation. The parameters of the model can be related both to product characteristics (volume, weight, material, thickness), as well as to the manufacturing process (Newnes, et al., 2007). The complexity in the structure of the model, as well as the choice in the typology and abundance of the parameters, and the use of actual information on the new product to be inserted, represent the main differences between a Parametric approach and a simple linear regression analysis. The major limit, on the other hand, is represented by the effort required for the identification and selection of the parameters, but when the cost estimation relationship (CER) is identified, the cost analysis can be rapidly performed.

To end, only two papers are Intuitive (4) cost estimation techniques (Helbig, et al., 2014; Naranje, et al., 2014). In this case, past experience and qualitative information are used to produce the estimation for a new product. Both of the revised contributions follow a knowledge-based approach, where the information on design, manufacturing and the operation of a particular component/product are collected from a database, from designers' experience (Helbig, et al., 2014)or acquired from industry (Naranje, et al., 2014). The main limit of applying Intuitive techniques alone, concern data collection and the reliability of experts' opinions. For this reason, often these techniques are integrated with more robust and rigorous approaches.

2.3.1.2 When different techniques are combined: The Integration Group

The 48% of the contributions account for the combination of more than one cost estimating technique[1]. The methodological difference proposed by these models mainly lies in the role played by each of the techniques, as well as in the

Among this group, eight papers integrate a cost estimation approach and optimisation methods, (e.g. Linear Programming or Genetic Algorithm), and for this reason, they must be considered separately.

way information is combined. The possible combinations of approaches are divided into three main groups, each one identified by a single column in Table 4. In particular, one of the two techniques is usually employed to structure (first column), pre-analyze (second column) or deepen (third column) the input data, while the other is integrated so to perform the cost estimation. As reported in Table 4, not all the combination have been detected among the paper included in this literature review. However, many of them can be taken into account in the development of a possible lifecycle methodology.

In the first column, Intuitive techniques are combined with all the other approaches. As previously stated, these are mainly based on past experience, expert knowledge or theoretical information, and usually, they are meant to structure and collect the input data, employed then by more quantitative cost estimation methods. Therefore, they result in the ones most often integrated (around 50%). In particular, these contributions mainly aim at the specific combination of Intuitive methods with respectively Analogical, Parametric or Analytic Approaches. Only a single exception shows integration between two typologies of Intuitive techniques (H'mida, et al., 2006), combining expert and rule-based system.

When Intuitive are integrated with Analogical methods, the information can be retrieved from historical cases (Chang, et al., 2012), or structured by the expert system (Mauchand, et al., 2008), as well as collected by querying a panel of industry experts (Ju, et al., 2009). Mauchand et al. (2008) in particular, propose a general rule-based expert system, which can be employed as a framework with different analogical techniques. To deal with uncertainty, a Decision Support System based on Fuzzy Logic is, for instance, proposed by Fazlollahtabar & Mahdavi-Amiri (2013).

Table 4 Subdivision of the Integration Techniques

			Intuitive Techniques (First Column)					Analogical Techniques (Second Column)				Parametric Techniques (Third Column)
				Decision Support System								
			Case-Based Methodology	Data Mining	Expert System	Fuzzy-Logic Approach	Rule-Based System	Grey Prediction Methods	Monte Carlo Analysis	Regression Analysis Models	Artificial Neural Network Models	Parametric Method
Intuitive Techniques		Case-Based Methodology	-									
	Decision Support System	Data Mining	-	-								
		Expert System	-	-	-							
		Fuzzy-Logic Approach	-	-	-	-						
		Rule-Based System	-	-	H'mida et al. (2006)	-	-					
Analogical Techniques		Grey Prediction Methods	-	-	-	-	-	-				
		Monte Carlo Analysis	-	-	-	-	-	-	-			
		Regression Analysis Models	-	-	Mauchand et al. (2008); Ju et al. (2009)	-	-	-	-	-		
		Artificial Neural Network Models	Chang et al. (2012)	-	Mauchand et al. (2008)	Faziollahtabar and Mahdavi-Amir (2013)	-	Xie N. (2015)	-	-	-	
Parametric Techniques		Parametric Method	Chougule and Ravi (2006)	-	Zhao et al. (2015)	-	-	-	-	Watson et al. (2006)	-	-
Analytical Techniques		Breakdown Approach	Tu et al. (2007)	-	-	-	-	-	-	-	-	-
		Feature-Based Cost Estimation	-	Sajadfar and Ma (2014)	Lin et al. (2011); Madan et al. (2007); Germani et al. (2011); Xiao-Bing et al. (2008); Wasim et al. (2013)	-	-	-	-	-	-	Kaufmann et al. (2008)
		Activity Based Costing	Wang et al. (2011)	-	-	-	-	-	Lindholm and Suomala (2007); Thokala et al. (2010)	-	Liu et al. (2008)	Quian and Tan (2008); Quian and Ben-Arieh (2008); Tang et al. (2012); Ardiansyah et al. (2013)

In the cases that combine Intuitive with Parametric approaches, data collection on product geometry attributes, material and processes information gathering and the identification of cost drivers are provided to the Parametric model automatically. The automation is provided by Case-Based Reasoning (Chougule & Ravi, 2006), or through Expert System (Zhao, et al., 2015).

Among the papers that show a combination of Intuitive and Analytical Techniques, accurate information both on the product features and on the process are reached by a computer-aided model (Germani, et al., 2011; Lin, et al., 2011; Madan, et al., 2007; Wasim, et al., 2013), or by employing specific data mining techniques (Sajadfar & Ma, 2015).

Finally, the Feature-Based method is preferred among the Analytical approaches. Two last examples of Intuitive-Analytical integration are finally represented by the combination of Case-Based Reasoning with ABC (Wang, et al., 2011) or with the Breakdown approach (Tu, et al., 2007).

In the second column, a step further in the data structure and estimation accuracy is reached by the combination of Analogical Methods with Parametric and Analytical Techniques. If the methods in the first column structure and make available past experience and experts' knowledge, in this second group, historical data are pre-analyzed by regression models (Watson, et al., 2006) or ANN techniques (Liu, et al., 2008), or pre-selected by Grey Prediction Methods (Xie, 2015), and the real estimation is delegated to more quantitative approaches. In particular, Watson et al. (2006) propose a multiple linear regression to derive the most effective cost driver for the parametric equation, while Liu et al. (2008) use existing product data to train ANN model aimed at performing an ABC analysis. Moreover, when a weak set of historical data must be extended or there is the necessity to deal with uncertainty related to the input data, Lindholm & Suomala (2007) and Thokala et al. (2010) propose Montecarlo simulations.

Finally, in the last column of Table 4, Parametric Methods are combined with Analytical Approaches. The benefit of this last typology of integration lies in the high precision and accuracy that can be reached, due to the use of Analytical Techniques to derive the information necessary for the cost estimation. In particular, some contributions employed an ABC to deepen the information related to the activities subdivision as well as the manufacturing and operation features (Ardiansyah, et al., 2013; Qian & Ben-Arieh, 2008; Qian & Tan, 2008; Tang, et al., 2012). Only one paper instead retrieves actual data on product structure, its geometrical and physical parameters by the use of a Feature-Based Approach (Kaufmann, et al., 2008). In all these last cases, information can be then immediately tested and used as cost drivers for parametrical equations, overtaking the usual inefficiency related to cost driver retrieving.

2.3.1.3 The difference between cost estimation techniques: The Comparison Group

The remaining 10% of the contributions focus on the comparison between different PCE techniques. In each paper, more than one developed model and provided estimation are mainly compared for their prediction power. Table 5 reports, the approaches employed for each comparison, the performance measures used for analysing the difference in the prediction power of each model, and a brief description of the comparison's results for the contributions identified in this group.

In most of the cases, the techniques belonging to the Analogical Methods are compared. In particular, Artificial Neural Network techniques and Regression-based techniques are mainly investigated. In almost all the contribution analysed, the ANNs-based techniques provide better performances than the regression models. However, the difference regarding the prediction power is not very high (de Cos, et al., 2008; Ciurana, et al., 2008), especially if one considers the effort required in setting the model (Che, 2010). In general, when several input variables are present, and the regression equation form is not well defined, artificial network approaches outperform the classical regression models (Verlinden, et al., 2008). However, the performance of the ANNs models is overcome in the cases of the use of advanced techniques for PCE (Deng & Yeh, 2011; Liu, et al., 2009). Those advanced machine-learning methods use Lagrangian multipliers to obtain a convex problem, and hence a globally optimal solution.

Table 5 List of papers of the Comparison group (Compared techniques and Performance Measures as defined by the authors)

Reference	Compared Techniques	Performance Measures	Results
(de Cos, et al., 2008)	• Multivariate local polynomial regression approach (LOESS); • Projection pursuit regression approach(PPR); • Artificial Neural Networks (ANNs).	Mean percentage error, mean absolute percentage error, and percentage accuracy cost interval.	The ANN model is marginally superior to the two non-parametric models. The PPR has overall the lower predictive power.
(Ciurana, et al., 2008)	• Multiple regression analysis (MRA); • Artificial neural networks (ANN).	R value and the mean absolute error rate (MAER)	The ANN provides a more accurate estimation compared to the MRA.
(Verlinden, et al., 2008)	• Multi-layer perceptron neural network (MLPNN); • Radial basis function (RBFNN); • Linear multivariate regression (MR).	Mean Prediction Error, and the Standard deviation; Timeliness; Precision; Repeatability; Accuracy.	The two neural network models reduce uncertainties related to the cost estimation. Both have better performances compared to the regression-based model. The MLPNN shows, in general, the best performances in all the metrics.
(Deng & Yeh, 2011)	• The least squares support vector machines (LS-SVM); • Backpropagation Neural Networks (BPN); • Statistical regression analysis.	Mean absolute percentage error(MAPE), mean squared error(MSE) and coefficient of determination(R^2)	The LS-SVM performs better than the other two models in all the three metrics.
(Verlinden, et al., 2008)	• Regression techniques; • Artificial neural networks.	The absolute deviation from the real cost, and the mean absolute percentage deviation (MAPD)	The accuracy of the two methods is high, and the differences between them are slight. The results show that for small numbers of parameters chosen for the model, the performance of the two model is equal.
(Caputo & Pelagagge, 2008)	• Parametric; • Artificial neural networks.	The percentage of error committed and the mean absolute percentage error (MAPE).	The ANN model confirms better performances compared to the parametric model, due to the lowest value in the cost estimation error.
(Hart, et al., 2012)	• Method of Improved Cost Estimation from Historical data of Engineering Systems; • Neural Networks; • Regression Analysis.	The average square error and the standard deviation.	The accuracy of the results obtained from the MISERLY approach is higher than the other two models.
(Liu, et al., 2009)	• Instance-Based Learning (IBL) algorithms; • Locally Weighted Regression (LWR); • Regression tree models (M5) • Artificial neural networks; • Support Vector Regression (SVR).	Mean Absolute Error (MAE) and the Root Mean Squared Error (RMSE)	The accuracy of the ANN and SVR models is better compared to the others. However, if the number of costs drivers increase, the SVR model has the better performances. On the contrary, when the number of cost driver decreases, the ANN is, in general, the best model.

2.3.2 Layer 2: The Nature of the Analysis

Looking at the nature of the analysis provided by the developed models, the majority of the contributions provides a deterministic estimation. Therefore, the output results is a single value, without taking into account the uncertainty related to the model. Among the deterministic methods, uncertainty either is neglected or is just faced using sensitivity analyses. In particular, Caputo and Pelagagge (2008) use sensitivity analyses to identify the most significant inputs and its correlation coefficient for the Parametric model. Johnson and Kirchain (2009) instead use it for taking into account the impact of different materials' prices, on the final cost estimation.

Some other contributions instead propose probabilistic approaches to deal with uncertainty, either considering its aleatory aspects (i.e. related to the model and difficult to eliminate without changing it) or taking into account its epistemic nature (i.e. related to the lack of reliability of data and knowledge necessary for the estimation) (Xu, et al., 2012). In aleatory cases, input variables (or a selected subset of them) are not assigned but are quantified through simulation, and hence by using probability density functions. These input variables are related for example to performance parameters (Chang, et al., 2013; Hart, et al., 2012), quality (H'mida, et al., 2006), the number of maintenance actions (Thokala, et al., 2010; Kleyner & Sandborn, 2008), the replacement rate (Loyer & Henriques, 2014), the price and the discount rate (Lindholm & Suomala, 2007).

In this group, four contributions (Lindholm & Suomala, 2007; Loyer & Henriques, 2014; Chang, et al., 2013; Kleyner & Sandborn, 2008; Thokala, et al., 2010) employ Monte Carlo method. Hart et al. (2012), instead, apply an advanced statistic model (namely the Kriging Regression Model), while Xie (2015) and Hongzhuan et al. (2013) use Grey Prediction, since they face with small-sized and atypical distribution samples. When uncertainty is also treated considering its epistemic nature, fuzzy approaches are used to model the different scenarios (H'mida, et al., 2006; Fazlollahtabar & Mahdavi-Amiri, 2013). In this way, the focus of the analysis is on the reliability of the knowledge used as input, instead of the uncertainty related to the model's structure.

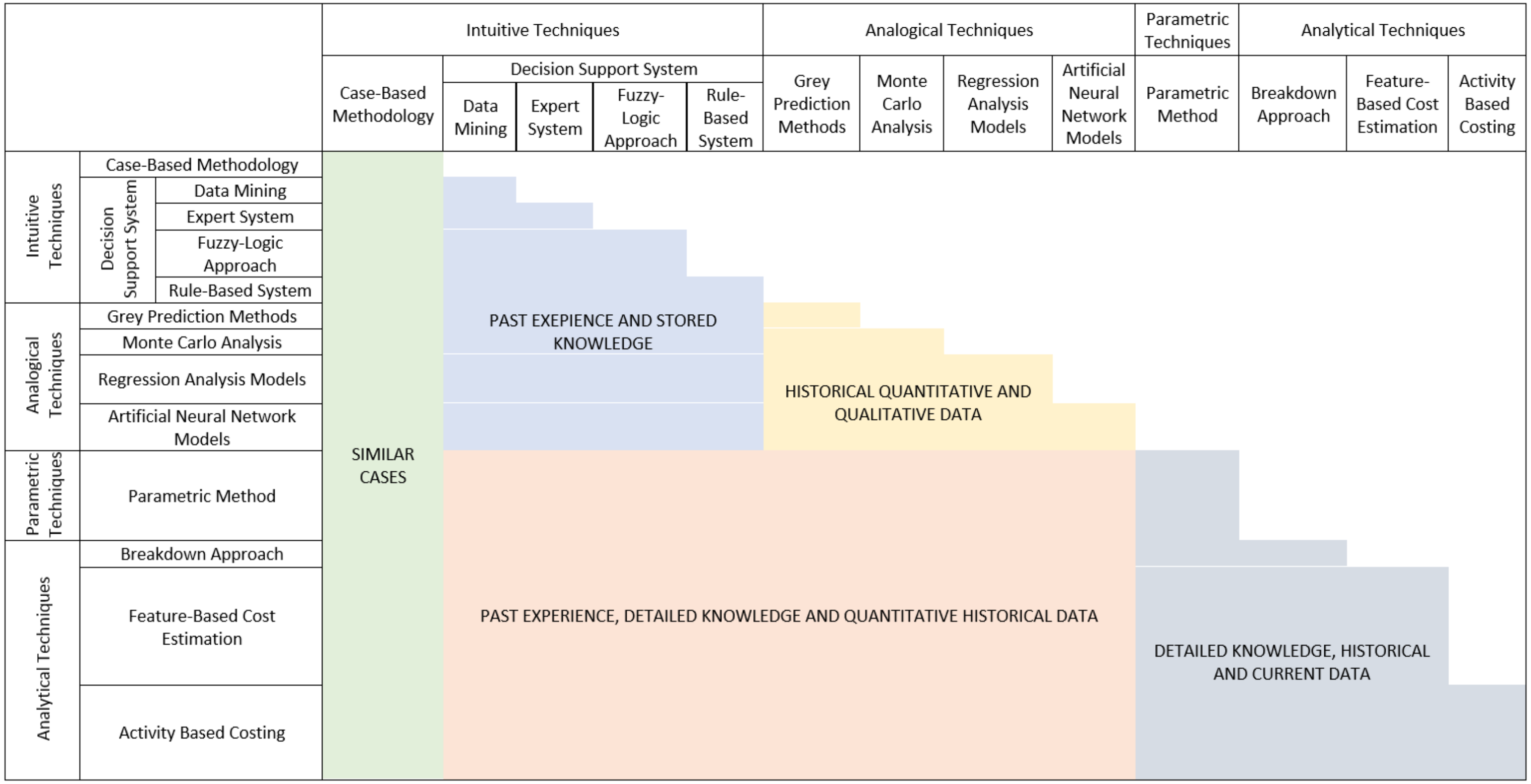
Actually, the quality and the accuracy of the output required for the estimation is the other complementary aspect that has to be taken into account in choosing the appropriate techniques for cost analysis. In fact, the accuracy of estimation is related not only to the nature of the adopted approach but also to the precision of the applied technique, whose choice often depends on the information available (the input).

In general, the accuracy increases moving from the Intuitive Techniques to the Analytical ones, both considered as standalone and integrated. Figure 7 clusters the different groups, according to the information available at the time of the cost estimation.

In particular, when detailed qualitative information (such as knowledge and technical experience on previous product or processes, experts' opinions, research papers, sector's catalogues and manuals, etc.) is available, Intuitive Methods are chosen in order to structure the data and prepare the input for the cost estimation methods. When this knowledge, in particular, is expressed for similarity to previous projects, the Case-Based Methodology is then preferred (Chang, et al., 2012; Fazlollahtabar & Mahdavi-Amiri, 2013; Wang, et al., 2011; Tu, et al., 2007) among the Intuitive Techniques. When extensive, and mostly qualitative, historical product configurations and cost data are instead available, Analogical techniques are applied, although the degree of precision of the data collected is different based on the purpose of the analysis. In some cases, the historical database is used to extract very detailed characteristic on the product and the manufacturing process (Duran, et al., 2009; Quintana & Ciurana, 2011; Luiza, et al., 2014). In some other cases, only a few quantitative and influential qualitative parameters are employed as input for the Analogical model (Seo & Ahn, 2006; Lee, et al., 2011; Hongzhuan, et al., 2013). If an exact estimation is not wished, Analogical techniques represent a good compromise regarding data availability and good result of the analysis.

If the quality of the stored knowledge, the amount of experience and historical data on previous projects increases, Intuitive or Analogical approaches can be integrated with Parametric or Analytical Techniques, to deepen the level of analysis and therefore improve the output precision. In these cases, data regarding product models (Tu, et al., 2007; Thokala, et al., 2010), product structure (Zhao, et al., 2015), design and process specifications (Watson, et al., 2006), material information (Madan, et al., 2007), resources allocation (Lindholm & Suomala, 2007), production and quality requirements (Madan, et al., 2007; Wang, et al., 2011) can be desidered as a input for the cost estimation.

Figure 7 Input information needed by different techniques



A similar requirement in the detail of the past cases, experts experience, storage knowledge and actual data, is necessary for integrating Parametric and Analytical Techniques, resulting in the highest degree of accuracy compared to the other techniques. Historical data are the mostly used to derive information regarding product decomposition, either by the BOM of similar cases (Castagne, et al., 2008; Cheung, et al., 2015) or referring to the cost drivers allocation among different costs centers (Park & Simpson, 2008; Tsai, et al., 2012; Johnson & Kirchain, 2009). As soon as the product development progresses towards the detail design, also data related to the current product and process features (Johnson & Kirchain, 2009; Tsai, et al., 2012), labour rate (Cheung, et al., 2015), material prices (Cicconi, et al., 2014; Waghmode, 2014) can be included. Moreover, for the cases in which it is not possible to obtain historical or current cost information, assumptions on the model inputs are provided, as for example, on the material specification (in terms of typology, volume weight etc) (Kaufmann, et al., 2008), the operation time (Cheung, et al., 2015; Ye, et al., 2009), or expected lifetime (Haroun, 2015).

Another important aspect regards the way information can be extracted and used for the cost estimation, as well as for general design purposes. Nowadays, this topic is even more crucial since the relevance of big data matters. In fact, the process of extraction, storage and reuse of data to be used for product development is becoming a strategic point for companies' differentiation. An up-to-date review of the commercial tools available for knowledge capture and reuse in product design is then proposed in Chandrasegaran et al. (2013). The authors pointed out the importance of the knowledge representation to better understand and use the information available. Coming from the Product Lifecycle Management (PLM) perspective, therefore, a set of IT tools and models are proposed for dealing with this kind of information (Cantamessa, et al., 2012; Chandrasegaran, et al., 2013).

2.3.3 Layer 3: The Product/Process Features

PCE has been widely applied in different fields and at different decomposition levels of product architecture (parts, components or products). H'mida et al. (2006) proposes a model for mechanical parts, while examples of machined components can be found in Qian and Tan (2008) and Watson et al. (2006). Seo and Ahn (2006) propose a cost model for tracking lifecycle costs of 200 different electronics devices; while Newnes et al. (2007), develop a computer-based tool for a specific group of injection-moulded products. Some other papers instead propose models for a particular manufacturing process, like flattering, milling and drilling operations (Germani, et al., 2011), die-casting (Chougule & Ravi, 2006; Madan, et al., 2007) and welding activities (Sajadfar & Ma, 2015).

Being aware of the high diversity in the application, a further aim is to understand if there were product or process characteristics that drive the selection of one technique instead of another.

In particular, in cases of standardised products/processes, characterised by a high number of parts and modules shared between different product variants, Analogical and Parametrical techniques are the most developed approaches (Xie, 2015; Ju, et al., 2010; Hart, et al., 2012). In fact, since that product nature is mainly driven by significant product and process commonalities, the estimation process is extremely facilitated, and the number of observations is reduced. The same analysis can be easily adapted to a different product that shares the product structure (Qian & Ben-Arieh, 2008; Ardiansyah, et al., 2013), complexity (Chang, et al., 2013), functions (Chang, et al., 2012), manufacturing process (Kaufmann, et al., 2008).

However, in a few number of cases in which it was either essential to tackle with a comprehensive estimation or to investigate the impact of different activities on a single part in the product family, the Activity Base Costing (Park & Simpson, 2008) and the Breakdown Approach (Tu, et al., 2007; Cicconi, et al., 2014) are the most applied techniques. In the case of non-standard, and/or large complex products, cost estimation is frequently performed analytically (Castagne, et al., 2008; Waghmode, 2014).

On the other hand, differences in the application of each particular technique can also be referred to the industrial sector the estimation is made for. In classifying the contributions according to a specific industry, the aerospace and aeronautic industries are the most investigated, followed by the automotive industry, as depicted in Figure 8.

The Analytical techniques are extensively used in the Aerospace and Steel Manufacturing sectors, while both Analytical and Analogical approaches are employed in the Automotive industry.

In particular, among the analytical techniques applied to aerospace products, the majority of the contributions use Parametric (Watson, et al., 2006; de Cos, et al., 2008; Chang, et al., 2013; Heller, et al., 2014; Zhao, et al., 2015), or Analytical methods (Lindholm & Suomala, 2007; Thokala, et al., 2010; Cheung, et al., 2015; Castagne, et al., 2008; Ye, et al., 2009; Lin, et al., 2011), both as a standalone (Cheung, et al., 2015; Castagne, et al., 2008; Ye, et al., 2009; de Cos, et al., 2008; Chang, et al., 2013; Heller, et al., 2014) or integrated approaches (Lindholm & Suomala, 2007; Thokala, et al., 2010; Watson, et al., 2006; Kaufmann, et al., 2008; Zhao, et al., 2015; Lin, et al., 2011), in order to generate high-quality analysis, mostly due to the geometrical characteristics or the complexity of the processes.

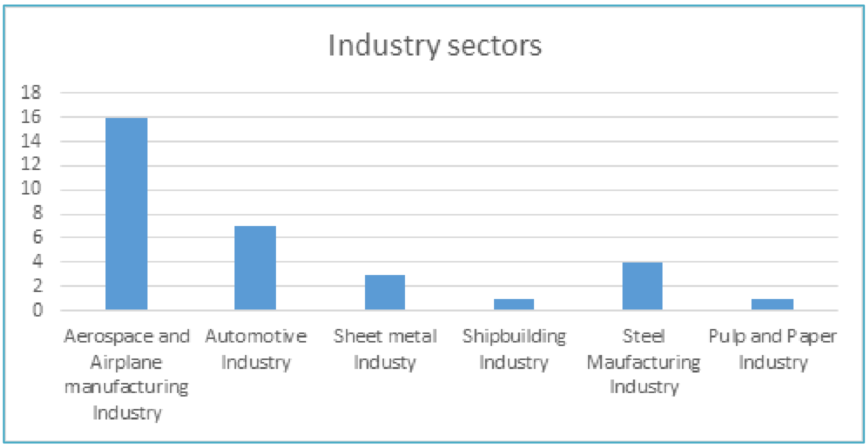


Figure 8 Subdivision of papers among industry sectors

In the steel manufacturing sector, the Feature-based approach is instead the most employed (Wasim, et al., 2013; Johnson & Kirchain, 2009; Liu, et al., 2008), due to the necessity of taking into account both technological features related to the product (as the steel typology, physical characteristics, and standards) and the high variety of manufacturing methods and process. This is common in the continuous production industry (e.g. for pulp and paper production (Tsai, et al., 2012)).

The high similarity of components and parts, as well as the presence of historical data, justify the use of Analogical techniques in the automotive industry; they, in fact, generally represent a good deal of accuracy and effort required (Ju, et al., 2010; Roy, et al., 2008; Ju, et al., 2009). Some cases characterised by a high product complexity, requiring more detailed analysis, represent an exception (Cicconi, et al., 2014; Agyapong-Kodua, et al., 2014; Ardiansyah, et al., 2013).

2.3.4 Layer 4: The Application Goal and Application Phase, and the Owner

The activity of PCE is commonly performed during the early development phases, as well as through the whole development process. However, as pointed out by several authors (Asiedu & Gu, 1998; Dowlatshahi, 1992), the majority of the costs are committed during the early design phases, while the actual costs occur mainly from the commencement of manufacturing. At this stage, it is fundamental to make the right design decisions (e.g. component choice, make or buy evaluation, supplier selections, resource planning) to avoid financial losses and inefficacy in achieving cost control.

The majority of the reviewed papers present models or approaches meant for an early application in product development. In particular, as shown in columns of Table 6, 59% of the contributions refer to conceptual design, followed by 33% of models/methods developed for more advanced phases such as detailed design. Only 6% of the papers are applicable at the planning phase. Just one contribution proposes a dynamic cost analysis that can be used at different phases of development, as well as at the later phases of product lifecycle (Lindholm & Suomala, 2007).

Figure 9 shows the frequency with which classes of techniques are used during the product development process. In particular, the Analogical category consists of the most employed techniques at the conceptual phase, both standalone and integrated, while quantitative techniques are more often applied at the detailed design phase (e.g. Rush and Roy (2000); Newnes et al. (2008); Farineau et al. (2001)). Some examples of Analytical application at the conceptual design phase are reported, especially considering the integration of these with Intuitive, Analogical and Parametric techniques. In fact, in these cases, the latter complement the former, since they feed analytical approaches with the right amount of detailed and pre-analysed data. In these cases, the benefit of the integration is demonstrated, by allowing an early use of more advanced approaches from the conceptual design phases.

In only two cases, Analytical Techniques are used as a standalone application. The particular examples, however, are based either on the redesign of an already existing product family (Park & Simpson, 2008) or on information coming from suppliers, designers and experts, as well as assumed by theoretical knowledge (Cheung, et al., 2015).

A final way to further classify the available cost estimation techniques is to include the viewpoint (and/or the purpose) adopted by the authors (Korpi & Ala-Risku, 2008; Asiedu & Gu, 1998; Settanni, et al., 2014) in performing the cost estimation, such as support a design evaluation, affordability studies, product or process comparison. Different purposes are indeed possible and the same analysis can be driven by several aims. However, often a leading perspective is identifiable, either because it has been declared by the authors or because it is evident from the result discussion.

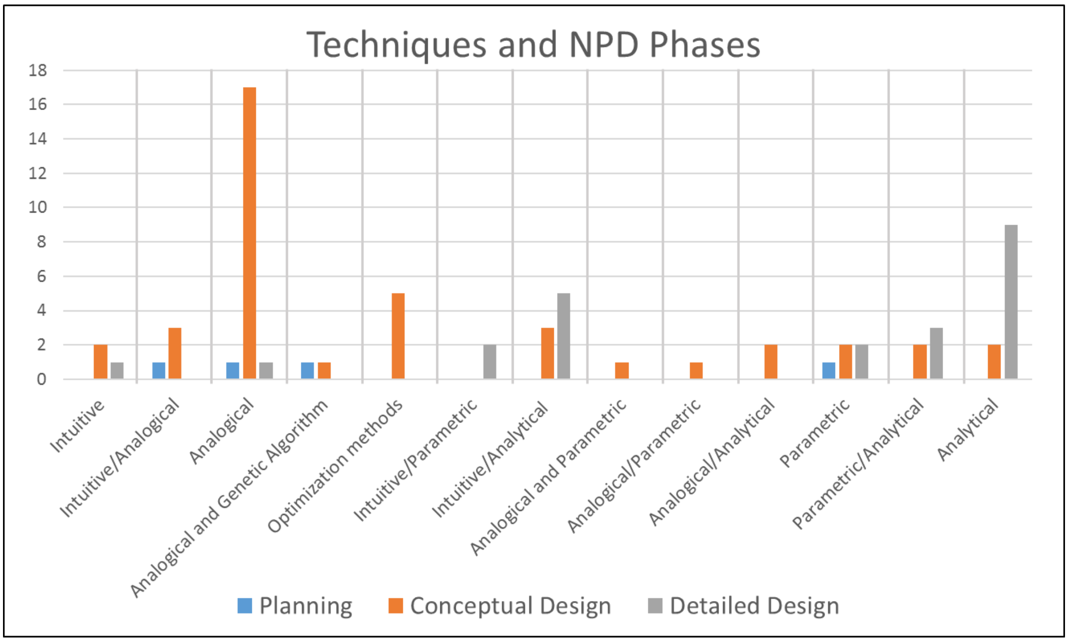


Figure 9 Techniques used by NPD phases

Table 6, consequently, aims to classify the main purposes of the analysis (i.e. the rows of the table) with respect to the development phases (i.e. the columns). What emerges is a clear characterisation of the proposed models and some possible patterns of application.

In 26% of contributions, the scope of the analysis is to provide a one-time cost estimation for evaluating the economic sustainability of a development project. The focus is on obtaining quick answers for product/project quotation, performed mainly between the Planning and the Conceptual Design phase. In fact, the majority of these contributions set their case study in Engineering-to-Order (Lee, et al., 2011), or Make-to-Order (Wang, et al., 2011; Verlinden, et al., 2008; Liu, et al., 2008) environments that are characterized by strict requirements of controlling the cost and forecasting profits before starting the development. The importance at this stage of high accuracy is evident since an underestimation will result in losses, while an overestimation will prevent a company from remaining competitive. However, only three contributions in this group perform the uncertainty analysis. Moreover, the most of them adopt Analogical approaches. This could be mainly due to the necessity of obtaining a good estimation without investing much effort in looking for detailed analyses usually required by more quantitative techniques.

For 16% of contributions, the aim of the developed model is to generate design alternatives and optimise them in terms of number of product functions (Brunoe & Nielsen, 2012), physical and geometrical characteristics (Kaufmann, et al., 2008), performances (Fazlollahtabar & Mahdavi-Amiri, 2013; Saravi, et al., 2008), or according to a target cost (Waghmode, 2014; Thokala, et al., 2010; Kleyner & Sandborn, 2008). The main difference of this group of papers, compared to the others, is in the techniques used to perform the analysis. In fact, optimisation methods are employed the most in this case. In particular, Cerri et al. (2013) propose a model for optimising product lifecycle costs and environmental impacts of an assembly line, manufactured by an Italian company. Saranga and Kumar (2006) deal with the optimisation of the maintenance costs and relative replace/repair decisions of an aircraft engine. Both of them use Genetic Algorithms for the optimisation since these techniques show a better robustness in dealing with complex problems with a large number of parameters. In simpler cases, instead, linear programming is considered enough (Lin, et al., 2007).

For the third group of contributions, the scope is to evaluate and select different design options, by narrowing down the choice to some sensible design alternatives, in terms of costs. This kind of activity is mainly performed at the Conceptual Design phase since cost considerations are required to carry out a concept feasibility analysis at this time.

Table 6 Techniques' subdivision based on the analysis purpose and NPD Phases

	NPD Phases		
Purposes	***Planning*** (6% of the papers)	***Conceptual Design*** (59% of the papers)	***Detailed Design*** (33% of the papers)
Economic sustainability (26% of the papers)	*Intuitive/Analogical:* (Ju, et al., 2009); *Analogical:* (Ju, et al., 2010); *Analogical and GeneticAlgorithm:* (Chou, et al., 2011); *Parametric:* (Heller, et al., 2014).	*Intuitive/Analogical:* (Chang, et al., 2012); *Analogical:* (Brunoe & Nielsen, 2012; Luiza, et al., 2014; Xie, 2015; Verlinden, et al., 2008; Liu, et al., 2009); *Intuitive/Analytical:* (Madan, et al., 2007; Tu, et al., 2007); *Parametric:* (Chang, et al., 2013); *Parametric/Analytical:* (Ardiansyah, et al., 2013).	*Intuitive:* (H'mida, et al., 2006); *Intuitive/Analytical :* (Wang, et al., 2011; Liu, et al., 2008); *Parametric/Analytical:* (Tang, et al., 2012).
Alternative generation and design optimization (16% of the papers)		*Intuitive/Analogical:* (Fazlollahtabar & Mahdavi-Amiri, 2013); *Analogical:* (Lee, et al., 2011; Loyer & Henriques, 2014); *Optimization methods:* (Kleyner & Sandborn, 2008; Saravi, et al., 2008; Cerri, et al., 2013; Saranga & Kumar, 2006; Lin, et al., 2007)*;* *Analogical/Analytical:* (Thokala, et al., 2010).	*Parametric/Analytical:* (Kaufmann, et al., 2008); *Analytical:* (Waghmode, 2014).
Alternative designs evaluation (35% of the papers)		*Intuitive:* (Helbig, et al., 2014); *Intuitive/Analogical:* (Mauchand, et al., 2008); *Analogical:* (Seo & Ahn, 2006; Wang, 2007; Duran, et al., 2009; Helbig, et al., 2014; Che, 2010; Roy, et al., 2008; Hongzhuan, et al., 2013; Deng & Yeh, 2011; Duran, et al., 2012; Hart, et al., 2012); *Analogical and Genetic Algorithm:* (Seo, 2006); *Analogical and Parametric:* (Caputo & Pelagagge, 2008); *Analogical/Analytical:* (Liu, et al., 2008); *Parametric:* (Newnes, et al., 2007); *Parametric/Analytical:* (Qian & Ben-Arieh, 2008); *Analytical:* (Cheung, et al., 2015), (Park & Simpson, 2008).	*Intuitive/Parametric:*(Chougule & Ravi, 2006); *Intuitive/Analytical:*(Sajadfar & Ma, 2015; Wasim, et al., 2013); *Analytical:* (Chen & Wang, 2007; Castagne, et al., 2008; Cicconi, et al., 2014; Johnson & Kirchain, 2009).
Product/systems comparison (17% of the papers)		*Intuitive:* (Naranje, et al., 2014); *Analogical:* (Ciurana, et al., 2008; Quintana & Ciurana, 2011)*;* *Intuitive/Analytical:*(Lin, et al., 2011).	*Analogical:* (Che, 2010); *Intuitive/Parametric:* (Zhao, et al., 2015); *Intuitive/Analytical:* (Germani, et al., 2011); *Parametric:* (Folgado, et al., 2010); *Analytical:* (Agyapong-Kodua, et al., 2014; Ye, et al., 2009; Haroun, 2015; Tsai, et al., 2012).
Supplier/Subcontractor selection (4% of the papers)		*Analogical/Parametric:* (Tu, et al., 2007).	*Parametric:* (de Cos, et al., 2008); *Parametric/Analytical:* (Qian & Tan, 2008).

Choices can concern functional requirements (Roy, et al., 2008), product architecture (Park & Simpson, 2008), the degree of commonality and modularization (Helbig, et al., 2014), maintainability (Seo & Ahn, 2006; Seo, 2006), and sustainability (Cheung, et al., 2015). At the Detailed Design phase, the evaluation of the design options concerns material selection (Johnson & Kirchain, 2009), shape definition (Castagne, et al., 2008; Sajadfar & Ma, 2015) and manufacturing alternatives (Cicconi, et al., 2014).

17% of the papers aim at comparing different products and systems. In a certain sense, the purpose would seem similar to the one of the previous group; the main difference is the specificity of the analysis that is narrowly focused on a few alternatives (Folgado, et al., 2010; Zhao, et al., 2015; Madan, et al., 2007), often concerning detailed designs.

For a few contributions, the aim of the model's application is to select different suppliers or subcontractors, at the detailed (Qian & Tan, 2008; de Cos, et al., 2008) or conceptual design phases (Watson, et al., 2006). In these cases, Parametric or Analytical techniques provide a quick benchmarking of supply possibilities, and they derive the price rather automatically.

Finally, a product development process requires the collaboration of different departments, and hence, the various actors (e.g. designers, product engineer, procurement, etc.) are involved in the analysis. Therefore, a model for PCE is often developed not only with specific purposes but also according to the different perspectives of the various owners of the analysis.

From this review, it is evident that the majority of the models are developed for designers (72%), although this cannot be their area of primary expertise (Seo & Ahn, 2006). As a result, in some cases, a team of cost engineer and a designer is proposed for performing the cost analysis (Roy, et al., 2008; Zhao, et al., 2015; Lindholm & Suomala, 2007; Verlinden, et al., 2008; Liu, et al., 2009). In particular, the cost engineers are freed up to concentrate on developing, estimating and validating the relations between cost driving parameters and final costs. Simultaneously, designers gain the opportunity to bring cost estimates into the design process, for using cost as an impact factor among the design concepts.

Only a few of models are meant for managers and designers, especially when the purpose of the cost estimation is either to come up with a final price for a specific product or to evaluate the feasibility of a project, as well as optimise the best configuration of a particular product design. Finally, only three contributions are developed for the procurement department (Quintana & Ciurana, 2011; Germani, et al., 2011; Ciurana, et al., 2008).

2.3.5 Layer 5: The Object of the Estimation

The last relevant aspect to be investigated is the object of the estimation, namely which lifecycle phases, and consequently, which cost categories (i.e. Research and Development Costs, Manufacturing Costs, Operation and Maintenance Cost, Retirement and Disposal Cost) are included in the analysis.

In most of the cases, a single phase is taken into account. Some of these models are developed considering two or more phases at the same time, while, only few contributions account for the cost of all the phases of the product lifecycle. The results are shown in Figure 10 associating every single technique to the different lifecycle phase, while in Table 7 the relative contributions are reported.

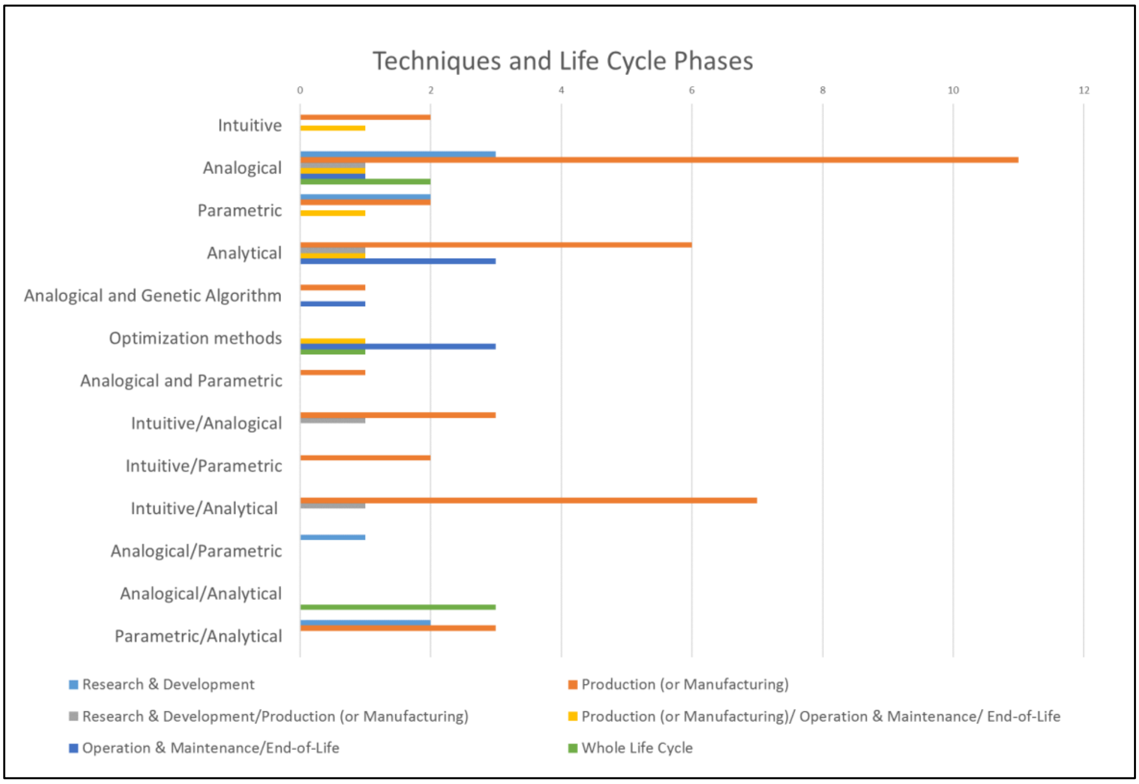


Figure 10 Techniques used in each Lifecycle Phase

Table 7 Techniques' classification according to the Lifecycle Phases

	Life Cycle Phases					
List of Techniques	*Research & Development (12% of the papers)*	*Production (or Manufacturing) (55% of the papers)*	*Research & Development/ Production (or Manufacturing) (6% of the papers)*	*Production (or Manufacturing)/ Operation & Maintenance/ End-of-Life (7% of the papers)*	*Operation & Maintenance/End-of-Life (12% of the papers)*	*Whole Life Cycle (8% of the papers)*
Intuitive	-	H'mida et al. (2006); Naranje et al. (2014)	-	Helbig et al. (2014)	-	-
Analogical	Quintana & Ciurana (2011); Ciurana et al. (2008); Deng & Yeh (2011)	Brunoe & Nielsen (2012); Che (2010); Duran et al. (2012); Duran et al. (2009); Hart et al. (2012); Lee et al. (2011); Luiza et al. (2014); Roy et al. (2008); Verlinden et al. (2007); Xie (2015); Wang (2007)	Ju et al. (2010)	Loyer & Henriques (2014)	Seo & Ahn (2006)	Hongzhuan et al. (2013); Liu et al. (2009)
Parametric	Chang et al. (2013); Heller et al. (2014)	de Cos et al. (2008); Newnes et al. (2007)	-	Folgado et al. (2010)	-	-
Analytical	-	Agyapong et al. (2014); Castagne et al. (2008); Chen & Wang (2007); Ye et al. (2009); Park & Simpson (2007), Tsai et al. (2012)	Johnson & Kirchain (2009)	Cicconi et. al. (2014);	Cheung et al. (2015); Haroun (2015); Waghmode (2014)	-
Analogical and Genetic Algorithm	-	Chou et al. (2011)	-	-	Seo (2006)	-
Optimization methods	-	-	-	Saravi et al. (2008)	Cerri et al. (2013); Saranga and Kumar (2006); Kleyner & Sandborn, (2008)	Lin et al. (2007)
Analogical and Parametric	-	Caputo & Pelagagge (2008)	-	-	-	-
Intuitive/ Analogical	-	Chang et al. (2012); Fazlollahtabar & Mahdavi-Amiri (2013); Mauchand et al. (2008)	Ju et al. (2009)	-	-	-
Intuitive/ Parametric	-	Chougule & Ravi (2006); Zhao et al. (2015)	-	-	-	-
Intuitive/ Analytical	-	Germani et al. (2011), Madan et al. (2007), Narges & Ma (2015); Lin et al. (2011); Liu et al. (2008); Wang et al. (2011); Wasim et al. (2013)	Tu et al.(2007)	-	-	-
Analogical/ Parametric	Watson et al., (2006)	-	-	-	-	-
Analogical/ Analytical	-	-	-	-	-	Liu et al. (2008); Lindholm & Suomala (2007); Thokala et al. (2010)
Parametric/ Analytical	Ardiansyah et al. (2013):Qian & Ben-Arieh (2008);	Kaufmann et al. (2008); Qian & Tan (2008); Tang et al. (2012)	-	-	-	-

A small number of studies aim at the estimation of the Research and Development Costs. All of them are applied at the very beginning of the development process (Planning and Conceptual Design phase). In particular, three contributions (Ciurana, et al., 2008; Deng & Yeh, 2011; Quintana & Ciurana, 2011) focus on the product acquisition phase, also including the procurement activities.

Regarding the techniques used for the cost model, in most of these cases, Analogical approaches are applied, and only a small number of contributions use Parametric Techniques (Ardiansyah, et al., 2013; Qian & Ben-Arieh, 2008; Chang, et al., 2013) that are appropriate in cases in which the development effort is to be estimated based on few known design parameters.

The Production (or Manufacturing) phase is the most commonly included in the reviewed contributions (around 55% of contributions). However, the adopted techniques are quite different, and no particular pattern can be identified. Both R&D and Production costs are considered simultaneously in a few contributions. In these cases, the discriminant aspect among the papers is related to the scope of the application, since for all of them the viewpoint of the estimation is exclusive for the manufacturers, which aimed at defining a competitive price for its product. In other papers, the primary focus is still in the manufacturing phase, but a first attempt at extending the analysis to the product utilization phase is provided, considering energy consumption (Helbig, et al., 2014; Cicconi, et al., 2014), maintenance (Loyer & Henriques, 2014), recycling and disposal costs (Saravi, et al., 2008; Folgado, et al., 2010). The entire picture of the whole lifecycle is not completed yet. However, a partial integration of the effect of a selected design on the users' cost is already included, mainly to evaluate different alternatives of design, or even provide the optimum solution for both manufacturers and customer needs.

Around 10%of contributions focus instead on the utilisation phase of a product during its lifecycle, neglecting the analysis of both R&D and Production activities. Among this group of papers, authors concentrate not on the users' costs, but instead on the possibility for a manufacturer to redesign and optimise a product concept, including warranty, maintenance, and end-of-life activities. In fact, the majority of the optimization models (Cerri, et al., 2013; Kleyner & Sandborn, 2008; Saranga & Kumar, 2006) are included in this category.

The last group includes simultaneously in their analysis the phases of product creation, use, and disposal, hence completing the entire lifecycle picture. While the scope of the cost estimation in these cases is different (and hence no distinctions among adopted techniques can be derived) a commonality between them is expressed by the use of Analogical techniques (Liu, et al., 2009; Hongzhuan, et al., 2013), also integrated with Analytical approaches (Lindholm & Suomala, 2007; Liu, et al., 2008; Thokala, et al., 2010). This approach may be related to the necessity of retrieving as many similar cases as possible to deal with the high uncertainty associated with the whole lifecycle process, in particular since all of the examples are at the Conceptual Design phase.

By merging the two perspectives of the object of the estimation and the application phase of the analysis, a clear picture of the most investigated phases of the product lifecycle is hence derived. The results are presented by a Bubble Chart depicted in Figure 11, where the size of each bubble represents the number of models developed in a specific phase of product development, aiming at the estimation of definite cost categories.

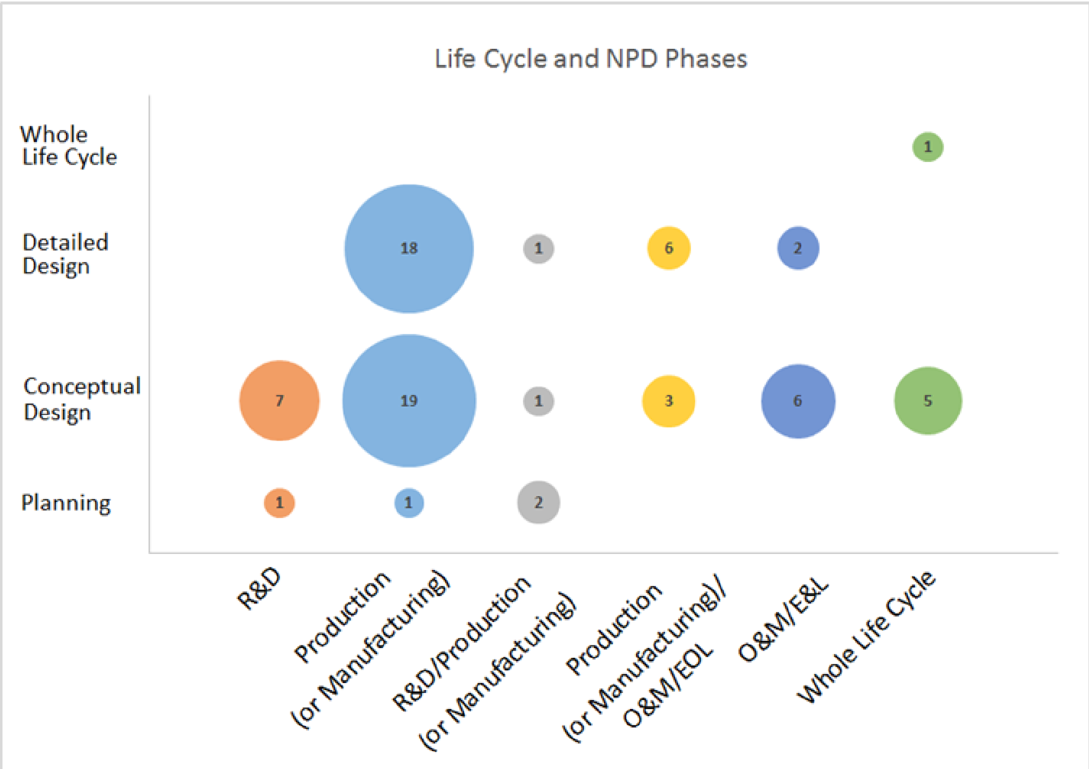


Figure 11 Number of models aiming at a specific Lifecycle Phase developed for a particular NPD process

While in general the majority of the models are designed for the Conceptual Design phase, the object of the research is on methods though for the Production phases. Although some papers try to extend the analysis to the Operation and Maintenance phase, the integration of all the lifecycle phases of the cost estimation analysis is still left, besides the relevance given to this topic in the literature.

The evidence is relevant to this research thesis since the lack of integration of all the lifecycle phases for a cost estimation can be due to the operative difficulties in the application of models for PCE in an organisation. In fact, the developed models for a whole lifecycle cost analysis, as well as the ones explicitly dedicated to the final lifecycle phases, are the most difficult to be implemented. The data collection represents one of the major obstacles, for at least two reasons. First, because the complete lifecycle process in companies is not very well understood yet. In fact, companies are still focused on their internal business activities, especially the ones until the Production phase. Second, because it is difficult to transform data into knowledge and consequently integrate this knowledge into the development process. A specific focus on these challenges will be provided in section 2.5.

2.4 Observations and Future Trends

Insights on the current trends can be derived by the analysis of the recent contributions in the PCE literature:

- While Analytical and Analogical are the most used standalone approaches, a general trend in combining different techniques in the reviewed literature results. These integrated models try to overcome the drawbacks within each single cost estimation technique. This is achieved mainly by enabling Quantitative methods to be used from the Conceptual Design phase, which in this way benefits from the accuracy of the analysis.

- The availability of the input information and how data are treated by different techniques are widely highlighted. From this analysis, what emerges is the increased use of tacit and unstructured knowledge from past products and processes in the estimation. This is made possible by using Intuitive approaches (mostly recognised in Expert Systems, Rule-

Decision System, and Data Mining Approaches) together with more Quantitative techniques.

- Another trend is also represented by the more recent interest in developing digital dynamic cost modelling, based on the most advanced methodologies available for cost estimation. In fact, dividing the contributions into Classical and Advanced techniques, based on the fourth classification suggested by Curran et al. (2004) in Table 1, some considerations can be derived. Figure 12 shows the subdivision of a number of publications (in percentage) between Classical and Advanced methods, on a yearly basis.

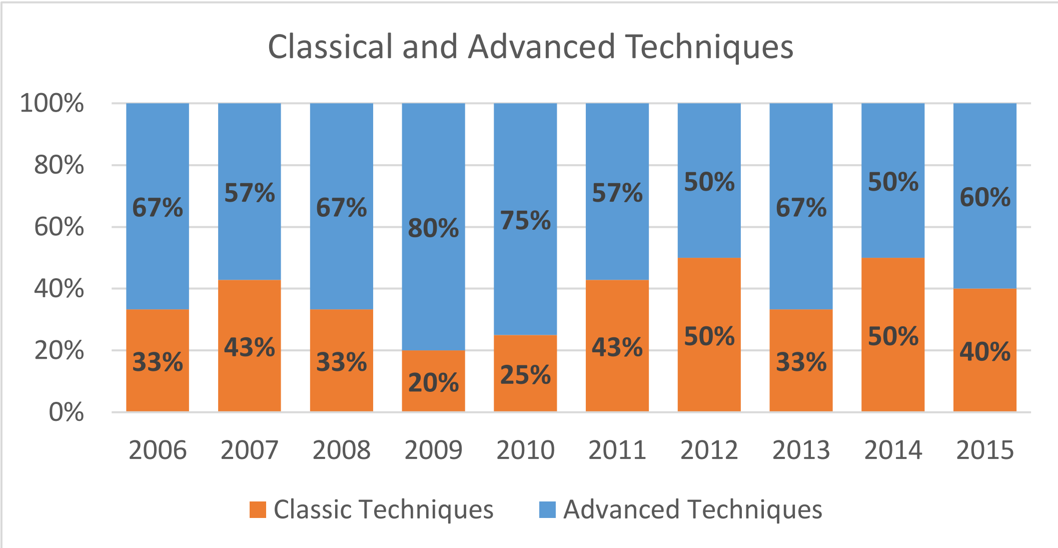


Figure 12 The subdivision between Classical and Advanced Techniques

Year by year, the number of contributions adopting Advanced techniques have been exceeding the number of models based on more Classical approaches. The difference is even more pronounced in the period from 2007 to 2012. In fact, there, the majority of the contributions insist to adopt unconventional methodologies, mostly based on Machine Learning approaches, thus showing a focus on the development of new methods in this stream of research.

During recent years (from 2013 until today) still, the use of classical methodologies are outnumbered by the most advanced ones, but the annual marginal gap between the two has been slightly lower. Based on the data collected, however, an inverse trend cannot be surely recognised. It is evident that the major effort is in providing more digital and dynamic support tools (e.g. Agyapong-Kodua, et al., 2014; Luiza, et al., 2014; Heller, et al., 2014; Zhao, et al., 2015; Wasim, et al., 2013; Sajadfar & Ma, 2015;) that dynamically reflects the change in the product design system, and provides a real-time estimation to the designers . Hence, the focus on the estimation analysis has shifted from the importance related to the single techniques adopted, be it classical or advanced, to the need for collecting quicker information and providing immediate response to the development team in particular, during the early phase of product development (Agyapong-Kodua, et al., 2014; Sajadfar & Ma, 2015)

- Still, there is a lack of models that deal with the uncertainty related to the cost estimation, proven by the deterministic output presented in the majority of the reviewed papers. Hence, this can be a future area of investigation.

- In general, the majority of the models are applied at the Conceptual Design Phase, sealing the recognised importance of the cost estimation at the beginning of a product development process. The purpose of the analysis still plays a more important role than the application phase, in the selection of the most appropriate technique. This underlines the importance of fixing the scope of the cost analysis right at the beginning, to understand the data that needs to be collected and level of accuracy to be expected.

- Moreover, studying the different phases and cost categories the estimation is focused on, the analysis shows that Production and Manufacturing costs are still the most frequently analysed. While a few attempts are reported in the analysis of Operation and Maintenance, only another few of the contributions consider the whole product lifecycle. The reasons can be different, spanning the availability of the data, the complete understanding of the entire lifecycle process, as well as the uncertainties that can result. Once again, this evidence shows that a lot must still be done in this stream of research.

The number of papers analysed and the different types of applications proposed can show the criticality of cost estimation in the field of Engineering Design. This work of systematisation has been necessary because even the analysis of the literature has demonstrated how differences and peculiarities among the techniques, and their applications, have not been clearly understood. The proposed multilayer framework aims to provide a more rigorous structure to the available methods, hence suggesting a reference in choosing and searching the best techniques for the specific purpose of the application.

2.5 Challenges in Implementing a Product Cost Estimation Perspective in an Organisation

From an applicative perspective, instead, the implementation of a lifecycle cost analysis is challenging for an organisation. Although companies are aware of the importance of conducting the economic evaluation of a new product or service, it has been demonstrated in several empirical studies (e.g. Korpi & Ala-Risku, 2008; Selech, et al., 2014) that it is problematic for them to define the practical use this analysis. First, because it leads to long-term cost management, when the horizon and the environment instead are uncertain (Lindholm & Suomala, 2007), second because the collection and usage of a significant amount of data from different sources (Ma, et al., 2014) require a complex data management process.

If one looks at a natural approach for building a PCE model, the main issues and challenges in an organisation can be discussed.

The general approach can be represented as divided into three modules, which contain the main steps for a product cost analysis, spanning from data collection, extraction, to their interpretation (see Figure 13). Data mining techniques, in the second module, are adopted to discover potential trend and pattern in data so to derive cost drivers, while the previously mentioned PCE techniques can be used in the third phase of analysis and estimation. For each module, the operative issues are discussed in the following.

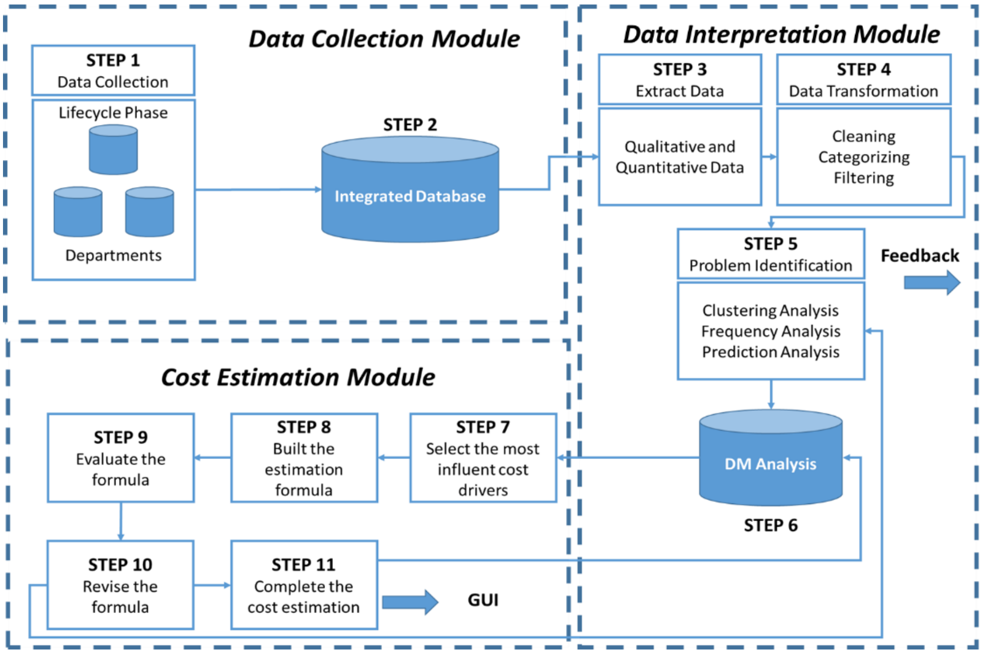


Figure 13 A general approach for PCE implementation

From a data collection point of view, the first issue is related to the need of collecting comprehensive information from different company departments, and even from several companies within a supply chain (Liu, et al., 2008). Hence, the process of extracting and evaluating data from different sources time-consuming and can, if done without rigour, affect the quality and accuracy of the analysis.

The majority of information available, as previously said, is related to the phases of product development and manufacturing; data coming from the later phases of the product lifecycle are challenging to be reached. Companies often do not have good and comprehensive IT systems, so to cover in particular processes outside the organisation (Choudhary, et al., 2009) and, consequently, this data is scarce, poorly integrated and sparsely detailed.

The problem of data reliability also concerns historical information accessible, independently of the phase of analysis. Over the years, organisations have changed and evolved, and consequently, their Information System (IS) have been updated or modified. This creates misalignments in the way information has been stored, especially for long-lasting products, and many data are missing or associated with different levels of aggregation of information.

Actually, with the objective of managing heterogeneous product-related data, companies have introduced systems to monitor and keep track of various information related to product lifecycles. PDM (Product Data Management) systems were introduced first to monitor and keep track of various information related to the product development process (Chandrasegaran, et al., 2013; Johnson, 1986). During the early 1990s, PLM (Product Lifecycle Management) was introduced, as an extension of the former. It has been defined as an integrated approach, which includes a set of methods, models and IT tools for managing knowledge along the different phases of the product lifecycle (Abramovici, 2007), exploiting, on the one hand, the increasing opportunity given by IT (Nambisan, 2003) and, proposing, on the other hand, frameworks by which enhanced knowledge management and coordination among the functional areas involved in NPD (Cantamessa, et al., 2012).

Supposing that data has been collected correctly, an enormous amount of information, daily generated, must be efficiently valued and companies must be put in the condition of benefiting from them. It is, in fact, crucial, although complicated, to convert data into information, and subsequently integrate it into knowledge, and then represent, store and reuse this knowledge (Chandrasegaran, et al., 2013).

It has been demonstrated, in fact, that designers spend a significant amount of time searching for the right product information during the design process; in particular, if one thinks that more than 75% of their activities involve the reuse of previously existing knowledge (Hou & Ramani, 2004). However, in managing this knowledge, the different software that hold the surrounding information lead to redundancy and information gaps (Labrousse & Bernard, 2008) at various phases and levels of the product lifecycle (Chandrasegaran, et al., 2013). Data is also in many cases generated by the different owners of the information (i.e. the production, maintenance function, etc.) and from here the importance of introducing previously a layer specifically on the owner of the analysis. The overall consequences are translated into a consequent turmoil and considerable inefficiencies for an organisation.

On the contrary, if knowledge is generated in an organised and reusable way, this could hence be useful for finding the better configuration of a product architecture (Hicks, et al., 2002), or for instance discovering the connection between a particular design decision at a component level and the number of failures during the product utilization. It resulted evident how much performing manually this analysis could be complicated (Shi, et al., 2015). Therefore, how to enable designers and managers to extract and effectively use available data remains still the problem (Wang, 1998), although computer-based and mining approaches are gaining importance in providing more in-depth and timely analyses (Germani, et al., 2011).

Also, the third module of cost analysis is characterised by other challenges. It has been previously discussed how different techniques, can be adopted at a specific time during the product development process. Moreover, it has been argued, how methodologically intuitive and analogical methods are usually implemented at the early phase of a product lifecycle, while Parametric and Analytical techniques have been used for the later phases of product design, as depicted in Figure 14.

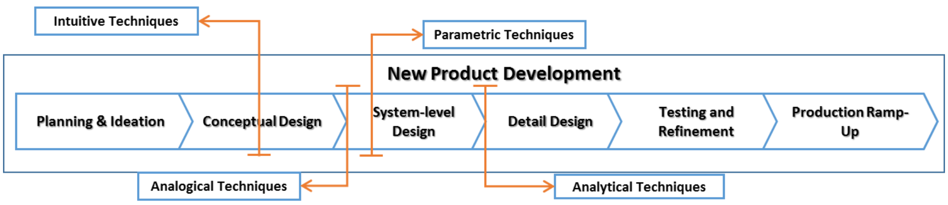


Figure 14 PCE methods and their use in the New Product Development.

The reason behind this usual practice is connected to the different aggregation level of the input information required by every single technique, which is also connected to the granularity of information obtained during the product development process itself. The granularity and level of accuracy of this information, in fact, follow the same flow of the design activities, going from a very rough set of data regarding the product and its main process until a well-specified set of production and operating details (Pahl & Beitz, 2013). The challenge is then to recognise the phase of the process and the aggregation level of information and knowledge obtained so to choose the right method for PCE and hence achieving the desired degree of accuracy. As previously said, the multilayer framework can help on this occasion. Moreover, when the analysis changes in scope and kind of evaluation at a different phase of progress of the development process, another challenge is then to integrate knowledge from the downstream phases of the product lifecycle, into the design process (Köhler, et al., 2013), reaching then the same level of data aggregation. Additionally, the interval of time between decision making and knowledge generation on its effects has to be closed and ready to be used for further changes during the development process (Bufardi, et al., 2008), being even more critical at the early design phases.

Therefore, besides the challenges described above, organisational difficulties and methodological approaches still represent the main issues. The dissertation will address both these aspects, arguing on the evidence derived from the operational and strategic impacts of rigorous implementation of PLC methodologies.

CHAPTER 3

An Integrated Approach to Product Lifecycle Cost Estimation

Based on the study of the literature, the research questions and the challenges previously identified, this Chapter will address the main research problems and issues methodologically. In particular, the first section deals with the issues of data and techniques integration, to ensure a lifecycle cost analysis from the early phases of product development. The aspects of novelty and differentiation, compared to a traditional cost estimation approach adopted in the industry, are then discussed in section 3.2. Finally, the strategic implications raised by the adoption of this methodology will be investigated in section 3.3. The idea is to go beyond a simple cost estimation purpose, thus affording opportunities for designers in their decision-making processes. This way, the purpose of the thesis will be investigated in terms of its main research questions on RQ1, how to efficiently implement PLC and RQ2, what are the strategic analyses that are consequently enabled.

3.1 An Integrated Model for Lifecycle Costing

The proposed lifecycle cost methodology (Altavilla & Montagna, 2015; Altavilla et al., forthcoming), aims to integrate qualitative information usually available since the beginning of the process, with quantitative data that is made available later, because the data is derived from lifecycle operations.

This approach, compared to others available in literature, is original both in the way it combines different cost estimation techniques and the way it achieves this integration at the early phases of the product development process.

In particular, Case-Base-Reasoning (CBR), Activity-Based Costing (ABC) and Parametrical Cost Estimation Relationship (CER) are integrated. The CBR technique is used to recover from a database past product designs that have the highest similarities with the new concept. Its integration with an analytical method, namely the ABC, is intended to include also information extended to the upstream and downstream phases of the lifecycle activities. The parametrical analysis, instead, is used to identify, at each level, the cost drivers.

This integration has been possible thanks to two main methodological assumptions:

- The requirement of moving between different data granularity levels. This was necessary because typically, the methods used are thought to be employed at different moments of the product development process, when designers move from a general concept (product level) down deep to the details (component level), to finally derive the entire design (product level again). Hence, the proposed methodology must change the reference level of the system, following the same flow of information and activities of a product development process dynamically.

- The use of a fixed set of cost drivers to perform the analysis among the different phases (used as parameters in the statistical analysis). These drivers are identified at each phase (e.g. Development, Production, Operation and Support, Retirement), but then they are shared among all the phases, and their validity has been tested on the entire product lifecycle. The benefit of this approach lies in the way designers or estimators can approach the analysis, based on a fixed number of factors that can be easily controlled and discussed for future product development and decision-making processes.

The complete methodological approach is shown in Figure 15 and described in detail hereunder.

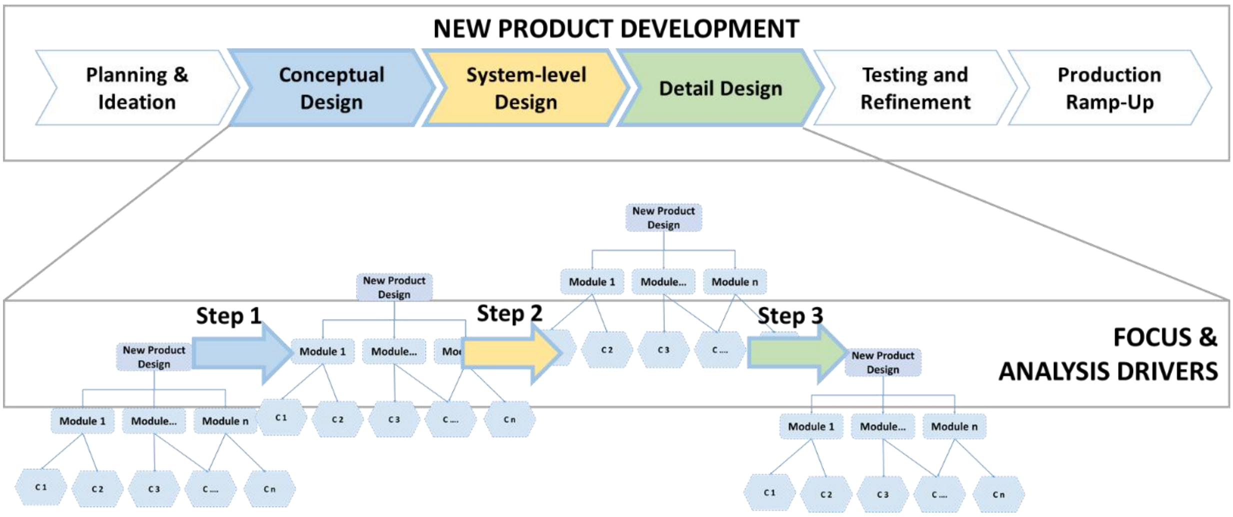


Figure 15 The integrated approach to Lifecycle Cost analysis

In *Step 1*, a traditional perspective that takes into account past product designs as a draft for the new one is adopted. Usually, designers start by considering previous products to estimate costs, verifying functional similarities between previously developed products and the description of the new design problem. Actually, different methods have been developed to retrieve previously stored knowledge from a database. In particular, Case-based Reasoning and Decision Support systems represent the two-macro categories of techniques (Altavilla, et al., 2017; Niazi, et al., 2006). However, while the former is usually employed to retrieve the closest matching between past products and the new design case (Watson & Marir, 1994; Watson, 1999; Li-hua & Yun-feng, 2004), the latter handles the information displayed in the form of domain's expert or ill-structured and fuzzy knowledge (Kingsman & de Souza, 1997; Gayretli & Abdalla, 1999; Niazi, et al., 2006).

For the purpose of the developed cost methodology, the CBR technique is better suited, primarily due to the facility of development compared to Rule-Based systems. In fact, the formalisation of past experience in the form of rules and decisions is rather complex (Duverlie & Castelain, 1999), and it is even more complicated in cases in which the area of application is wide and not very well defined (Aamodt & Plaza, 1994). Case-based reasoning systems, instead, thanks to their capacity of relying on specific knowledge of previously experienced product solutions, can be quickly developed and implemented. They can provide a suitable structure for incremental and sustained learning, due to their ability of immediately storing solutions to new experiences of products to be designed (Duverlie & Castelain, 1999). Then, the CBR is frequently used when the new design and the previous similar solution belong to the same domain, namely a specific process or a product typology (Aamodt & Plaza, 1994). Finally, the intrinsic hierarchical structure of the information provided by this technique matches perfectly the assumptions of the new cost methodology, which require exploiting data stored at different product levels (Aamodt & Plaza, 1994; Chang, et al., 2012; Rehman & Guenov, 1998). The case-based memory, in fact, can be organised in a structure of categories, following the same structure of a Bill-of-material (BOM), as represented in Figure 16. Different product levels can be hierarchically represented, and each successive step corresponds to a different level of product design, going from the end-product to the single component.

Consequently, the primary goal of implementing the CBR technique is searching for similarities, starting from the hierarchical data structures.

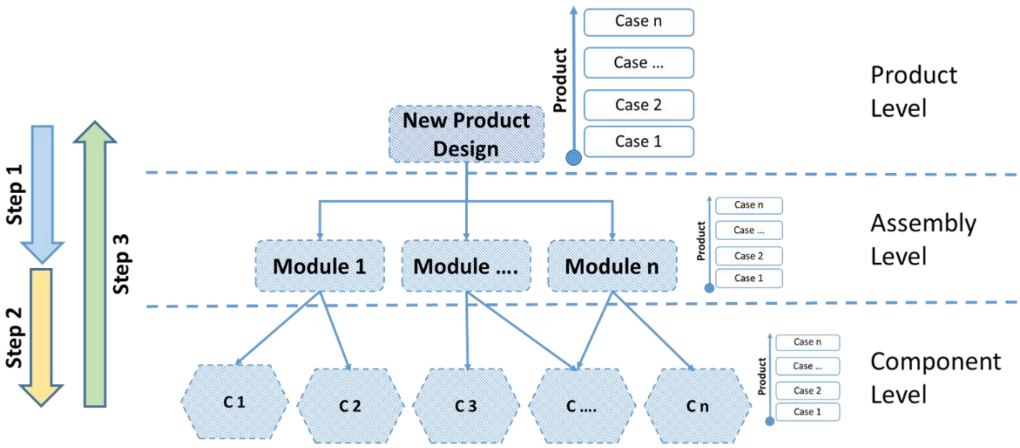


Figure 16 The hierarchical data structure for retrieving product information

It is then important to select the appropriate similarity measure, i.e., the proper measurement function between the new design and previous cases, in order to quantify similitudes between two or several product attributes (Slade, 1991).
A great number of similarity measures are available in the literature (Liao, et al., 1998), which can be easily adapted to this specific case of application. In general, the form of a similarity measure is the following:

$$Sim(N, P) = \sum_{i=1}^{n} w_i \cdot sim(n_i, p_i)$$

$$sim(n_i, p_i) = 1 - dist(n_i, p_i)$$

$$dist(n_i, p_i) = \sqrt{(n_i - p_i)^2}$$

where

Sim (N,P)	is the total similarity of the new case compared to previous examples in the database
$sim(n_i, p_i)$	is the similarity of each product attribute of the new case compared to previous examples in the database
$dist(n_i, p_i)$	is the geometrical distance of each product attribute of the new case compared to previous examples in the database
n_i	attribute i value of the new case
p_i	attribute i value of the previous case
w_i	the weight of the attribute i
n	number of attributes

The similarity of each attribute ranges from 0 to 1, where 1 corresponds to two cases having exactly the same values. The similarity analysed depends on the attributes taken into account (e. g. functional, geometrical, etc.). In cases of functional attributes then the analogy is mainly on product functionality.

Actually, in the case of the proposed cost methodology, the aim is not only to look at the similarities between two products, but also to understand the number of standard parts shared between two cases, as well as to investigate the architectural complexity of the entire product structure. For this reason, a particular set of similarity measures is adopted, going under the name of Commonality Indexes, mainly reviewed in Thevenot and Simpson (2006). In these cases, in fact, the percentage of the parts reused in the other previously developed product models is counted, considering the degree of standardisation between two product architectures (Martin & Ishii, 1997).

Among the different indexes proposed for this last purpose, the one employed by this methodology is the Total Constant Commonality Index (TCCI). As represented in the upper part of Figure 17, TCCI computes the relative value of the number of common elements between two products, based on the complete set of available sub-assemblies (or modules):

$$TCCIp = 1 - \frac{m-1}{\sum_{j=1+p}^{m+p} \Phi j - 1} \quad [0,1]$$

where Φj is the sum of the number of times a single module j is shared among different products

m is the total number of distinct modules

p is the total number of different end products to compare

As for the majority of similarity measures, the value of the TCCI ranges between 0 and 1. In fact, the closer the value is to the upper bound, the higher is the similarity between the two products.

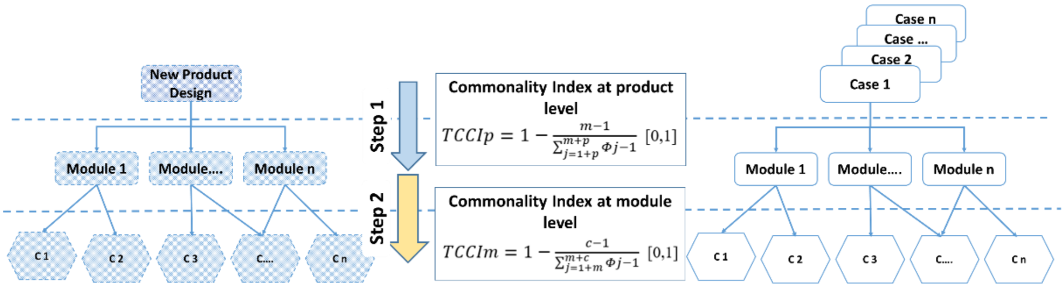


Figure 17 The commonality measures at the different level of the product tree

The information extracted and made available at this point is usually related not only to the type of product, the product segment, its performance and production volume, but also the input and output material, etc. Since past product information is already related to its lifecycle (as previous designs are already on the market), information on the production (i.e., the number of assembly operations), maintenance, usage and disposal phases is already available, a proxy of the lifecycle cost for the new product can be derived. All these data can be used by the designer as a reference to commence the cost analysis.

Step 2 focuses on breaking down the product to the level of components that can be employed in the new product design, as depicted in the lower part of Figure 17. Also in this case, the index TCCI can be employed:

$$TCCIm = 1 - \frac{c-1}{\sum_{j=1+m}^{m+c} \Phi j - 1}[0,1]$$

where Φj is the sum of the number of times a single component j is shared among different modules

c is the total number of distinct components

m is the total number of different modules to compare

In the meantime, the product development process is already at the system-level design phase. Hence, the information gathered at this step is more detailed and mainly based on the physical attributes (e.g. quantity, geometry, shape, and material) or procurement (make or buy decision) of each component. Moreover, at the component level also, the activities related to the entire product lifecycle, dividing the analysis by the phases of Research and Development, Production, Maintenance and Disposal, can be associated, as reported in Figure 18.

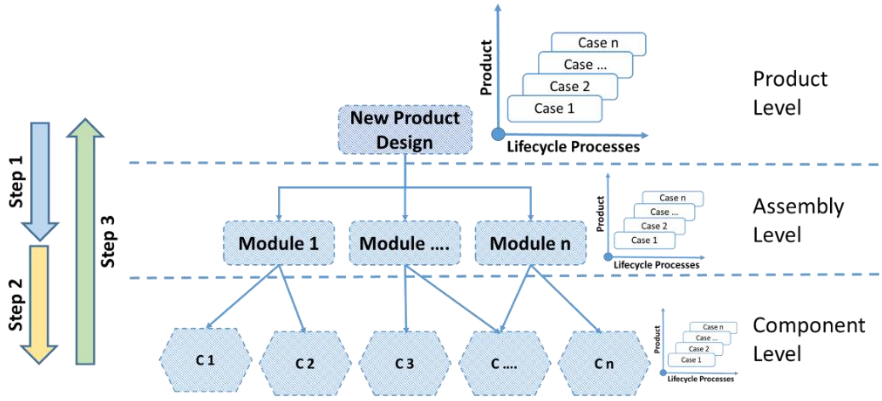


Figure 18 The hierarchical data structure for retrieving product and process information

Among the approaches available for activity cost estimation (Altavilla, et al., 2017), the Activity-Based Costing is selected. At this step, in fact, there is a need for structuring the lifecycle information coming from the CBR retrieving process, and for this purpose, the ABC is the best-suited approach (Cooper, 1988; Qian & Ben-Arieh, 2008).

Compared to other process-oriented cost estimation techniques (such as the Breakdown and the Operation-Based approaches), the ABC reasons in terms of each activity related to lifecycle phases. Moreover, the ABC is preferred in contexts where decisions should be taken on new product families design (Park & Simpson, 2008). In fact, this method allows a precise definition of which costs can be directly allocated to a single product, activity by activity, together with the identification of the main cost drivers.

When an entirely new product is designed, and there are no previous cases available in the database for it, the ABC can still be an adequate bottom-up approach, although onerous, for cost estimation, which can be immediately implemented at the early design phases (Qian & Ben-Arieh, 2008).

If one adopts Activity Based Costing for this purpose (Cooper & Kaplan, 1988), the first integration between methods occurs. On top of the past information coming from the CBR approach, the resources consumed by each activity, together with the operational (i.e. working days, hours per day, etc.) and the economic data (i.e. material cost, labour wage, etc.), are then added to complete the knowledge frame for the component' cost estimation. At this point, data available is still related to past design solutions and hence what is obtained is the total cost of a component related to a previous product.

However, the fact that the reference is still a previously developed product implies that components and activity costs can be used to derive the drivers that mainly influence the entire cost of each part. Hence, the level of detail obtained is such as to identify all those cost drivers that would perhaps be hidden with a higher aggregation level analysis. A list of possible cost drivers is represented in Table 8.

Once the costs drivers are identified, they can be finally considered as candidates for inclusion in the Parametric Method.

Table 8 Activity cost driver divided by lifecycle phase

Cost Drivers	*Name*	*Unit of measures*	*Activities*	*Lifecycle Phase*
Lifecycle Phase Duration	[D]	Hours	Planning, Design, Development, Prototyping, Testing, Repair	R&D, Production, Operation & Maintenance
Number of Product Variant	[NV]	Number of Finished Products	Design, Development, Prototyping, Assembling, Testing, Quality Inspection, Disassembling	R&D, Production, Operation & Maintenance, Disposal
Number of Parts	[NP]	Number of Components	Design, Development, Prototyping, Assembling, Testing, Quality Inspection, Disassembling	R&D, Production, Operation & Maintenance
Volume	M	m3 /cm3	Testing, Transportation, Prototyping	Production, Operation & Maintenance, Disposal
Number of assembly	[NA]	Number of Assembly Actions	Assembling, Testing, Quality Inspection, Disassembling	Production, Operation & Maintenance, Disposal
Quantity	[Q]	Pc.	Assembling, Testing	Production, Operation & Maintenance
Number of Modules	[NM]	Modules Number	Design, Development, Prototyping, Assembling , Testing	R&D, Production, Operation & Maintenance, Disposal
Number of Options	[NO]	Options Number	Design, Development, Prototyping, Assembling, Testing	R&D, Production, Operations & Maintenance, Disposal
Weight	[W]	Kg	Prototyping, Assembling, Testing	Production, Operation & Maintenance
Time to failure	[TTF]	Days	Transport, Repair, Testing	Operation & Maintenance
Number of disassembling operations	[ND]	Number of Disassembling Actions	Disassembling, Reassembling, Transport	Production, Operation & Maintenance, Disposal

In the PCE literature, at least two different Parametric cost estimation methods can be identified (Duverlie & Castelain, 1999; Qian & Ben-Arieh, 2008), viz., the method of scales and statistical models. The former expresses the estimation as a ratio of cost to a leading driver essential for the cost analysis (e.g. €/kg in cases in which the main driver is the weight). Hence, it is necessary to identify the most significant technical parameter and the ratio of the cost to the parameter. Although it is a straightforward method, most of the time, it lacks in accuracy due to its inherent assumption of a linear relationship between the value of the selected parameter and the cost (Qian & Ben-Arieh, 2008). Statistical models, instead, organise historical information using a mathematical relationship to connect the cost of a product to a set of selected parameters (Dean, 1995). In particular, multiple linear regression models (Brunoe & Nielsen, 2012; Liu, et al., 2009; Poli, et al.,

1988) result in the most adequate approaches to perform the analysis, for which previously retrieved and structured knowledge must be connected to total cost data. In this case, indeed, the previously retrieved (by means of the CBR) and structured (by means of the ABC) knowledge must be connected to the cost of a single component or product; therefore, the cost of a single component can be described by a set of independent variables built into a statistical and logical equation, usually based on linear, exponential, and polynomial models (Sheldon, et al., 1991). This equation 0is then used to extrapolate from past and current experience the forecast to the cost of future components (Dean, 1995). The following equation can express the costs:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon$$

Where Y represents the response variable. At this stage of the methodology, it represents the total lifecycle cost of a single component

X_i represents the *i*th predictor, with i=1, 2,…., k. Each predictor corresponds to one of the previously identified cost drivers

β_0 is the intercept of the equation

β_i corresponds to the coefficient which quantifies the association between that variable and the response. It can be interpreted as the average effect on Y of a one-unit increase in Xi, holding all other predictors fixed.

ε is the prediction error that is the increment by which any individual Y my fall off the regression line. It is typically assumed independent from the predictor *X*.

The cost drivers in Table 8 are therefore used as predictors. Designers can simulate and estimate the expected cost of the components of the new product since different types of parametric functions can be experimented with, until the best one is found. The parameters for the Parametrical model are subsequently derived. They, in fact, time by time, can link their design alternatives to cost alternatives, by evaluating how design variations affect component lifecycle cost (e.g. they can assess how by choosing a material or a component, the cost of future maintenance would change).

In *Step 3*, the method aggregates information back to the product level, in order to calculate the overall lifecycle cost of the product. The cost drivers identified at step 2, together with the parametrical equation, can be re-employed to provide the lifecycle parametric equation, at the product level.

Meanwhile, since the product development process already has progressed at the Detail Design phase, the cost estimation can be replaced, at least partially, by the actual data on the new product now made available (e.g. being the cost of some components known at this point). This is not an obvious step since designers have the opportunity to replace the estimation with actual data, to finally obtain a more accurate calculation of cost information.

Figure19 shows the flowchart of the entire methodology, explaining, step by step, the integrations between the cost estimation techniques.

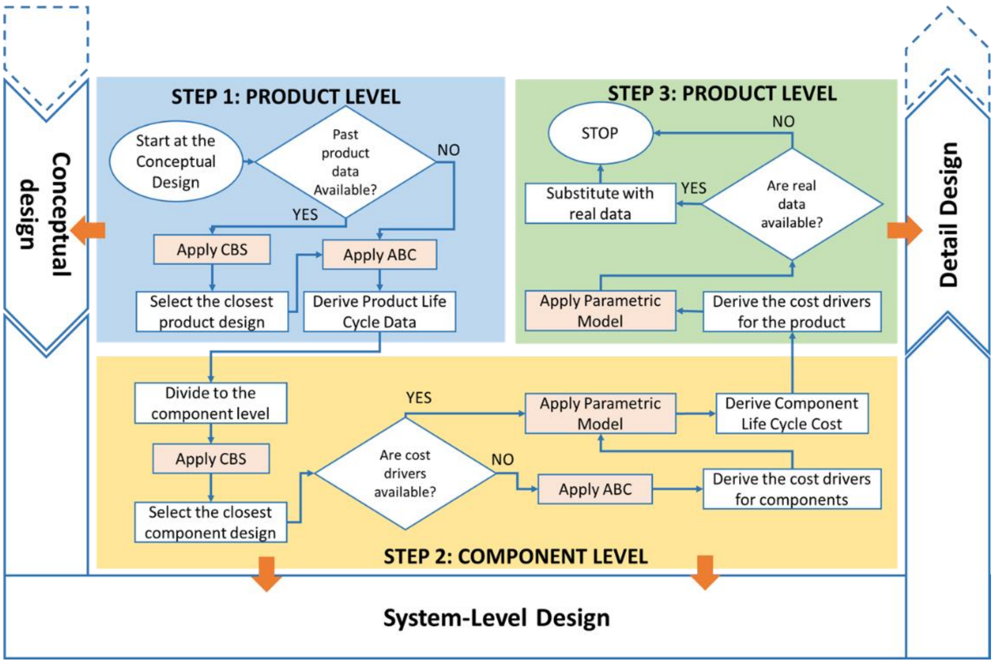


Figure 19 The flow chart of the integrated approach for Lifecycle Cost analysis

The obtained output is first an early evaluation of costs, which can be immediately implemented at the conceptual design phase. However, what is more, important is the information structure that results from the data collected and analysed. In fact, structuring the information at the different levels of the product tree provides a symmetrical framework to the lifecycle knowledge. This can be successively implemented in greater depth operative and strategic analysis. Figure 20 lists some instances of knowledge elements that are derived.

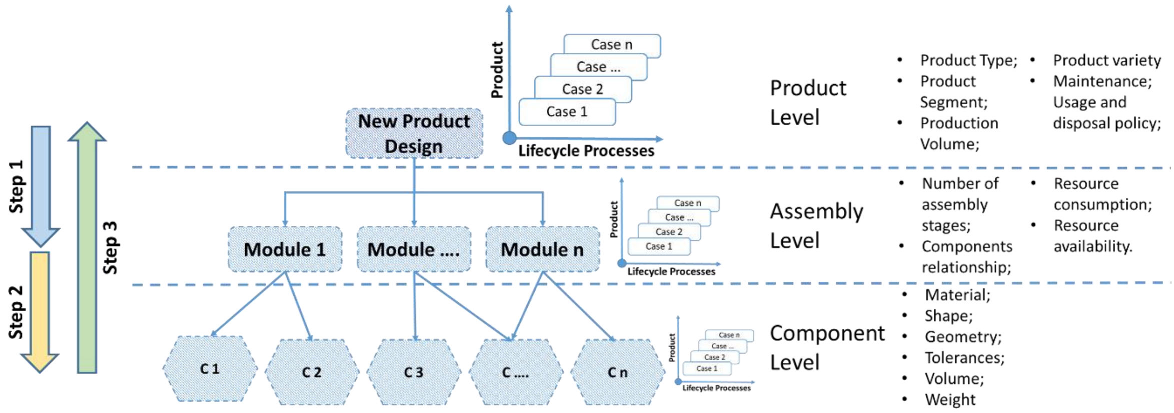


Figure 20 The data framework related to the different aggregation level of the Product Tree

At the component level, data concern the shape, geometry and tolerances, together with the volume and weight of each part. At the assembly aggregation level, for instance, the process aspect is fundamental, since that is where the highest consumption of resources for product production occurs. Hence, at this point, a better view of the possible operative costs is available as data, which can be analysed to define the cost of the activity. Finally, at the product level, the information extracted and made available is usually related to the type of product, the product segment, and its performance and production volume. The abstraction at this point is such that a general view of the possible product variants is available in a single family and the degree of the offered variety.

Therefore, once the data is presented at these different degrees of granularity with respect to the product tree, there are various advantages for further investigations. For instance, if the aim is to choose between different production processes of a single component, maybe the bottom level of the data frame can be useful to inform decisions. On the contrary, if the concern relates to the degree of differentiation of a product line on the market, data coming from the product and assembly aggregation level are better suited.

Considering the high number of information sources, as well as the intrinsic nature of the cost estimation itself, taking into account the uncertainty (both epistemic and aleatory) may be useful. Different approaches at this point can be applied. Analytical and computational methods such as the Monte Carlo simulation can be at this point used for uncertainty propagation. However, probabilistic methods although suitable for characterising aleatory uncertainty may be less useful when statistical data is seriously lacking or when the uncertainty is caused by lack of knowledge (Xu, et al., 2012).

3.2 Conceptual Validation

Comparing the three techniques used in the methodology, against the characteristics of each layer proposed in the previously introduced multilayer structure according to section 2.2, as reported in Table 9, it can be understood as to how integration makes possible the fulfilment of all the requirements proposed by the structure.

Table 9 Layers' requirements list for the three techniques included in the methodology

Legend: ○ Not Fulfilled; ◖ Partially Fulfilled; ● Fulfilled	**Layers' requirements**									
	Layer 1		**Layer 2**				**Layer 3**	**Layer 4**		**Layer 5**
Techniques	*Need of integration*	*Compatibility with a new product or process concept*	*Qualitative input information*	*Quantitative input information*	*Qualitative findings*	*Quantitative findings*	*Adaptability to complex products and processes*	*Compatibility with early design phases*	*Easiness of development and use*	*Applicability to the whole lifecycle*
Case-based Reasoning	Fulfilled	Not Fulfilled	Fulfilled	Not Fulfilled	Fulfilled	Not Fulfilled	Not Fulfilled	Fulfilled	Partially Fulfilled	Not Fulfilled
Activity Based Costing	Not Fulfilled	Fulfilled	Partially Fulfilled	Fulfilled	Not Fulfilled	Fulfilled	Fulfilled	Not Fulfilled	Not Fulfilled	Partially Fulfilled
Parametric methods	Partially Fulfilled	Partially Fulfilled	Not Fulfilled	Fulfilled	Not Fulfilled	Fulfilled	Partially Fulfilled	Partially Fulfilled	Fulfilled	Fulfilled

In particular, where one technique fails in providing a specific benefit to the cost estimation process, its integration with the other two can help in this purpose.

Looking at Layer 1 (the Nature of the Technique), while CBR, by nature, needs to integrate with other techniques, ABC is included here to provide a stable structure to the methodology. Moreover, ABC and in part Parametric methods, allow the use of the new method for the cost estimation of entirely new products or technologies.

Going to the second Layer (the Nature of the Analysis), the need for handling both qualitative and quantitative information is fulfilled, thanks to the combination of all the techniques. The accuracy of the estimate is also taken into consideration, is taken into consideration as now CBR is complemented by ABC and Parametric Methods, which allow a more stable result than the CBR technique alone.

Going to Layer 3 (the Product/Process Features), the adaptability to complex situations has also been satisfied, thanks to the use of the ABC method, which, as a bottom-up technique, can be applied to complex and innovative products and processes.

As concerns Layer 4 (the application Goal and Application Phase, and the Owner), it has been argued that the objective of achieving an estimate in the early phases of product development can be achieved through the use of qualitative techniques. To this purpose, the new methodology employs the CBR approach immediately in the estimation process.

Finally, going to Layer 5 (the Object of the Estimation), the requirement of obtaining a whole lifecycle estimation is fulfilled thanks to the employment of the Parametric techniques, which more than the others, allows quantitatively exploration of each phase, using information that has been obtained with the CBR and ABC techniques.

3.3 Elements of Originality

If one compares the proposed new approach with the traditional one adopted in the industry (e.g. the general ones proposed by Niazi et. al. (2006)), some aspects of differentiation can arise. In particular, as represented in Figure 21, they differ methodologically both in the estimation process and in the integration between techniques.

The proposed methodology, in fact, integrates qualitative and quantitative methods from the very beginning, regardless of the type of information available at the Conceptual Design Phase. If on the one hand the possibilities of integration have already been explored in the literature (Altavilla, et al., 2017), this methodology is different, because it focuses more on the typology and amount of data that can be extracted and made available for the cost estimation, followed by the integration of the best methods that can help this purpose. In fact, the two phases of exploring the available data and choosing the technique should be usually contextual.

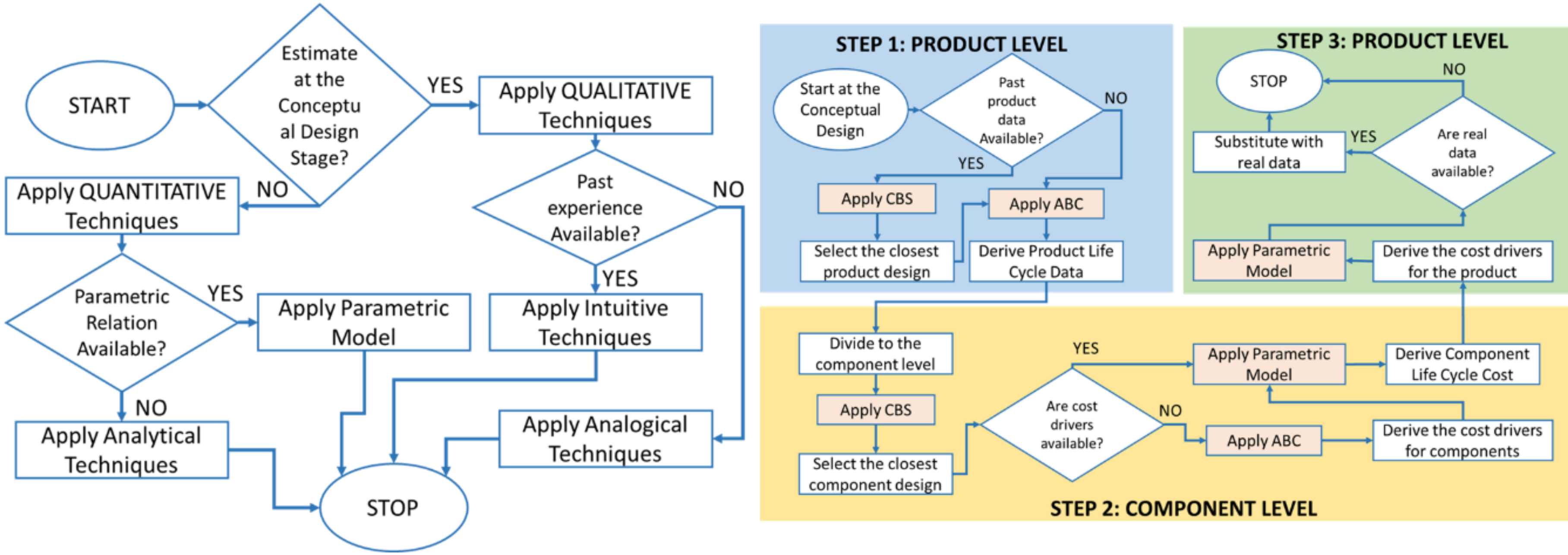


Figure 21 A traditional approach for PCE (adapted by Niazi et al., 2006) (a), and the integrated model for Lifecycle Costing (b)

This type of approach moreover allows an unusual pairwise integration among the three techniques, namely the Case-Based reasoning, the Activity Based Costing, and the Parametric Methods.

The first integration of the CBR and ABC techniques is already different from the other combinations available in the literature (e.g. Wang et al., 2011; Qian & Ben-Arieh, 2008). In fact, the two approaches are used mainly for retrieving (CBR) and structuring (ABC) past information on similar cases. The singularity relates to how a quantitative bottom-up approach, like the ABC, is proposed here as organiser of data coming from the lifecycle process, instead of merely providing the final estimation. Moreover, it is also employed early in the design process.

ABC is used as a generator of information also, in its integration with a Parametric model. This combination, however, enhances a detailed application of a Parametric technique in the early phases of the development process. In fact, one of the major drawbacks of a Parametric approach is its inaccuracy in cases in which the cost drivers have not been identified yet (Caputo & Pelagagge, 2008). In this case, the problem has been overcome by using the ABC to provide as input the right amount of detailed information required.

The systematic change of the reference system of the new methodology, which moves between the different levels of the product structure, finally represents one of the main aspects of novelty, if one considers the way data can be collected, stored and analysed at the right granularity level, as already argued in the assumptions of section 2.5. The derived information structure represents a source for more in-depth analysis, as well as for monitoring the product during its entire lifecycle. In fact, the data collected and stored in this way can be employed for different investigations that are not immediately related to a cost analysis. It represents instead a way to store data in a more systematic and precise way, directly related to the level of granularity to which they belong, and hence allows designers to retrieve information for specific purposes.

3.4 Strategic Implications Derived from a Lifecycle Cost Analysis

Once a cost estimation methodology is applied in an organisation, different operative and strategic consequences occur, mainly due to the further analyses that are enabled. In fact, cost estimation can be seen not only as a way to evaluate the design alternatives that better solve the cost/performance trade-off, but its output can represent a resource for companies to identify and consider possible strategic decisions.

Traditionally, methods and techniques for PCE were developed for specific and very detailed applications (Altavilla, et al., 2017; Asiedu & Gu, 1998; Loyer & Henriques, 2014). Usually, the aim was to suggest most cost effctive design alternatives (Brunoe & Nielsen, 2012; Fazlollahtabar & Mahdavi-Amiri, 2013; Waghmode, 2014), or to evaluate and help selecting different design options, by narrowing down the choice to some possible design alternatives (Helbig, et al., 2014; Lee, et al., 2011; Loyer & Henriques, 2014). As a consequence, the implications derived from the cost analysis were limited to the most regular evaluation of different cost profiles.

However, at the end of a cost estimation process, a detailed breakdown of costs, besides in-depth knowledge of a product lifecycle processes, can enable further relevant operative and strategic decisions. In fact, at this phase, investigations on the relevance of product standardisation and the role of different product variants (as consequences of the broadness of product line) can be taken into account. In fact, by investigating the appropriate mix of component standardisation, the optimal degree of product variety can be searched, and hence more conscious planning of the product portfolio can be provided. Beyond the estimated economic return, this type of investigation can enable better decisions in the product portfolio management. Hence, a link between the specific activities of Product Costing to the strategic activities of product portfolio planning can be provided.

Coping with the effect of product variety and the quest for approaches to manage the economic impact of platform strategies have been the focus of a wide stream of literature, for years. Numerous studies have been carried out in order to exploit the advantages and disadvantages of a platform design approach (Meyer & Utterback, 1993; Meyer & Lehnerd, 1997; Meyer, et al., 1997), or the profitability of a more extensive product line (Hauser, 1999) (Kekre & Srinivasan, 1990). Moreover, the impact of product variety on manufacturing operations has been the object of several empirical evaluations, which mainly look at the influence of the variety proliferation on marketing performance and manufacturing costs (e.g. Kekre & Srinivasan, 1990).

By looking more specifically at cost implications, it has been proved that, besides obvious advantages (more market segments addressed, higher volumes, etc.) a broader product portfolio leads to both risks (e.g. cannibalization and lower product margins, Cantamessa & Montagna , 2016) and higher manufacturing and labou costs (Abegglen & alk, 1985). These can be (Clark, et al., 1988), higher product complexity (Foster & Gupta, 1990), higher material handling and inventory expanses (Abegglen & alk, 1985; Johnson & Kaplan, 1991), wider sets of defect to be detected (Datar, et al., 1990). However, with a few exceptions, the majority of studies focuses on the effect of platform strategies and variety proliferation against the production and manufacturing phase (Lin, et al., 2007). Even the models which adopt a lifecycle perspective are implemented later in the product development process, or even when the product is already in the production phase, since they require data not available during design.

Hence, very few examples are available on the evaluation of the implementation of lifecycle methodologies in an organisation, in particular on how to exploit the cost analysis, which, if applied to the whole lifecycle, provides a tide of information in support of a platform strategy.

Accordingly, in this thesis, variations in the architecture of products are examined right from differences in product lifecycle costs. Are these differences in any way explained by past design decisions at a platform level? Is it possible to provide designers with a lifecycle-cost driven tool for measuring the impact of variety proliferation?

Hence, starting from the output of the integrated methodology described in section 3.1, an empirical evaluation on the platform/architecture issues, such as the impact of product standardisation, as well as the proliferation of product variants on the entire product lifecycle is further proposed (see Chapter 5).

Chapter 4

The Application Case: Research Setting

This chapter applies the previously introduced cost estimation methodology to quantitatively measure the link between lifecycle costs and design decisions taken at the early design phases of a product development process.

The empirical study was conducted at a company that develops powertrain (both established and future powertrain systems) and successfully operates as a supplier, in the automotive sector. The integrated lifecycle cost estimation model was implemented in a particular family of products, to validate the analysis and evaluate the implications of its implementation in the company. The study was conducted by exploring the company's main business processes, to have a complete view of the entire product lifecycle. The three integrated cost estimation techniques were applied to each product lifecycle phase. Different significant costs drivers were selected and extracted from each phase (namely Research and Development, Production and Operation and Maintenance), and the final Parametric model was then presented.

In particular, in section 4.1, the main challenges for the automotive industry are explored, and the requirements for cost estimation methodologies are derived. section 4.2 focuses then on the selected company, as a technology supplier to leading automakers in the sector and hence it explores its specific requirements for the application. The steps in data collection and integration are clarified in section

4.3, while the dataset and the methods used for data extraction and cleaning are finally reported in section 4.4.

4.1 The Context: The Automotive Sector

The automotive industry is one of the most challenging and vital sectors of the modern world. In 2017, more than 80 million vehicles (auto and trucks) have been produced, accounting roughly for 12% of the GDP of the world's developed countries. The automotive industry carries the manufacturing sector across the world. Based on 2016 data, it amounts to more than 5% of the world’s manufacturing capacity, with around 10 million workers employed between the major automakers (hereafter identified as Original Equipment Manufacturers, OEMs) and suppliers (Rich, et al., 2017).

However, the automotive market is evolving, and many challenges will shape the near and medium-term competition of the entire sector (Mohr, et al., 2013).

The first challenge is directly connected to the high level of competition that characterises this sector. In fact, OEMs and suppliers, to remain competitive, are expanding the variety of product and services offered to customers, trying to make differentiation of consumer-facing features profitable. If variety, from one side, provides benefits of differentiation and customisation, on the other side, the high number of derivatives increase the overall product costs. Automakers are hence facing problems in managing this differentiation issue, since it is essential for them to have tight control over the costs, while also successfully managing their product portfolio to ensure it is aligned with real preferences of consumers.

A second challenge is represented by the tighter regulations concerning environmental and safety standards, which are directly reflected in the rise of product complexity (due to the increase in the number and complexity of components) and consequent increase in product costs and reduction in their profitability (Rich, et al., 2017). The search for the leading alternative in the future powertrain technology, in fact, is forcing both automakers and suppliers to spend an enormous amount of time and resources in developing different competitive technologies.

Moreover, the shape of the industry is also changing, regarding the different roles played by OEMs and suppliers. In particular, the suppliers play a crucial role in bringing innovation and help the entire industry to meet the new global challenges and regulatory policies. Only in Europe, they represent the most prominent private investors in research and innovation, investing more than 20 billion Euro (CLEPA, 2017). In fact, compared to the past, automotive suppliers represent the leading innovation carriers with respect to the different technologies related to the powertrain. A dominant role in future vehicle innovation is in fact represented by the electronics and software technologies (Rich, et al., 2017). As a consequence, OEMs are more and more opting for vertical partnerships with software and electronics companies to cut the research and development costs and being more proactive in implementing new features.

Amidst this turmoil, companies, being OEMs or suppliers, have to provide the best solutions in terms of the chosen technology, design, manufacturing and quality (Park & Simpson, 2008, Roy et al., 2011), since customers always demand new and technologically advanced products with better quality and functionality. Obviously having previous performances at the same price (Roy, et al., 2011). Most of all, companies have to develop new products looking to cost consequences, recognising the importance of their decisions to the entire product lifecycle. In fact, now, more than ever, this constant pressure to reduce costs is emphasising the need for earlier information on costs in the development process (Roy, et al., 2011).

Hence, cost analysis is still a key activity, becoming more and more relevant in the sector, considering the historical period the industry is going through. According to the PCE literature previously introduced in Chapter 2, specific requirements for a possible methodology which complies with this sector, are as follows:

- A cost estimation methodology should take into account the high technologically intensive content of new products in the industry, being aware of the high degree of innovation that is also lately required (Rich, et al., 2017);

- There is a need for methodologies that can incorporate considerable knowledge and experience relating to previous projects, technology trends and new developments in other industry sectors (Roy, et al., 2011). This is even more important, considering the influences exerted by different other sectors (e.g. software and electronics).

- There is a need for more reliable approaches that will allow quick and more realistic estimations, permitting a fast comparison of the different new technologies to be developed in the near future (Rich, et al., 2017).

4.2 The Case Company

The company under investigation is one of the largest automotive suppliers for development, simulation and testing technology of powertrains (such as hybrid, combustion engines, transmission, electric drive, batteries and software) to be employed in passenger cars, trucks and large engines of all the major OEMs. This sector is highly concentrated: there are six major competing companies, most of them of European origin, which have been active in this field for decades, plus several new small players from emerging markets.

The instant company employs over 8000 people around the world, spread over the headquarters and the over 40 affiliates. In particular, tech centres, sales and service points are carried globally with local teams, in order to maintain a closer relationship with customers.

In line with the growth of the automotive supplier sector, the investigated company too has experienced tremendous growth. The turnover for 2017 was around 1.015 Million Euro, approximately 12.5% of which is reinvested in research and development. In this way, the company is able to offer innovative and effective technological solutions to the many new arising challenges. In fact, the company has recently entered new markets and broadened its product scope, as customer demand for powertrain development and testing is in continuous change due to different alternatives available.

The product portfolio has also registered an expansion, as the direct consequence of the expertise built up over the years. In fact, the company at first entered the market of non-road engines, providing specific testing solutions for this segment. Later, it extended its competencies to develop and test all sizes of engines and fuel, thus broadening its portfolio. Due to the demanding legislation in terms of emission, the product portfolio evolved to provide up-to-date applications for the entire automotive sector.

The different segments of products offered are also immediately mirrored in the company's business organisation. The company, in fact, is divided into three main business units aimed at developing 1) powertrain systems, 2) simulation tools and models for engine development and prototyping, and 3) instruments and systems required for engine and vehicle testing.

The company operates in an assembly-to-order mode: product models are modularly pre-designed, and components are assembled once products are sold. Hence, after a preliminary market analysis, the research and development of products start. Production will begin only when an order is confirmed. During this period, sales activities, order fulfilment and customer service of the product follow one after the other, until the ownership of the product shifts from the company to the customers.

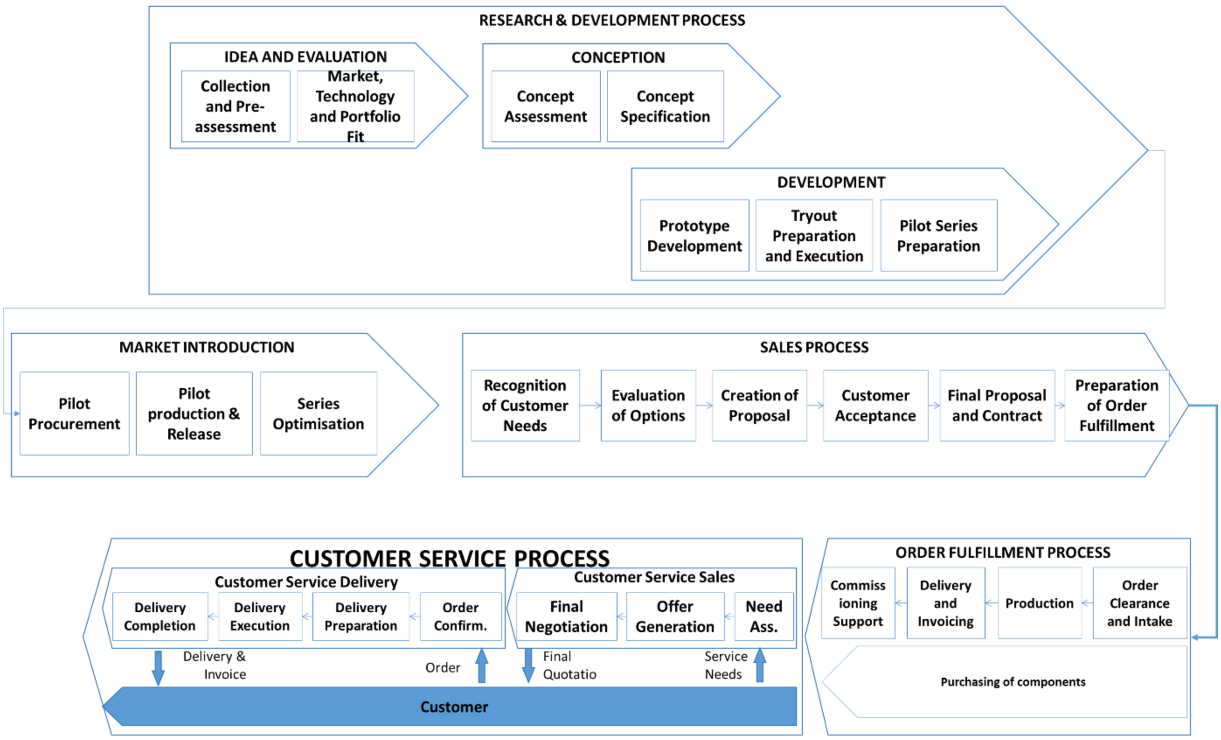


Figure 22 Company's Lifecycle Process

The research has been hence organised among the three main lifecycle phases of the company, namely Research and Development, Production and Operation and Support[2], deepened in the following.

2 The phases have been named consider the general phase of the product lifecycle

- The Research and Development process is at the basis of the primary purposes of the company’s business. In fact, besides representing the internal motion of continuous innovation and fulfilment of the regulation requests, the Research and Development process is the direct link with the customer. The company organises its development process around a regular release schedule. The development teams have monitored periods for planning, feature development, prototyping and testing, and quality control. The process is managed by a stage-gate management procedure so that between each phase, there is a checkpoint (design review) used as a control and subsequent admission to the next stage. Each step has the form of an individual project headed by a manager, who may be either the project manager or product manager. Hardware and software development, follow two different concurrent processes, with a final phase of integration and testing of the complete system. Each development cycle ends with the commercial release of a new product or an updated product variant to the market.

- Following the market launch, the product enters the phase of Production. The manufacturing, or better, the final assembly of the main part of the product, takes place as a result of the sale and the consequent acceptance and execution of the order received from the customer. Products are sold through the company sales organisation, which is responsible for the recognition of a need coming from the market, following the evaluation of the options and the creation of the proposal. Once the order is approved by the customer, it is followed by preparations for the order fulfilment and final delivery to the customer. The majority of the company’s products are plug and play, but the customer could request an additional installation and commissioning support.

- Once the product is sold, the phase of Operation and Support starts. The company provides support to products during its operative life through the helpline service, as well as with commissioning services during the first phase of product installation and early testing. During the process of repair, maintenance and calibration, according to the problem, the company provides different solutions. Preventive or Corrective maintenance (repair and adjustment in the event of a system failure) is carried out in "ad hoc" service interventions, with spare parts provided by the company, both during the warranty period and after, until the product disposal.

In order to regulate all the internal and external activities, the company recently developed corporate policies aimed at controlling the products during their entire lifecycle. Specifically, a Product Lifecycle view was considered for the implementation and fulfilment of strategies for bringing successful products on the market. The lifecycle phases as presented in the company follow the same stages of a product on the market, with a specific marketing view (Introduction, Growth, Maturity and Decline).

The content of each phase includes all relevant policies, procedures, documentation and responsibilities for the lifecycle of the product, in order to enhance the communication internally and with the customer. From the company's point of view, the application of the Lifecycle of Product view has a target of optimising product mix, affording high efficiency and alignment in respect of the product portfolio and a clear execution of tasks and duties of all the company's segments. From the customer's point of view, the application of the Product Lifecycle view provides a precise and uniform way of clarification of all the major procedures of product generation, release cycles and order fulfilment.

Apart from internal policies, the company is continuously on the lookout for methods and innovations, which can affect not only the development of products and the satisfaction of customers' demands, but also the way the company deals with the competitive environment. Hence, they are oriented towards more sustainable practices in conducting their activities, to enable identification of opportunities for cost reduction and improved efficiencies in the use of resources. However, they have never systematically applied cost analysis, but have implemented a traditional cost estimation usually based on the analogy of the new product with the previously developed ones, looking at the trends and performance of these products in previous years.

According to this perspective, the company is expected in the future to implement a policy that aims to control products from the point of overall lifecycle costs, to ensure, for the company itself and for the customers, product sustainability during its life.

The reasons why the company ideally represents the right case study are as follows:

- Initially, research and development activities were conducted in a clear and systematic way, and developers used standard tools, databases, procedures and terminology. Hence, the introduction of new cost methodologies could happen easier within a standard development process.

- It was also given the opportunity to explore the cost estimation, not only for the effects that it has on the products, but also on the development decisions and strategies. It was interesting to look at project alternatives generated after the implementation of the new methodology. Here, evaluations on how design decisions can be taken with or without considering cost estimation analysis were experienced.

Finally, the company had a robust story of data collection. In particular, data was collected for long periods without changes in IT systems; this situation represented a perfect case for investigating those design cases that had analogies with past solutions.

In implementing the presented methodology, however, different difficulties were experienced:

- First of all, the method was applied directly by designers or product managers, who were generally employees with a strong technical background, but were not always used to performing cost analyses. However, an opportunity was given to validate the presented approach, in order to acknowledge difficulties in performing the cost analysis, as well as in reading the results.

- Secondly, despite data richness and the company’s good control over the entire lifecycle processes, collecting and extracting the information from the company’s IT system was not easy. In fact, all the activities and processes involved from the earliest phases of product development to its production, as well as the post-sales policies, were already defined and specified by the company. However, this information was not organised product-wise and created difficulties in recognising the overall costs of a single product. It also created problems in the implementation of cost analysis, which in this case, was sought for a single product. Moreover, most of the information was divided among different departments of the company. That is usual: the larger the size of the companies and the greater the complexity of systems/products involved in the analysis, the higher the degree of difficulty in retrieving and integrating useful information for a rigorous implementation of PLC methodologies. This implied having a misaligned in the information collected between different departments and in the final dataset, with the consequent misunderstanding in evaluation and inaccuracy in the cost estimation.

Hence, a first step in the application of the methodology was to reorganise and centralise the available information in order to allow a more straightforward application of a cost estimation analysis.

4.3 Research Steps and Data Collection

Considering the general approach for cost analysis described in section 2.5, and focusing on its first module, the two steps of lifecycle cost data 1) Collection and 2) Integration should be performed, as depicted in Figure 23.

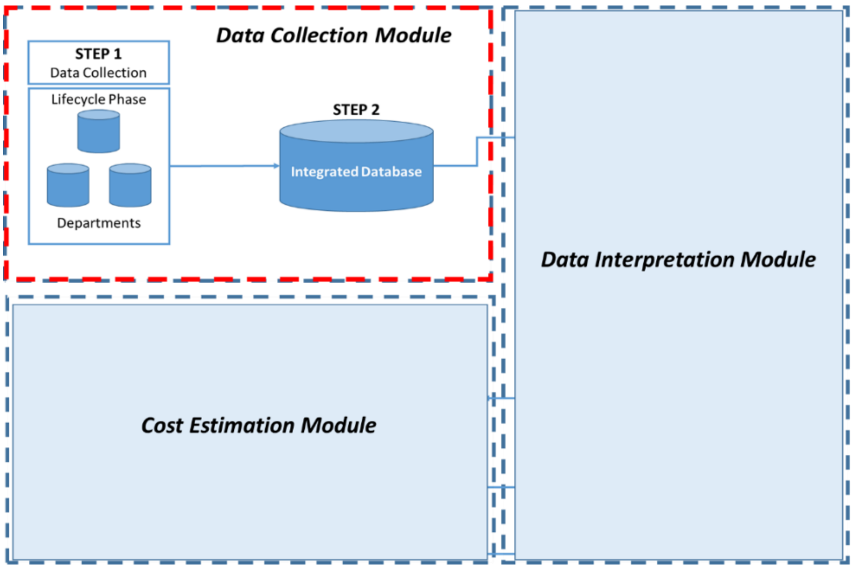


Figure 23 The Data Collection Module of the general approach for PCE implementation

Product lifecycle data, in the organisation, were scattered among different departments. All the data were available in different formats (txt, image, pdf, etc.), and the specificity of the costing information ranged a lot among the various datasets. Moreover, the amount and granularity of available information were also different among the various products, as well as throughout the different lifecycle phases.

Nevertheless, information about tangible and intangible entities, consisting of product families and their structure (as also physical relationships among components and parts), activity subdivision and required resources, product and process cost data, as well as unstructured knowledge collected by interviews and questionnaires with the central persons in the organisation were collected.

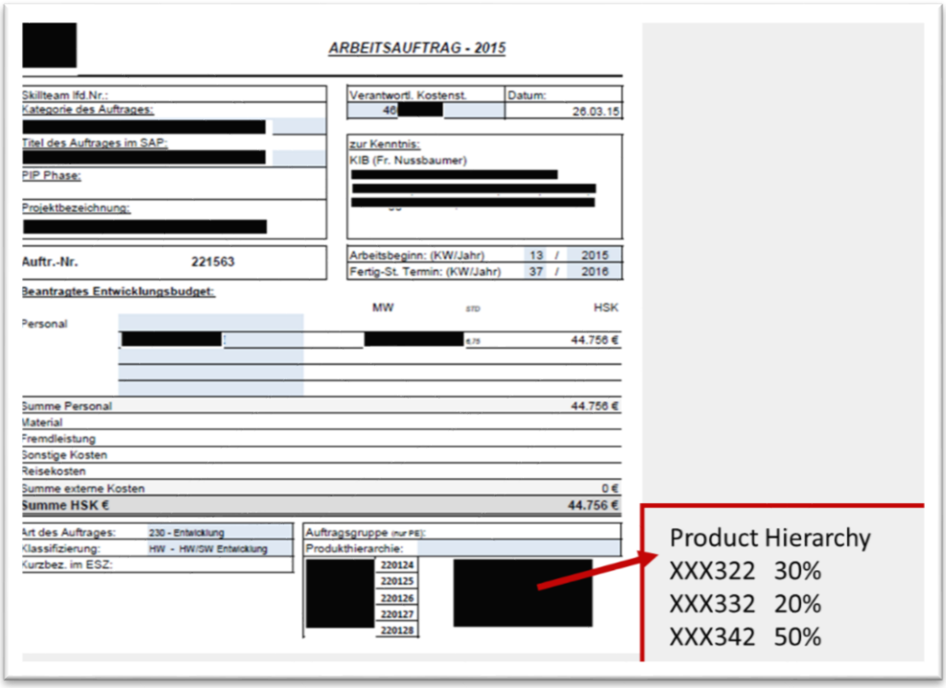
Hence, in Step 1, data was collected from the different departments. From the Research and Development Phase, data were obtained from the Accounting and Engineering departments, in particular about planned and actual cost information, requirements lists, technical descriptions, drawings, BOMs, etc. Information on the Production phase was spread among departments within the company, and data were collected from the Accounting, Purchasing, Engineering and Manufacturing departments. In this case, assembling and testing instructions, material requirements, suppliers' reports were examples of information obtained. For the Operation and Support Phase, data was obtained mainly from the company's Affiliates, the Customer Service and Manufacturing departments. In this case, warranty reports, invoices, customer complaints, repair instructions and costs, etc. were the set of data gained.

All data was gathered within the departments and in most of the cases extracted from the ERP system, for the specific case of the investigated company is SAP.

However, a inconsistency between the various sources of data was detected. In the majority of the cases, inconsistencies were between the main departments' datasets and the central database of the Accounting division. As a solution, a centralised database for cost analysis was therefore created, to better aggregate information and efficiently understand product performance. Moreover, for the purpose of a lifecycle analysis, a representation of a product at different levels of lifecycle phases was hence created.

Step 2 of data integration was not straightforward, but rather complex and time-consuming. For example, one of the biggest problems related to handling research and development data. In this case, data was obviously collected project-wise, and not product-wise. For this reason, it was essential to analyse the various research and development activities, to understand how to allocate the total research costs of the project on a product base, given the different nature of the projects themselves, whether they were platform, next-generation projects, or a single product development project. In this regard, it was decided to consolidate a practice that was rarely used in the past in the company, which foresaw the association with every single research and development activity, a percentage that could make it possible to understand how much of the activity carried out can be allocated to a single product.

Figure 24 shows an extract from an activity report, where the precise amount of hours, and therefore costs, that can be allocated to each product was manually entered by the project leader. In this particular case, the total of hours and costs of the activity was divided between three specific product (defined as product hierarchy in the company), namely the XXX322, XXX332 and XXX342, considering different percentage.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ARBEITSAUFTRAG - 2015

Skillteam lfd.Nr.:
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[redacted]
Titel des Auftrages im SAP:
[redacted]
PIP Phase:
Projektbezeichnung:
[redacted]

Verantwortl. Kostenst. 46[redacted]
Datum: 26.03.15

zur Kenntnis:
KIB (Fr. Nussbaumer)
[redacted]

Auftr.-Nr. 221563

Arbeitsbeginn: (KW/Jahr) 13 / 2015
Fertig-St. Termin: (KW/Jahr) 37 / 2016

Beantragtes Entwicklungsbudget:

		MW	STD	HSK
Personal	[redacted]	[redacted]	6,75	44.756 €
Summe Personal				44.756 €
Material				
Fremdleistung				
Sonstige Kosten				
Reisekosten				
Summe externe Kosten				0 €
Summe HSK €				**44.756 €**

Art des Auftrages: 230 - Entwicklung
Klassifizierung: HW - HW/SW Entwicklung
Kurzbez. im ESZ:

Auftragsgruppe (nur PE):
Produkthierarchie:
[redacted] 220124
220125
220126
220127
220128
[redacted]

Figure 24 Activity report with cost allocation on a single product (black boxes obscure confidential data)

The process of data collection, integration and storage has therefore been completed and introduced in the company, but the cost estimation model has been applied to on particular family of products, chosen from the company's portfolio.

4.4 The Dataset

Among the company’s units, the segment of combustion measurement systems was chosen for the empirical investigation. This business unit provides a combustion analysis platform, depicted in Figure 25, consisting of traditional indicating products (pressure sensors, crank angle encoders, amplifiers, indicating systems and indicating software), as well as products for detailed optical analysis (optical sensors, visiolution evaluation systems), environments for combustion research tasks (single cylinder systems) and all related services for these products. The post-processing software is also included in the portfolio of products offered by the segment.

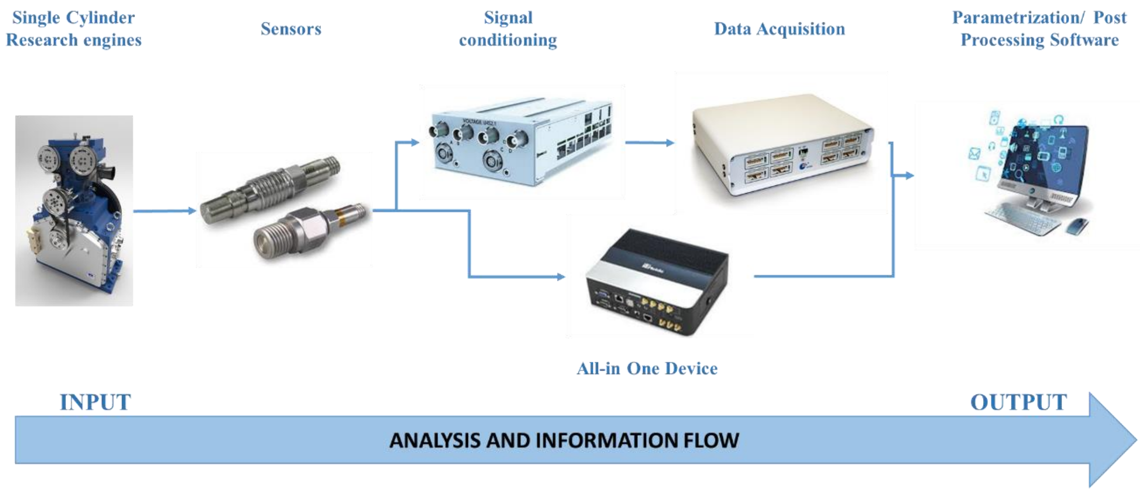


Figure 25 The platform of combustion measurement devices

However, the company was planning an upgrade of the data acquisition devices (DAD) family, on which the methodology was tested. DADs are multi-channel indicating systems for data acquisition and evaluation of processes in internal combustion engines. Three line of products are for data analysis, as shown in Figure 26, and the differences among them are mainly due to the set of different product specifications and to the type of applications. Moreover, they are intended for diverse market segments. For instance, the low-end product line, the xxx322, was developed for non-complex and first-time-user applications. The medium and high-end lines are instead suitable for light/heavy-duty, racing, and large engines development and calibration. Consequently, the differences among the derived six product variants are due to the number of input-analogue channels (ranging from a minimum of 4 and a maximum of 64 channels), the speed of the analysis, and the compliance with a more complex version of the post-processing software.

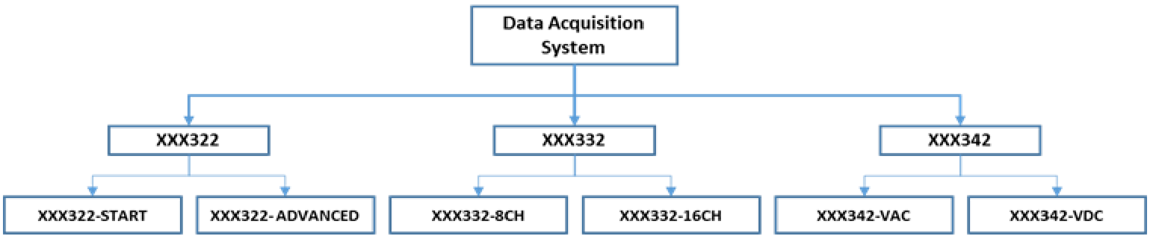


Figure 26 Product Family of Data Acquisition Devices

The instruments are basically simple; however, the company provides to customers a large number of options to extend the possible measurement applications. In fact, the process of customisation, which brings the real value to the end product, requires high complexity and precision in the testing and calibration phase. Hence, the final customised product is highly complex, usually characterised by low sales volume, with no more than 500 devices sold in a year.

The data set was consequently organised according the lifecycle perspective and included:

- For the *Research and Development* phase: research and development projects on a time span of more than 20 years, taking into consideration all information about project's phases (divided into the main phases of planning, pre-development, hardware and software development, prototyping, testing, validation, and documentation). For each phase, activity information (or work orders), such as the number of developers, the duration, the type and quantity of material used, the planned and actual costs, also distinguishing between material and personnel costs, were reported. Despite data clarity, in 20 years of information storage and collection, some data was missing, along with some quality issues. Moreover, data was available on projects and allocation to a single product was necessary. Hence, an understanding of each project was required, as to its nature, distinguishing between platform project, next-generation projects, or a single product development project. A total of 5 projects and 76 work orders were analysed initially. The sample size, however, was not enough to ensure a robust and reliable investigation. For this reason, contrary to what was initially stated, the analysis was extended also to other products close to the Data Acquisition devices, and these similar products were included in the study. In this way, the final dataset consists of 9 product families (such as amplifiers and crank angle calculators), a total of 16 products and 37 product variants and 255 work orders belonging to 17 different projects.

- For the *Production* phase: all the orders placed to the company have been collected over a five year period (2010-2015), for the three data acquisition instruments, and their six variants. The total number of orders are reported in Table 10, also divided by product variant. During the time span selected, all the three systems have been sold as stand-alone products (only the basic equipment), customised with the available options, or bundled in more complex orders with other instrumentations. The information collected is related to the customer order (customer information, number of products ordered, number of options selected, product hierarchy, and the planned and actual cost of the order, the planned and actual margin). The costs are also divided by each production activity, such as assembling, testing and quality control. A first cleaning of the dataset, due to the presence of missing data, has resulted in a reduction of the orders. The final amount is reported in the last columns of Table 10.

Table 10 Number of Products Ordered over the 2010-2015 period on the DAD product family

Product	Sales Article	Number of Orders (Pre Cleaning)	Final Number Of Orders
XXX322	XXX322-START	304	252
	XXX322-ADVANCED	11	11
XXX332	XXX332-8CH	8	8
	XXX332-16CH	117	85
XXX342	XXX342-VAC	52	51
	XXX342-VDC	2	2

- For the *Operation and Support* phase: data was again collected over a five year period (2010-2015), taking into account for each product sold the possible warranty claims over the 24-month period from the delivery date of the product to the customer.

  In this case, warranty reports, invoices, customer complaints, repair instruction and costs, were the set of information gained. In particular, for each claim, the available data was related to the component, the customer, the usage and the total costs. In particular, the dataset consists of the serial number of the claim, the date of production and the date of sale, together with the date of delivery and failure, in order to calculate the time to failure (TTF) (in days). More detailed information on the failure mode, the defective components and the total cost of repair (divided between the hourly costs of preliminary checking, actual repairing and final testing, and the cost of the spare parts material) was included. The total number of warranty claims for the three devices was 494, which corresponds to 10% of the total devices produced over the selected period.

Chapter 5

The Application Case: Results

Based on the data previously collected and integrated for the DAD product family, the three steps in the integrated cost methodology (as shown in chapter 3) are going to be described in this chapter. In Step 1, described in section 5.1, a qualitative method (namely the CBR) is applied to derive costs at the product aggregation level. In section 5.2, the product is divided into its components, and the ABC technique is employed to derive costs of activities and resources. All the data collected is then implemented as cost drivers to be used in the parametrical equation. Finally, the third step of the methodology is described in section 5.3, where the information is aggregated to the product level, through a parametric evaluation to calculate the overall lifecycle cost of the product. Based on the output of the methodology, in-depth analyses of the consequences of product variety on the total lifecycle costs is reported in section 5.4. The evidence described in this last section also represents a validation of the presented methodology. In fact, when applied to different alternatives of product customisation, it provides precise solutions, coherent with the expected results discussed in literature.

5.1 Step 1: When the Analysis is at the Product Level

The first step aims to find the main differences between the old and the new architectures in terms of technological and design data. Referring to the integrated cost methodology, provided in Chapter 4, the main activities carried out in this first step are as follows:

1. Description of the new product to be developed. As it is in the early phases of a design process, the information is generally qualitative, with no precise product specifications.

2. Selection of possible similar cases previously developed, using CBR as an intuitive technique that allows retrieval of product knowledge from a database. At this stage, the expertise of designers and product managers can be useful to pre-select the most similar cases based on their experience.

3. Evaluation of the similarity between the new and the selected cases. Specifically, the metric adopted by the methodology is the Total Constant Commonality Index (TCCI). At the end of this process, the most similar product to the new product being developed will be selected and used as a basis for the development of the new product.

4. Creation of a preliminary data structure, which will allow the acquisition of all the information needed in the development of the new product by analogy, at the highest level of data granularity.

In applying the first step to the application case, the existent DAD family was first queried from the case-based memory. In fact, as previously discussed in section 4.3, the company was planning the release of a new product, which would have completely replaced the three instruments in the DAD family, namely the XXX322, XXX332 and XXX342 product lines.

However, the new product would have been modified, with new features being added to the original concept. Firstly, it would have had a streamlined and compact structure, flexible with the different types of applications for engine calibration, monitoring and development. Secondly, in combination with the standard data acquisition module, the new product would also have been used as an amplifier, including an additional module. In this sense, the product would have had a dual end-use in order to cover all the main measurement requirements.

The company was already equipped with a line of amplifiers. Moreover, they also proposed a line of "All-in-One" devices (aka instruments with a bundle of amplifier and data acquisition system). The new product would have had improved the integration between the two measurement functions, also providing better performances.

Hence, the CBR technique was applied using the three instruments of the DAD family, together with a line of amplifiers and two products of the All-in-One family, as shown in Figure 27. The products have been chosen considering the experience of the designers and product managers. In fact, they were able to give an opinion on the best case to use for undertaking the adaptation.

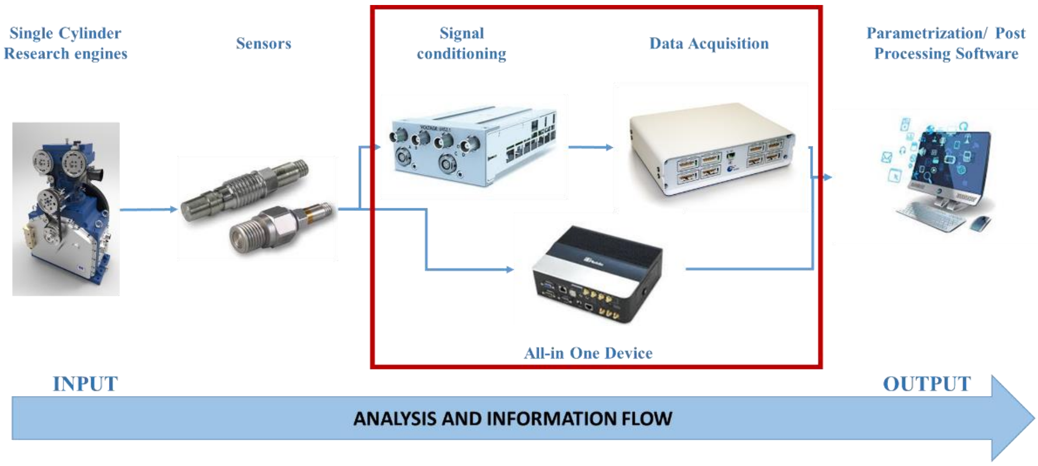


Figure 27 The devices selected for the application case

The CBR was then applied after considering similarities at the upper level of the product structure, which corresponds to the first level of the BOM. In Figure 28, an example of first level BOM for the XXX322 product is illustrated.

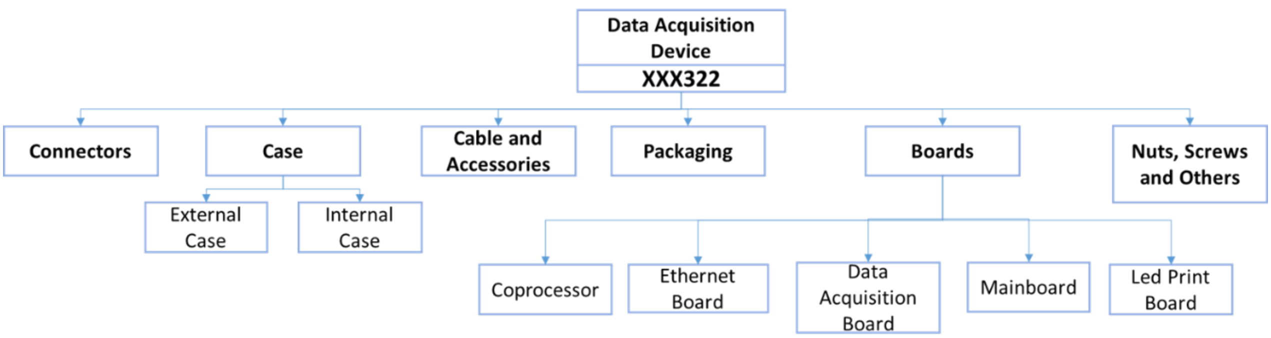


Figure 28 First Level of the XXX322 BOM

The product has a relatively simple structure, with around 80 components at the first level of the BOM. Although connectors and cables and accessories make up for the majority of the costs, the boards constitute the core of the product, and in particular, the Data Acquisition Board, which affects the total material costs by more than 40%.

At first, the similarities between all the existing devices was investigated using the TCCI index, as reported in Figure 29. The aim was to test the efficiency for product development in providing a good standardisation among product variants and to verify the appropriateness of the products chosen for analysis.

The total TCCI was 80%, which confirmed a high degree of commonality between the product families since different variants of the components have the same functions, showing good use of the platform approach in the previous years. Moreover, the high level of commonality between the existing products confirmed how each of the selected similar product can be taken into account in the development of the new instrument.

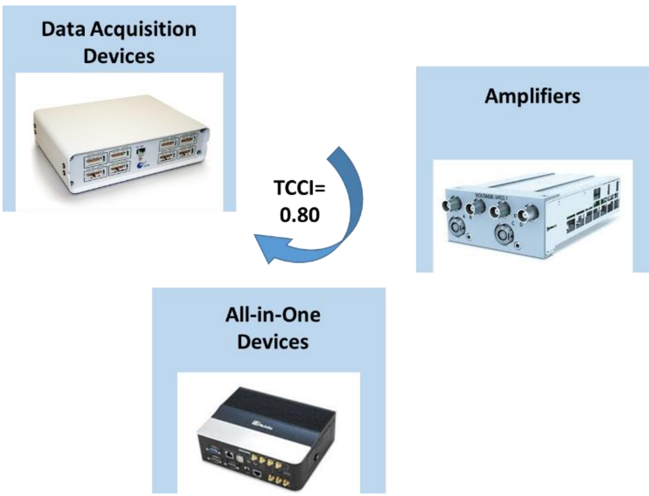


Figure 29 The TCCI for the existing products

However, at this early phase, the primary aim was to find the best similar case for the new product to be developed. Therefore, the TCCI similarity index was applied again, this time to calculate the pairwise comparison between the old and the new structure, for each selected case.

The TCCI index calculates the value of common elements between two products, based on all the set of possible components. Table 11 reports the value of the TCCI index for the six similar products. For each case, the number of times a single module is shared over a set of end products has been calculated along with the total number m of distinct modules. The similarity value is then provided in the last column of Table 11.

Table 11 Six sample patterns of similar devices with their TCCI values

Product number	Product Name	Product Type	m	$\sum\Phi_j$	TCCI
1	XXX322	Data acquisition device	121	400	0,699
2	XXX332	Data acquisition device	120	260	0,540
3	XXX342	Data acquisition device	118	200	0,412
4	XXX422PIEZA	Amplifiers	98	150	0,349
5	XXX312MPSA	All-in-one device	148	250	0,409
6	XXX402	All-in-one device	124	310	0,602

As shown in Table 11, the new product shows a high similarity level with case numbers 1 (around 70%) and 6 (around 60%), which correspond to the data acquisition device XXX322 and the XXX404 all-in-one device. Although both the two products represent a good proxy in the estimation of the new concept costs, the XXX322 was finally chosen as a baseline for further analysis. The decision was taken taking into account the designers' opinions. In fact, the new product would have had characteristics closer to the data acquisition device, not so much in terms of technical performances, but regarding ergonomics and manageability of the structure. Moreover, the lower similarity with the all-in-one device, was also due to the idea of combining a different type of amplifier, so to bring the new product replaces the previous product line completely.

At the end of this process, information on the product structure was collected, and the data framework was derived, as shown in Figure 30. Moreover, a baseline for the new product that should be designed was provided, already available for possible changes to be made.

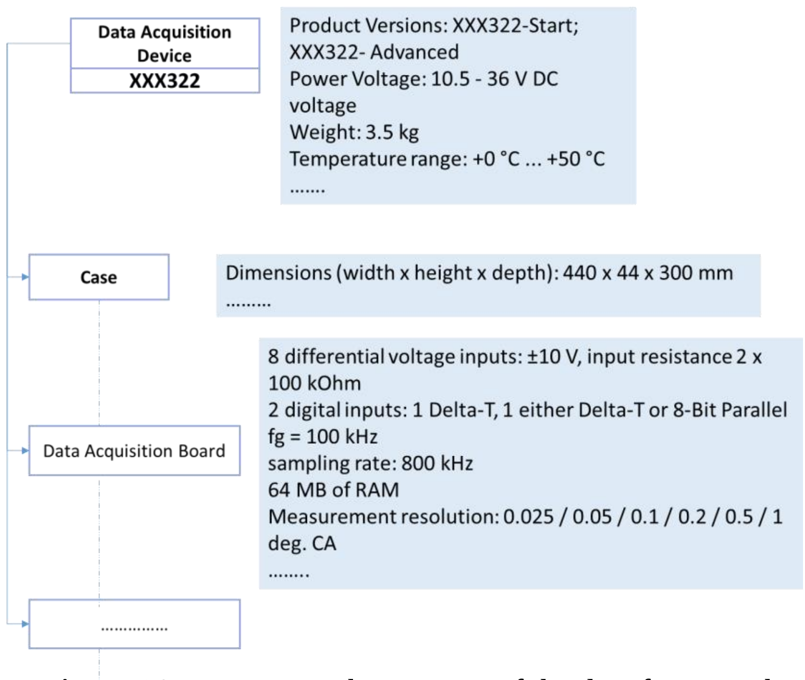


Figure 30 First step in the creation of the data framework

Based on these results, the second step of the methodology was applied, which requires adding the process information to the newly created data framework.

5.2 Step 2: When the Analysis goes Down to the Component Level

In Step 2 of the integrated methodology, the previously retrieved product structure is divided up into the single component level by applying the CBR techniques. In particular, the main activities are:

1. Application of the TCCI similarity index to obtain the analogy between the new product and previous similar cases at the single component level.

2. Application of the ABC method to associate lifecycle cost drivers, activity by activity, to the previously obtained data structure. Hence, the first integration between qualitative and quantitative techniques occurs.

3. Employment of components and activity costs to derive the drivers that mainly influence the total cost of each activity, and calculate the component costs parametrically.

For the selected case study, the first level of the product BOM is relatively simpl, and is characterised mainly by a few circuits that represent the core of the product, as shown in Figure 28. The granularity of the data already obtained at this level was hence deep enough for the purpose of cost analysis, without decomposing the structure to a lower aggregation level. Moreover, each single board is entirely designed in the company but produced and purchased externally. The company then takes care of assembly, testing and final product calibration. However, the methodology allows understanding the right level of granularity for data decomposition and collection, deciding the degree of detail to be provided for the cost analysis according to the type of product developed.

Hence, information on the lifecycle processes was associated then, activity by activity, with the data framework obtained in Step 1, through the application of the ABC method. The first integration between qualitative and quantitative techniques was thus achieved.

To obtain the data, the company's development, procurement and accounting departments were interviewed, besides querying the database. Another task was to complete the set of data, including the ownership costs for the customer (through interviews and questionnaires submitted to a selected set of customers) in terms of operating time and frequency of maintenance.

In implementing the ABC method, the steps proposed by Cooper and Kaplan (1999) were taken into account, namely 1) the identification of the resource centres used for all lifecycle phases; 2) the identification of the overall costs associated with these resource centres; 3) cost drivers identification for the resource centres; 4) the identification of the lifecycle activities; 5) the calculation of the cost of the activities based on resource consumption; 6) the identification of the activity cost drivers. Usually, the ABC model requires computing the value of the activity cost drivers to derive all process costs based on the performed activities. However, in the case of the presented methodology, the primary objective was to obtain, activity by activity, the cost drivers for the Parametrical model.

Hence, starting from the organisational structure, the cost centres that were used directly to design, develop, assemble and maintain the product during its whole lifecycle have been identified. The total cost of the cost centres was derived from the sum of all resources employed by each cost centre. For example, cost drivers for the human resources such as designers, project managers, assembling coordinator were their work hours. The cost drivers for the assembling centre were the number of assembling operations, and for the material handling costs, it was the number of material moves. Table 12 lists, as an example, an extract of the main cost centres and their cost drivers for the product under investigation.

Table 12 Lifecycle cost centres and their drivers

Cost Centres	**Cost driver**
Designers	Design Hours
Product Managers	Work Hours
Sales and Business Developers	Work Hours
Supporting Research and Administration	Work Hours
Controlling	Work Hours
Assembling Centre	Number of assembling operations
Assembling Coordinator	Work Hours
Material Handling Centre	Number of material moves
Testing and Calibration Centre	Number of products tested
Order Handling Centre	Number of Order Handled
Maintenance Centre	Number of products received
Repair Centre	Number of products received

Each cost centre is then dedicated to performing the activities that will characterise the entire product lifecycle. Therefore, the cost factors that best described the costs, activity by activity, were determined. The experiences of the designers and product managers involved in the process were also taken into account to acquire a broad spectrum of possible cost factors.

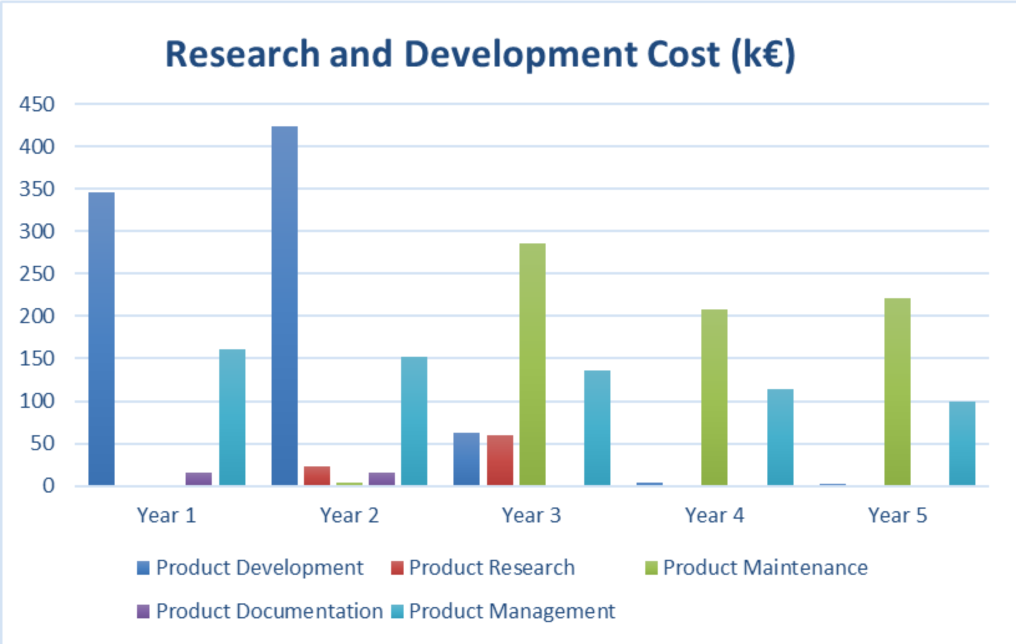
For example, the process of product planning required the project manager and the designer to talk to the manufacturing engineer about the product requirements. The cost centres employed in this activity included the designer, project manager and manufacturing coordinator. It was seen how the discussing time, and hence, the duration (in hours) of the activity, was a good estimator of the total activity costs. When the product is at the conceptual design phase, the time to complete the activity is directly determined by the complexity of the product. Hence, the best drivers for costs were represented by the number of modules included in the preliminary product concept, which, in the case of the selected product, was associated with the number of boards to be developed.

The best set of activity drivers was eventually recognised for each life cycle phase, as shown in Table 13. All the activities that contributed to the lifecycle process were driven by these inputs. A total of nineteen possible variables were hence identified. A simple linear regression analysis was performed to investigate and model the one-to-one relationship between the identified cost factors and each activity cost. These activity drivers reflected the characteristic of the single product (e.g. number of components, volume, width, depth, etc.) of the product family (e.g. number of product variants, number of standard parts, number of hardware and software options), and of the process (e.g. activity's duration, number of work orders, number of projects).

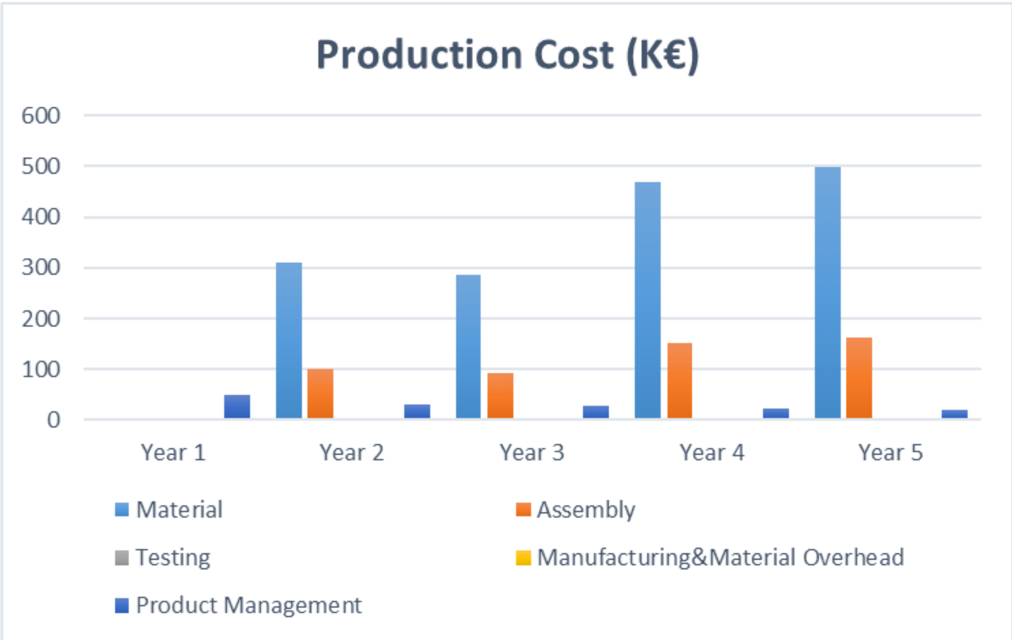
Figure 31 shows the output of the ABC analysis and describes the three main categories of costs (i.e. Research and Development, Production, Operation and Support). The early use of ABC method is not common at this phase of product development. Usually, cost estimation in the early phases results from information on past product structures, and does not integrate information on lifecycle processes, and this is even true if the ownership of costs is on customers.

Table 13 Activity cost driver divided by lifecycle phase

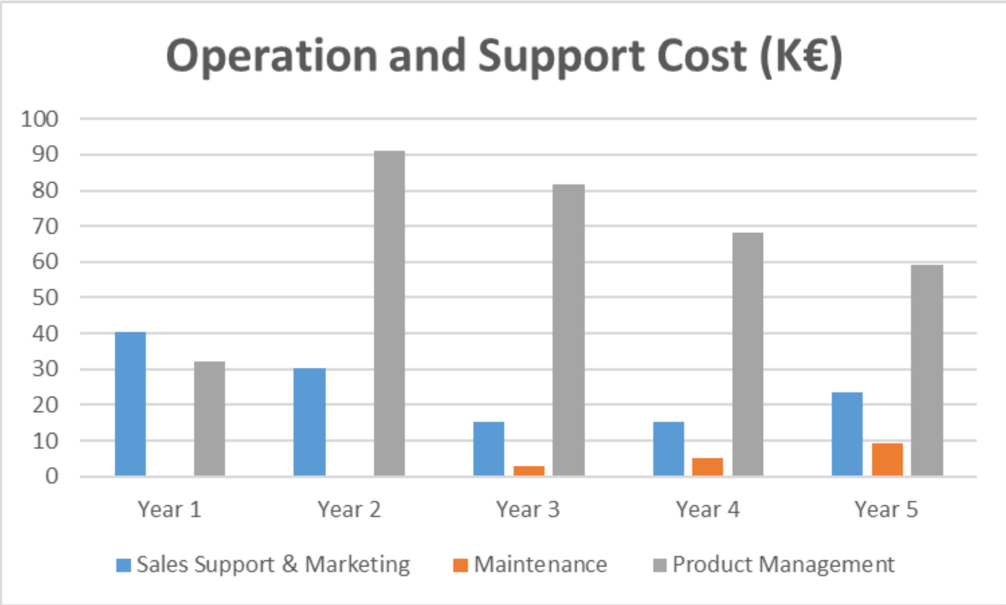
Lifecycle Phase	Activity	Activity Driver
Research and Development	Planning	Duration of the activity
	Conceptual Design	Number of Modules
	Development Hardware	Number of Parts
	Development Software	Number of Modules
	Development Firmware	Number of Product Variant
	Integration Hardware/Software	Number of Parts
	Prototyping	Number of Product Variant
	Documentation	Number of Parts
	Testing	Duration
Production	Purchase Material	Quantity of units sold
	Assembling	Number of Modules, Number of Hardware and Software Options
	Testing	
	Quality inspection	Number of Parts
Operation and Maintenance	Transport	Weight
	Repair	Number of Parts
	Assembling	Number of Modules, Number of Hardware and Software Options
	Testing	


Research and Development Cost (k€)
450
400
350
300
250
200
150
100
50
0
Year 1
Year 2
Year 3
Year 4
Year 5
Product Development
Product Research
Product Maintenance
Product Documentation
Product Management

(a)


Production Cost (K€)
600
500
400
300
200
100
0
Year 1
Year 2
Year 3
Year 4
Year 5
Material
Assembly
Testing
Manufacturing&Material Overhead
Product Management

(b)



(c)

Figure 31 Cost Breakdown Structure for Research and Development Phase (a), Production Phase (b), Operation and Support Phase(c)

By comparing the graphs above, it can be seen that extra cost of research after product launch is accounted as maintenance cost, whose value has risen in the past years of product operation. These costs are normally due to some extra repair and maintenance required by the customer during the warranty period. They often result from saving choices in the design phase that impact the quality and feature of the components. Moreover, in Figure 31, the costs of the support by the management during the entire product life is also reported. Also in this case, a major attention is also at the product when it is already to the customer, due to the extra maintenance that the products require.

At the end of this second step, information on both the product structure and the lifecycle processes was collected, and the data framework was completed, as shown in Figure 32. The structure provided to the development team was enriched at this step with the information useful for not only redesigning the new generation of products but also for discussing and reflecting on the consequences of past development on the entire lifecycle.

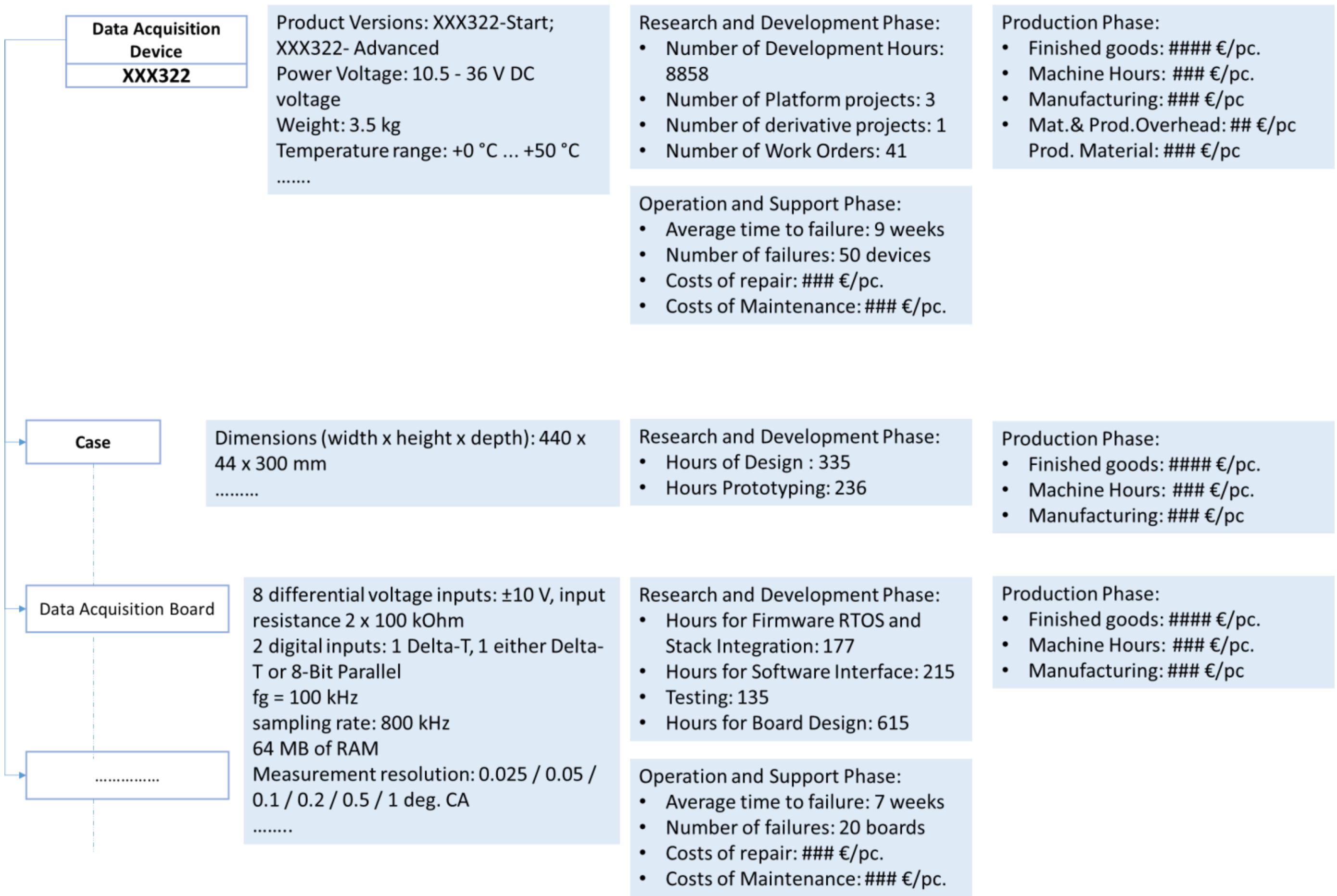


Figure 32 Second step in the creation of the data framework

Based on these results, the third and last step of the methodology was applied, which required using the information collected to finally derive the product lifecycle cost.

5.3 Step 3: When the Analysis goes back to the Product Level

In Step 3 of the integrated methodology, the information was aggregated back to the product level to calculate the overall lifecycle cost of the product. In this case, the main activities are:

1. Development of a parametrical equation at the product level for each phase of the product lifecycle, using the same cost drivers identified in the previous step.

2. Substitution of the estimated cost, at least partially, with the actual data available on the new product (e.g. the cost of some components being known at this point), if the product development process is already at the detail design phase.

3. Storing the information on both costs and designs of the new product as knowledge useful to feed further cost estimations.

The cost drivers previously identified through the ABC analysis were then employed as variables in the Parametrical models in this phase. Starting from the nineteen possible cost drivers, a stepwise regression procedure was applied, and the unnecessary parameters, which did not fit into the model, were dropped based on their p-value and collinearity with each other. The best set of variables used in the creation of the Parametrical models have been described in Table 14.

All the regression analysis was performed using the IBM SPSS statistical software, version 18.0. Regression results for models predicting the total cost by phase are shown in Table 15. In particular, the regression coefficients, their statistical significance, and their variance inflation factor (VIF) have been mentioned for each model.

Table 14 Activity drivers and their definitions

Activity Driver #	Activity Driver N:une	Description
Xl	Duration (h)	It is the amount of projects ' hours, directly assigned from projects to a single product.
X2	Quantity (pc.)	The variable expresses the number of units of product sold in a single order
X3	Number of Software Options (pc.)	The number of software options sold in a single order.
X4	Number of Hardwar Options (pc.)	The number of hardware options sold in a single order.
X5	Number of Parts (pc.)	The variable expresses the average number of parts in the product. In particular, corresponds to the average of parts between different product variants.
X6	Number of Boards (pc.)	The variable represents the number of the modules that is a proxy of product complexity.
X7	Number of Product Variant (pc.)	The variable accounts for the different number of product versions available for the product family.
X8	Finished Goods [€/unit]	The variable accounts all the material costs related only to the instrument.
X9	Machine Hours [€/unit]	The vo1ce expresses the costs of the productions and testing activities.
X10	Machine Overhead [€/unit]	The variable accounts for all the material and production overhead in the assembling of a single instrument.

In particular, the regression coefficient (e.g. β1, β2… βn) for the i-th predictor (variable) is the expected difference in response per unit difference in the i-th predictor, all other things being equal. That is, if the i-th predictor is changed 1 unit while all of the other predictors are held constant, the response is expected to change βi units. The p-value for each term tests the null hypothesis that the coefficient is equal to zero (no effect). A low p-value (< 0.05) indicates that you can reject the null hypothesis. Hence, a predictor that has a low p-value is likely to be a meaningful addition to the model because changes in the predictor's value are related to changes in the response variable. The variance inflection factor quantify the degree of multicollinearity among the variable in the regression analysis.

Table 15 Linear Parametric models

	Model 1							Model 2							Model 3						
	Unstandardized Coefficients		Standardized Coefficients		Sig.	Collinearity Statistics		Unstandardized Coefficients		Standardized Coefficients		Sig.	Collinearity Statistics		Unstandardized Coefficients		Standardized Coefficients		Sig.	Collinearity Statistics	
	B	Std. Error	Beta	t		Tolerance	VIF	B	Std. Error	Beta	t		Tolerance	VIF	B	Std. Error	Beta	t		Tolerance	VIF
(Constant)	91710*	67715		2,9	,014			495,4***	53,887		1,603	,110			-18310,56***	907,942		-20,167	,000		
Duration (h)	54,945**	4,231	0,93	12,987	,000	0,654	1,529	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Quantity (pc.)	-	-	-	-	-	-	-	-3,28*	1,736	-,014	-1,890	,060	,551	1,814	-52,928**	21,226	-,054	-2,494	,013	,383	2,611
Number of SW Options (pc.)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6,84	8,502	,017	,805	,422	,392	2,551
Number of HW Options (pc.)	-	-	-	-	-	-	-	2,5**	1,192	,015	2,075	,039	,515	1,942	20,516**	9,134	,040	2,246	,025	,567	1,765
Number of Parts (pc.)	175,673**	73,91	0,16	2,377	,037	0,762	1,312	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Number of Boards (pc)	-3339,886**	1512	-0,18	-2,209	,049	0,515	1,941	-0,53	,364	-,010	-1,461	,145	,585	1,710	44,9***	2,047	,894	21,944	,000	,110	,585
Number of Product Version (pc.)	-55133,025**	18025	-0,21	-3,059	,011	0,697	1,434	-	-	-	-	-	-	-	177,9	121,496	,059	1,465	,144	,112	,394
Finished goods [€/unit]	-	-	-	-	-	-	-	0,824***	,014	,445	42,210	,000	,249	4,023	-	-	-	-	-	-	-
Machine Hours [€/unit]	-	-	-	-	-	-	-	2,4***	,026	,632	93,417	,000	,621	1,610	-	-	-	-	-	-	-
Machine Overhead [€/unit]	-	-	-	-	-	-	-	4,67*	2,815	,016	1,659	,099	,295	3,388	-	-	-	-	-	-	-
Adj. R^2	*0.95*							*0.98*							*0.92*						
*Significance Codes *<0.1, **<0.05, ***<0.01*																					

The three parametrical models have the same structure in terms of dependent variables, which represents the total cost incurred during research and development, production and in the operative and support phase. Moreover, as required by the methodology assumption, the three models share the same set of independent variables, which was the most significant factor in the lifecycle of the product.

The first model derives the cost of the research and development activities. It comprises the *Duration* of the activities in hours, the *Number of Parts* designed for a single product, together with the *Number of Boards,* plus the total *Number of Product Variants,* as independent variables. All the variables in the model have a p-value below 0.05. The signs of all the beta coefficients are consistent with the expected results of the model. Obviously, as development hours increase, the total cost of research and development increases. The same applies to the number of components in the new product. Costs then decrease as the Number of Variants increases, which justifies the positive effect of platform development. In fact, research and development costs are based on the Number of Variants produced. Modularity, expressed by the number of boards developed, also has a positive effect on cost reduction.

The second model is aimed at calculating the total cost in the production phase. The independent variables, in this case, are the *Quantity* of product manufactured in a single customer order, the *Number of Boards* and the costs of *Finished Goods, Testing* and *Production Overhead*. In order to include the degree of customisation in the model, the total *Number of Hardware Options* was also included. Also, in this case, all the variables have a p-value below 0.1. Only the variable for Number of Boards is not statistically significant in this model. However, the variable is maintained due to the importance related to its interpretation, as the number of boards, in this case, is interpreted as the total *Number of Modules* in a product. Again, the coefficient signs are consistent with the expected results of the model. Mainly, the impact of all the other variables of costs is positive; this obviously means that the increase in the cost of each activity causes the increment in the total production costs. The degree of order customisation positively impacts the actual unit cost of production, meaning that the increase in the number of options, particularly the hardware options included in the order, generally affects the total production cost negatively. As for the previous model, the modularity has a positive effect on the reduction of the total production costs. The other negative value of the beta coefficient is provided by the quantity of units sold in a single order, which shows the presence of economy of scale.

The third model calculates the total cost of the operation and support activities. The variables included in this model are the *Quantity* of products sold in a single customer order, the *Number of Boards* and the *Number of Product Variants*. In this case, the degree of product customisation is also taken into account, including the *Number of Hardware* and *Software Options* added to the basic instrument. While the majority of the parameters present a p-value below 0.05, the two variables, *Number of Software Options* and the *Number of Product Variants*, are statistically not significant. Also, in this case, their interpretation is taking into account.

As for the previous model, the degree of order customisation positively affects the actual unit cost of operation and support. Contrary to the other phases, in this case, the modularity and the number of variant affect the total unit costs negatively due to the positive signs of both beta coefficients. This is probably because these variables also represent a proxy of product complexity. Hence, the higher the complexity of a product, the higher is the cost for its disassembly, repair, and testing.

To validate these three models, previously separated data were used, resulting in an average absolute error of around 5.34%. This performance level could be further improved by extending the historical database as new data becomes available and by improving the quality of the data in the database by conducting a more precise accounting of actual cost data.

Substituting the values in the three previously introduced models, a total life-cycle cost of 6000 euro (on average) can be obtained for a single product. Considering that an instrument is designed for maximum life of 10 years, the profile in Figure 33 shows the total lifecycle cost reduced to the present equivalent value. This pattern can eventually be used either to evaluate the impact of different design alternatives (but still using past data as input) or to assess how the various functional choices create different trends in the overall costs, especially in the maintenance cost sustained by the customer. In particular, Figure 33, shows the case of a design alternative (red line) that provides an additional function to control the deviation of the measurement respect to the standard one (blue line). The designer has the chance to assess either a cheaper product version (blue bar), without the additional function, or a smarter solution (for which the customer will be avoided frequent product calibrations in factory), with higher internal development and production costs.

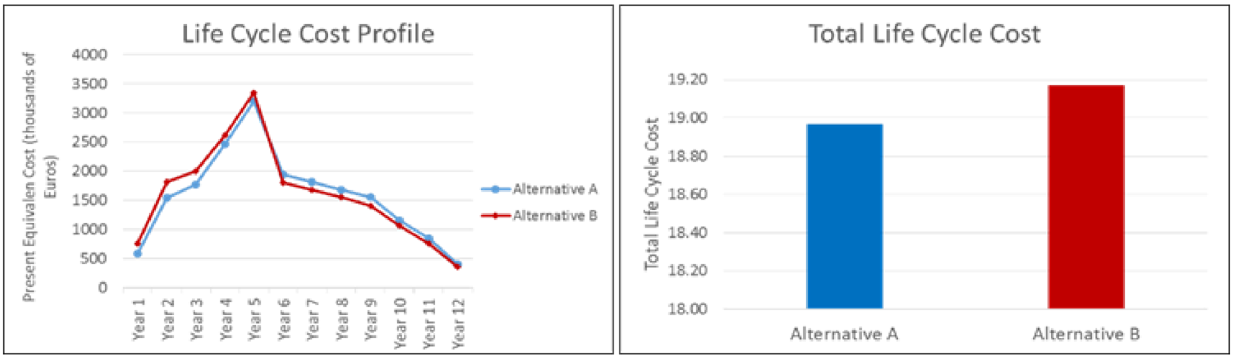


Figure 33 Lifecycle cost profile

Usually, even if these models do not represent the actual costs, rather a proxy for the cost estimation, obtaining such level of detail is challenging at the beginning of the design phase, though it is valuable information for the products to be designed. Based on the validated coefficients obtained, the actual data will be used to predict the cost of a new product by replacing the cost estimation models with the set of available information.

5.4 When Lifecycle Cost Analysis Enables Strategic Design Considerations

Based on the findings of the cost estimation methodology, further in-depth analysis can be conducted. For instance, decisions regarding the degree of platform standardisation, the breadth and depth of product lines to be developed, as well as the degree of variety to be offered, can be deepened and empirically supported. In fact, in designing product families, estimating cost savings becomes a challenge for developing cost-effective products. At this point, customers' needs in various market segments are translated into individual products in the family, and standard components or subsystems of the products are combined as a product platform that supports the products (Simpson, 2004). Increasing the degree of standardisation in the product family decreases the costs related to the product design and development, as well as all the indirect cost owing to inventory, setup, inspection, maintenance, material handling and storage. Instead, the spreading of product variants, as well as the uncontrolled planning of differentiated products on the market, can reduce the overall benefit of platform strategies. Considering these aspects might represent a strategic way of conducting a cost analysis, which, beyond the estimated economic return, enables better evaluation of the impact of product configuration and platform decisions on the entire product lifecycle.

To this purpose, this section starts with the output of the cost estimation methodology, and a cluster analysis on different platform alternatives is built. Cluster analysis (CA) is a well-known technique within the field of data mining (Wallace & Rai, 2004; MJ., 2004). CA has developed to simplify a complex structure by assigning a set of objects into homogenous groups according to their similarities (proximity), such that, it maximises intra-cluster similarity while minimising inter-cluster similarity. It has been widely used in the literature of decision-making processes for finding undetected or unexpected patterns of concentrations embedded in databases (Lee, et al., 2012). In this case, the aim was to

1) divide the customer orders into groups to recognise patterns in the most preferred product configuration, evaluating the possible mix of component standardisation, and

2) discuss the differences in the identified groups regarding their costs. The object is then to evaluate the optimal number of product variants and the performances of platform structures to provide more conscious planning of the product portfolio.

From this analysis, some insights on the optimal degree of product variant can be derived, thus determining the degree of customisation provided.

In the specific case of the DAD family, each product can be manufactured as standardised equipment, or different hardware and software options can be added to the basic product configuration, reflecting on a different customisation level. The platform evaluated was characterised by 150 possible product variants, and for each product line, 50 possible mixes of options were available to customers, as shown in Figure 34.

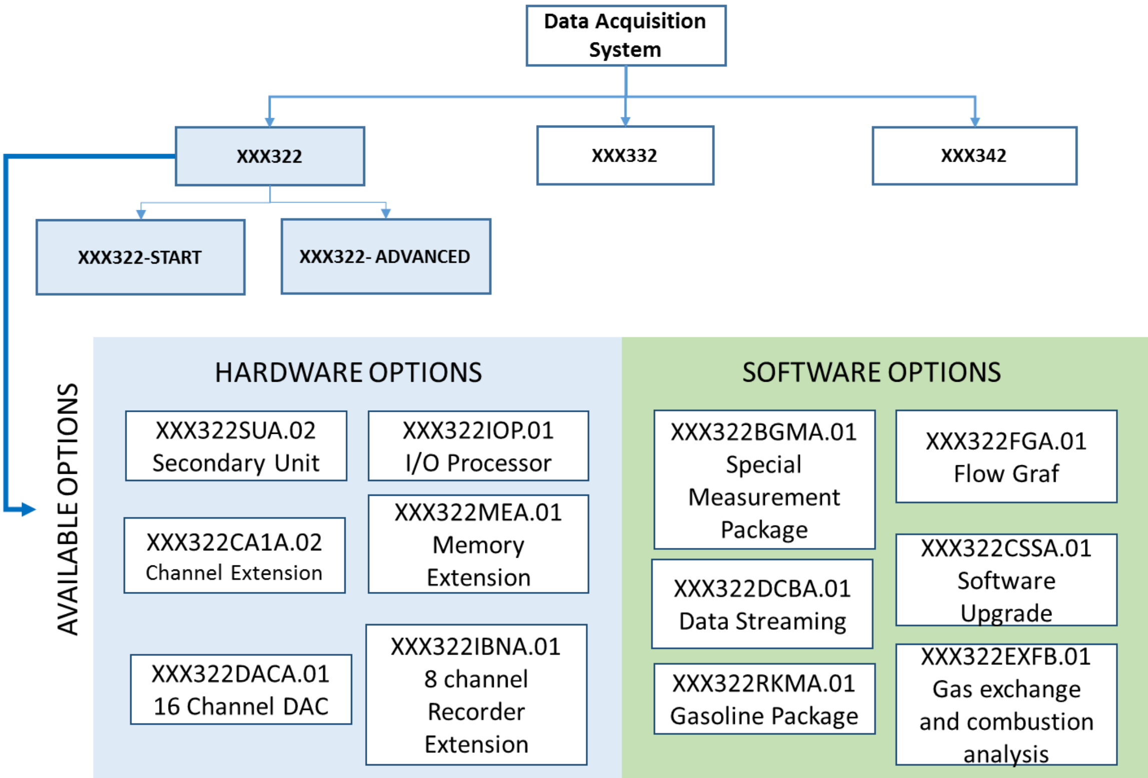


Figure 34 Example of hardware and software options for the XXX322 product line

Figure 35, as an example, plots the predicted cost values of each personalised architecture for the low-end product XXX322. A mix of hardware (H) and software (S) options characterises each variant. A minimum can be reached when the product is assembled mainly using software options. Hence, the increase in costs among the values is primarily due to the rise in the number of out-of-platform hardware options that have been added to the standard product configuration, as well as due to a rise in their level of customisation.

Figure 36, instead, compares the graph for each product line in the DAD family. The analysis shows that not only the level of customisation (high/low) and the kind of option (hardware/software) have an impact on the total production costs but also the product segment (low/medium and high-end), which plays a role in cost differences.

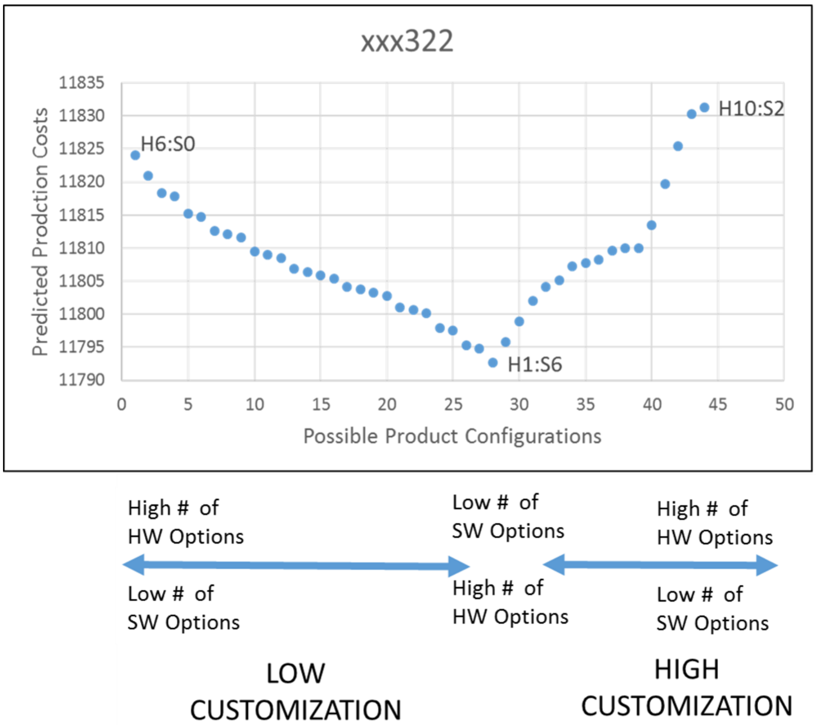


Figure 35 The Predicted Costs of the possible variants on the low-end product

In particular, for medium and high-end products, the range of variants decreases, and around 30 and 20 personalisations, respectively, have been realised (of the 50 available). This can be justified by the set of functions provided by these products: as standardised instruments, they are already equipped enough and do not need any further customisation.

Moreover, the production costs reach a minimum value when the product is standardised. This reflects a typical problem of the adverse effect of platform design in cases of multiproduct families (Krishnan and Gupta, 2001), i.e. companies usually tend to exploit excessively the benefit of a platform by increasing variety in a product family, without paying attention to the cost of variety. Indeed, when a high complexity characterises the product, the distinction between market segments does not justify this excessive proliferation of variants.

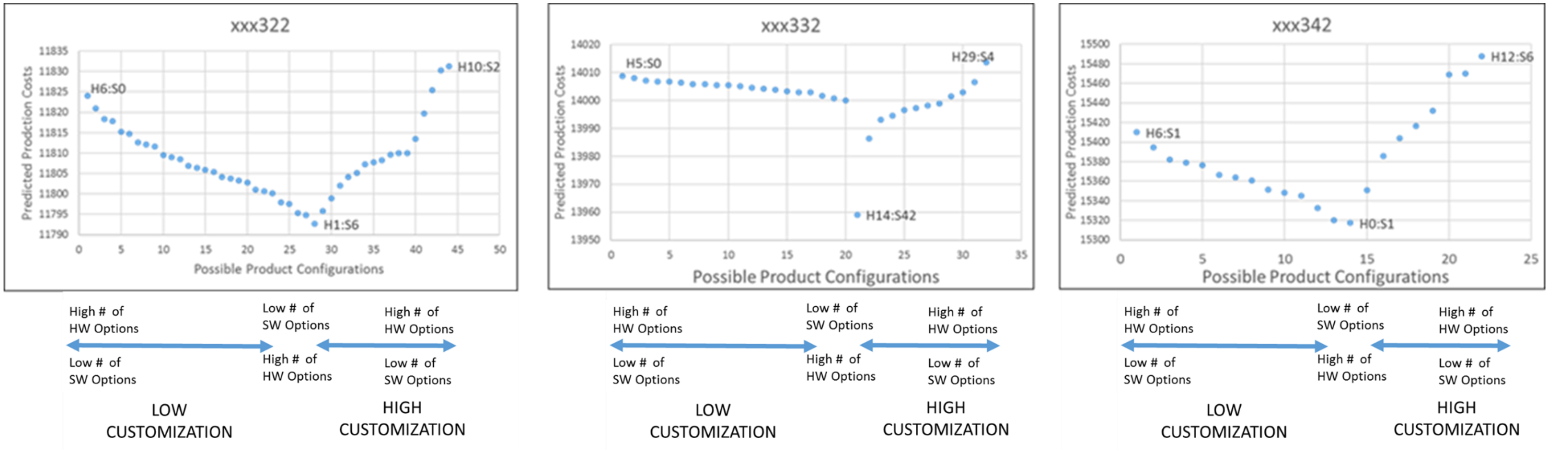


Figure 36 The Predicted Costs of the possible variants on the entire product family

These findings show that the lifecycle cost approach is valid (also in this kind of studies). The model, in fact, behaves according to the expected results discussed in the managerial literature, hence its validity is confirmed. At this point, it has been confirmed that the model can be employed as a supporting tool for decision-making at the conceptual design phase. Therefore, designers can choose between different solutions against a precise knowledge of cost consequences.

To further investigate this effect, the K-means cluster analysis can be applied to all the product configurations. K-means clustering is an approach for partitioning a data set into K distinct, non-overlapping clusters. To perform K-means clustering, it is necessary to specify the desired number of clusters K; then the K-means algorithm will assign each observation to exactly one of the K clusters. In this case, we looked at the composition of customer orders over a five-year period (from to 2010 to 2015). In particular, for the XXX322 product line, the dataset contained 284 records, together with all the options available for the customisation. The data were analysed using Ward's method, with the squared Euclidean distance measured in the IBM SPSS statistical software, version 18.0.

Two of the most frequently used techniques for clustering were adopted here: Hierarchical and K-means algorithms. In particular, the Hierarchical cluster analysis (HCA), using squared Euclidean distance and Ward's partitioning method, was selected to derive the dendrogram, and consequently, to recognise the most suitable number of clusters. Then, the non-hierarchical technique (i.e. the K-means algorithm) was chosen to assign, through an iterative process, each contribution to the most appropriate cluster.

The hierarchical clustering model generated a dendrogram that graphically illustrated how the architecture quickly grouped into four main clusters. Thereafter, three iterations of the K-means cluster analysis were performed, with a number of clusters set at four, five and six, to check the stability of membership in the four groups. Anova was used to prove the differences between the four clusters, as shown in Table 16. The Anova look if there exists a significant difference between means. In particular, it tested whether the means of various group are equal or not. The F-statistic indicates strong evidence that the cluster means differed from another for all the defining variables at the 0.05 level of significance or less. Table 17 shows the number of cases in each cluster.

The four clusters resulted in four different types of customised architecture, as shown in Figure 37. The radar graphs show the average number of options ordered in each group. In particular, on the right side of each graph, hardware options have been reported, while the left side figures the software ones. The first group joins all the standard product variants. It represents the most significant group, with 88% of the cases in four clusters. The second group is similar to the first in terms of the degree of standardisation but is characterised by a higher quantity for a single customer order. The third cluster regards customised architectures, particularly, with software options. Similarly, the fourth one is highly personalised, but in this case, hardware options are added to the basic architecture. Moreover, as for the second group, the quantity order is higher.

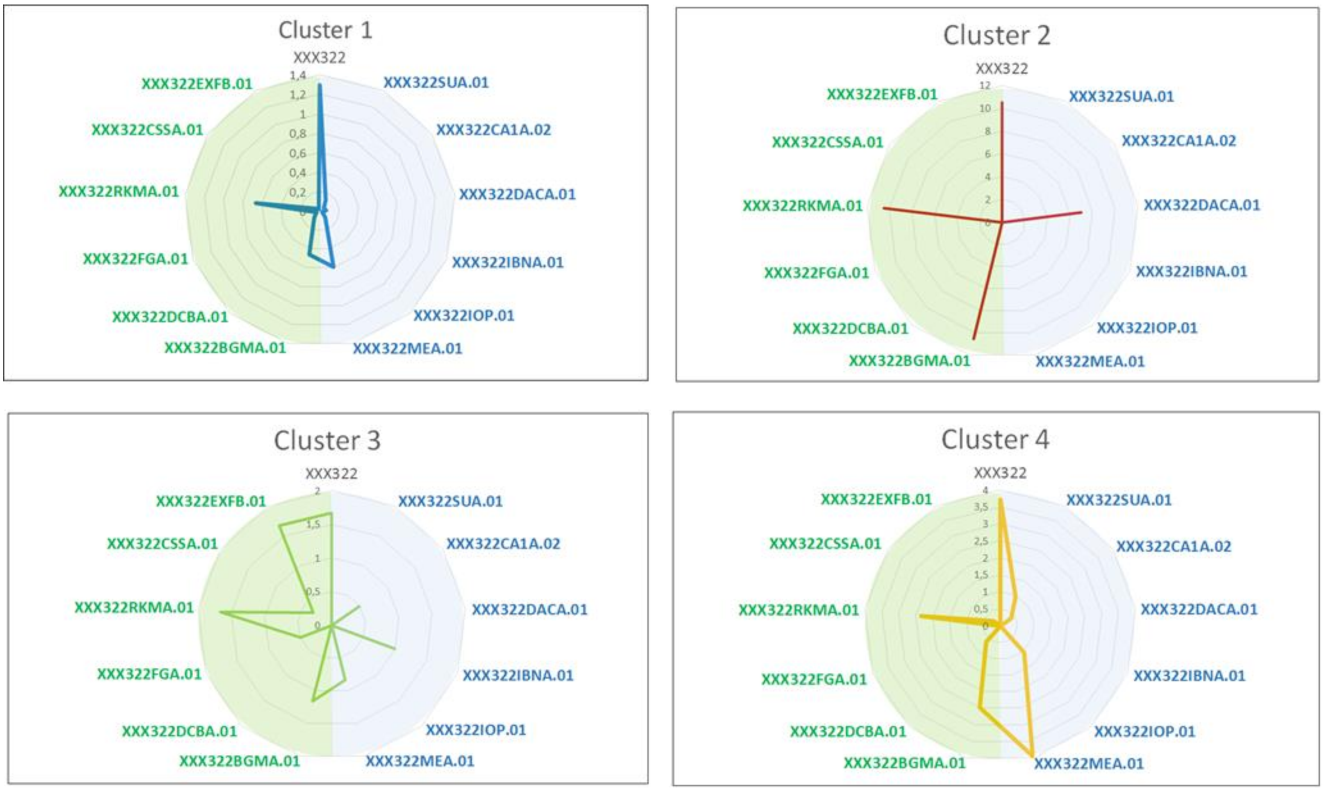


Figure 37 The four customised product variants

These observations were then validated statistically by means of a one-way Anova, using the four clusters as classes for the analysis. A one way Anova is used to compare two means from two independent (unrelated) groups using the F-distribution. The null hypothesis for the test is that the two means are equal.

Table 16 Comparative analysis of variances for the K-means method (with different Ks)

	K-means Clustering (K=4)				K-means Clustering (K=5)				K-means Clustering (K=6)			
	Mean Square	df	F	Sig.	Mean Square	df	F	Sig.	Mean Square	df	F	Sig.
XXX322	52.768	3	115.957	.000	36.869	4	75.903	.000	26.053	5	46.744	.000
XXX322SUA.02	11.962	3	13.523	.000	12.340	4	14.735	.000	19.852	5	29.767	.000
XXX322CA1A.02	4.227	3	4.375	.005	2.901	4	2.983	.020	40.181	5	130.565	.000
XXX322DACA.01	42.451	3	75.312	.000	63.597	4	620.097	.000	51.571	5	484.169	.000
XXX322IBNA.01	30.946	3	45.192	.000	30.305	4	52.263	.000	29.086	5	57.736	.000
XXX322IOP.01	13.688	3	15.798	.000	10.829	4	12.606	.000	6.206	5	6.835	.000
XXX322MEA.01	44.587	3	82.386	.000	31.581	4	56.237	.000	28.207	5	54.317	.000
XXX322BGMA.01	58.871	3	150.629	.000	37.631	4	79.250	.000	26.397	5	47.883	.000
XXX322DCBA.01	11.289	3	12.660	.000	33.747	4	63.612	.000	27.255	5	50.836	.000
XXX322RKMA.01	48.503	3	97.013	.000	31.326	4	55.424	.000	23.667	5	39.477	.000
XXX322CSSA.01	11.522	3	12.957	.000	47.350	4	141.140	.000	38.560	5	114.629	.000
XXX322EXFB.01	60.858	3	164.522	.000	37.550	4	78.888	.000	20.218	5	30.613	.000

The F tests should be used only for descriptive purposes because the clusters have been chosen to maximise the differences among cases in different clusters. The observed significance levels are not corrected for this and thus cannot be interpreted as tests of the hypothesis that the cluster means are equal.

Table 17 Number of Cases for the K-means method (with different Ks)

Number of Cases in each Cluster		
Cluster	1	257.000
	2	2.000
	3	6.000
	4	24.000
Valid		289.000
Missing		.000

Number of Cases in each Cluster		
Cluster	1	240.000
	2	20.000
	3	7.000
	4	19.000
	5	3.000
Valid		289.000
Missing		.000

Number of Cases in each Cluster		
Cluster	1	241.000
	2	5.000
	3	1.000
	4	40.000
	5	1.000
	6	1.000
Valid		289.000
Missing		.000

Therefore, a significant result means that the two means are unequal. In Figure 38, the differences in the mean of the four groups are depicted, divided for each variable. It is immediately visible how the customization, in general, affects the production costs negatively. In particular, this is visible in the differences between the clusters one and three.

Hence, it is confirmed that platform-based product benefits from lower costs, although with higher margins. However, group two and four reacted differently. In this case, the high quantity of products required for a single order led to lower cost of production (due to the economy of scale), as well as lower margins (due to discounts offered to customers when selling the product). However, the analysis has statistically confirmed the difference in the four clusters for the assembling, testing and overhead costs, with a p-value less than 0.05. This may be due to the weight of the first clusters in relation to the others.

Based on this analysis, decisions to reduce the variety was taken by the company. In particular, ten different hardware options, designed mainly for a specific customer requirement, have been discontinued. The consequences will be visible on the all product lifecycle. For designers, it is a lesson learned in order to reduce the design effort in unnecessary portfolio variety. During the production, reducing the variety will reduce also the number of articles of components purchased, stored, assembled, and tested, as well as repaired and exchanged at the O&S phase. Therefore, thanks to the application of PLC methodologies, as the one proposed, different other investigations can be allowed. In this case, the results will be helpful in order not only to understand the effect of product variety on the lifecycle costs but also will allow designers in eciding on the optimal degree of product components to standardise.

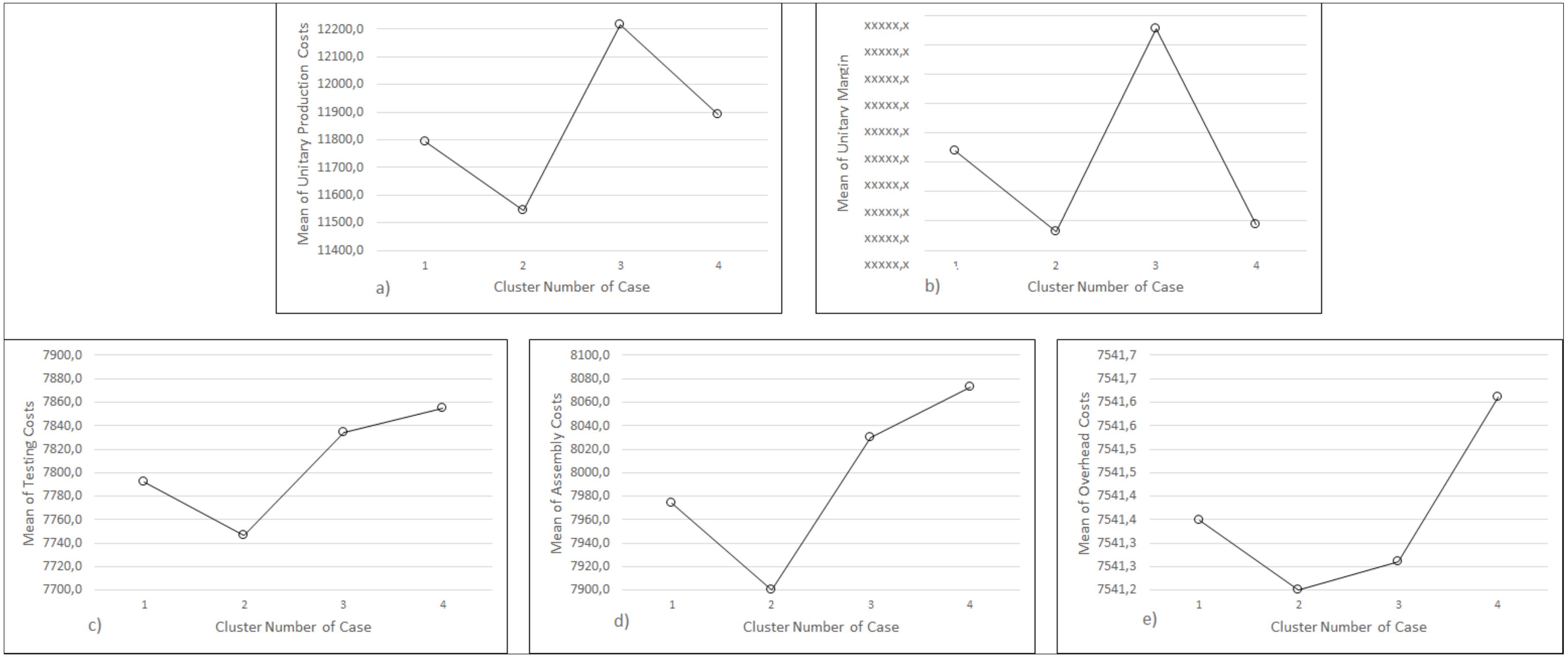


Figure 38 Cluster Differences on the Total Production Cost a), Margin b), the Testing Cost c), the Assembling Cost d), the Overhead Costs e)

CONCLUSIONS

In this chapter, the findings of this research are going to be summarised. The chapter outlines the research goals, the models that have been introduced, and the recommendations that have been presented. In addition, limitations of the study, and academic and industrial implications are also been discussed. The chapter concludes with reflections on further research opportunities.

6.1 Research Goals and Contributions

The product development process plays a crucial role, as different trade-offs and issues arise that require managerial attention (Trott, 2008). This thesis investigates specifically the issues related to the development cost and aims to reflect on models and methods developed for enhancing the life cycle cost analysis in the initial phases of the product development.

Although a multitude of applications and methods are available for Product Cost Estimation in literature, the thesis highlights their limited adoption in the industry (Layer et al., 2002). From a methodological perspective, this is due to the confusion regarding the approaches available, and ambiguity about their application (Korpi and Ala, 2008). From an implementation perspective, the main challenges lie in data gathering, analysis and effective utilisation. In fact, helping designers and managers to effectively understand the strategic, operational consequences of the implementation of cost analysis remains a problem, although advanced methodologies for more in-depth and timely analyses are available.

Therefore, the dissertation addresses all the previous aspects by structuring the discussion using three main research questions. The first goal was to understand the methodological and practical issues related to the implementation of a lifecycle perspective in a new development process. Once these methodologies were adopted by an organisation, the second aim was to understand the possible strategic implications. This is because product lifecycle cost methods usually require dealing with an enormous amount of data coming from operation processes. Hence, the effort required for data collection and integration for a lifecycle cost analysis can be further exploited for more in-depth consideration of the overall product performance. The third aim of the study was to investigate the possible strategic opportunities coming from the digitalisation of all industry processes. The massive amount of data that can be daily generated and the data mining-based techniques can represent a new trend in the way PLC methodology. Questa tesi funge da collegamento tra queste implementazioni futuristiche e ciò che viene attualmente fatto nel settore, dimostrando che ad oggi non esiste ancora una reazione sistematica all'acquisizione dei dati e delle informazioni giuste per gli obiettivi di analisi fissati.

The concluding answers to the research questions, together with the academic and industrial implications are summarised below.

6.2 Answer to the First Research Question (RQ1)

RQ1: How is it possible to operatively implement a PLC perspective in the complexity of an innovative product development process of an organisation?

In Chapter 2, the methodological aspects related to the use and adoption of cost estimation models have been highlighted through a systematic review of the traditional and more recent models available in the PCE literature. At first, the peculiarities of the existing models were examined, looking into the aspects that could prevent their wider diffusion. After analysing the most used taxonomies and techniques, a lack of standard was observed in the PCE literature. Cost analysis could, in fact, be performed by considering a different point of view, mainly regarding the qualitative or quantitative nature of a technique, the typology and degree of complexity of the product or process under investigation, or even the phase and objective of application. In spite of a number of exhaustive reviews, no reference was found in the literature that organises the different models simultaneously, based on various viewpoints, thereby ensuring a multilayer view of the cost analysis problem. Hence, in this thesis, a multilayer framework was provided that simultaneously takes into account the methodological nature of the technique, the typology of product or process to be analysed, the amount and typology of data to be collected, the intended application purpose and phase, and the object of the estimation. In this framework, methods, models and tools used for cost estimation in the last ten years were reviewed. The focus was specifically on the models suited to the analysis of the entire product lifecycle. Here, the main challenges of the existing models were highlighted, considering the dynamic changes in requirements for a cost methodology over the years, therefore drawing future research trends in this field. Apart from methodological aspects, issues in implementing the lifecycle cost analysis have also been outlined in this chapter. In particular, considering the general steps in applying a cost methodology, all the way through the data collection to the cost evaluation, many issues exist for an organisation. The information was selected from different phases and departments of a product lifecycle, as well as from the data integration, cleaning and interpretation process represented in examples of unsolved, although obvious and widely discussed, issues.

Therefore, in Chapter 3, this dissertation addresses all these aspects, providing a methodological approach to assess a rigorous implementation of PLC methodologies, while discussing the evidence derived from its operational and strategic impacts. In particular, a lifecycle cost approach has been introduced. The first objective of the methodology is to propose a solution for the lack of information to conduct a reliable cost analysis, especially in the early phases of development. Therefore, the model proposed in this thesis has taken inspiration from the product development process itself and has structured the analysis on the different degree of data granularity. Hence, the novelty of this method is in the way the information has been employed, dynamically moving the investigation with respect to data aggregation level and the product structure. To achieve the right level of granularity, different cost estimation techniques have been integrated, namely the Case-Based Reasoning, the Activity Based Costing and the Parametric method. In fact, the CBR technique has been employed to retrieve information hierarchically from similarly designed product structure. The ABC method has supported collecting lifecycle process data. The Parametrical method, in addition, has created the link between process and product parameters and the total lifecycle costs. The way the techniques have been combined represent another aspect of novelty. In fact, the introduced approach contributes to the new trend in the PCE literature, which suggests the integration of different techniques for product life-cycle cost analysis (Altavilla et al., 2017).

The methodology has then been implemented and validated on a real case study, and the results have been presented and discussed in Chapters 4 and 5.

In particular, in Chapter 4, the description of the case study was provided, defining the product family selected for the analysis, as well as the boundaries and limitations of the investigation. The process of data collection and organisation has been deeply tackled to propose a solution to all the main organisational issues previously discussed. In Chapter 5, the three steps of the methodology have been implemented. The discussion is organised in a way to present, phase by phase, the partial results of each step in the methodology, to demonstrate the difficulties, but at the same time, to show the benefit that can be derived by implementing a cost-estimation methodology.

6.3 Answer to the Second Research Question (RQ2)

RQ2: What are the strategic implications of the application of a PLC methodology in an organisation?

Based on the proposed cost-estimation methodology, a further analysis was proposed. It mainly focuses on the impact of a platform design strategy and variety proliferations on the total lifecycle cost. The analysis is proposed both in Chapters 3 and 4.

In particular, in Chapter 3, the thesis theoretically investigates the possible consequences that the implementation of PCE methods could have on the evaluation of product alternatives, particularly on the possible strategic analysis of the amount of data already collected and structured. In fact, at the end of this process, the knowledge collected is more than that acquired through the usual cost estimation process.

In Chapter 4, a cluster analysis was applied to assess platform alternatives on the overall life-cycle cost. This type of analysis allows detailed reflections on the product architecture and hence explores different design decisions. It, in fact, allows, for instance, the investigation of the relevance of product standardisation, as well as the role of different product variants in determining the product costs (e.g. what is the impact of variants proliferation?). Therefore, the analysis results were not neutral, neither when referring to the next steps of the operating processes, nor in terms of strategic consequences. Hence, a link was found between product costing and product portfolio planning. If the planning phase strategy informs and drives operations, cost estimation (so an operational activity of detail) can enable a more data-driven strategy, as also suggested in the literature (Settanni et al., 2014).

6.4 Contributions to Academic Literature and Managerial Practice:

This dissertation contributes to the academic literature in the areas of Innovation Management and Engineering design, because:

- This study reorganises the early literature on PCE methods, considering the most recent techniques and methods developed in this stream of research.
- The proposed multilayer framework suggests a guideline in choosing and searching the best techniques for the specific purpose of the application.
- The integrated approach proposed in Chapter 3 represents a contribution to the PCE literature and in a way tries to solve all the main issues related to data collection and integration, the use of quantitative detailed information since the beginning of the development process, as well as the use of a set of process and product parameter in order to express the lifecycle costs of a newly designed product
- The results obtained from the three steps of the proposed methodology again represent a contribution to the PCE literature, in that they help in supporting real-time evaluation of new product design, providing designers with an automatic way to perform lifecycle cost estimation. The output can be used either to evaluate the impact of different design alternatives or to derive the actual costs of the new product once the design choices are made.
- In this sense, the proposed methodology insists in changing the perspective with which designers look at costs. These issues, which have always been considered a pure constraint, are a driver for concept generation and evaluation since the beginning of a new product development process. Moreover, the verified effects of product variety and variants proliferation justifies attention to the multi-product development approach by creating a competitive advantage.

A number of insights gained over the course of this research also have the potential to contribute to the managerial practice.

- By conducting a case study within a representative commercially successful powertrain development firm, the development of various complex products that are both mature and rapidly growing can be studied, besides experiencing the development process of a new design concept. This increases the possibility that the methodology can also be applicable in other firms or organisations responsible for developing and maintaining other typologies of complex product/systems.
- The second contribution of this work to managerial practice is in providing a means for managing the design effort. By employing the steps that have been proposed in this work, managers would have a means of tracking the progress towards cost reduction and selection of the most efficient and sustainable design solutions. They will have the ability to visualize, phase by phase, the improvements in the product design at each aggregation level, and can track cost reduction by monitoring the impact of selected cost parameters while the product development process is in progress.
- Both the product managers and the development team would feel more confident when choosing between different design alternatives because they would have a crucial feedback mechanism, allowing their team to move, learn, and adjust as needed. Without the ability to monitor the product design decisions and the cost it imposes, managing its development process is a much more uncertain challenge, often leading to costly failures when the product is already on the market.
- This thesis also provides other general insights for practice. It demonstrates that some parameters, such as product modularity, number of parts and number of product variants, can be added to the list of variables that successfully express the costs at different phases of the product lifecycle. Hence, by tracking this limited number of cost drivers, the development team could increase the ability to proactively understand the overall performance of a product, adapting the development effort to optimize the product design, since its beginning.
- The problems of lack of knowledge in the exploitation of platform benefit point to the fact that the conditions for the achievement of platform effects are not well understood and are underestimated in the platform development projects. Often, the over-exploitation of platform benefit, without

estimating and quantifying the effects, is a challenge, but examples in this thesis document how it can be approached, especially the identification and estimation of the impact in the downstream phases of product lifecycle has shown the potential of product platforms. In the academic context, the findings indicate the need to focus on modelling of the platform effects (especially in the downstream phases) in combination with the cost estimation models.

6.5 Limitations of the Work

This work has a few significant limitations that should be highlighted. Although many steps have been taken to ensure a high degree of internal validity, a single firm study suggests some threats to further validation. It is possible that the selected case company is unrepresentative and the thesis conclusions, therefore, have limited applicability. However, the company has some unique attributes: it is reasonably representative of large firms that produce complex products. Over the years, they have adopted several industry standard languages, development tools, and techniques. Its design and project-management practices are similar to those of other large automotive companies.

One potential barrier to a broad generalizability is related to the domain of the thesis itself. An analysis on PCE methodology on a specific sector, as the automotive one, is characterised by particular requirements for a typology of product and processes. This concern is real, and the reader should understand that lessons learned here might not be directly applicable to products of a different type. However, there are enough similarities and we believe the results established in this work could be generalised outside this specific case. One reason is that the thesis looks at how designers cope with complex concept generation and their economic performances. However, other organisations may face the same experiences and challenges, no matter what they are developing. A second reason is that the thesis does not focus much on properties and parameters that are unique to the automotive sector. Instead, it focuses on the interconnection patterns between lifecycle elements. These common patterns are found in any product. It is therefore sensible that the influence of these universal properties, associated similarly, will influence cost drivers, regardless of the product type.

6.6 Answer to the Third Research Question (RQ3) and Directions for Future Work

RQ3: Due to the new challenges and opportunities provided by the digitalisation of all the industry processes, what will be the consequences for a PLC cost analysis?

This work raises many interesting aspects, particularly regarding the new opportunities provided by big data in the context of Industry 4.0. Nowadays, the industrial digital transformation imposes new challenges and opportunities in all manufacturing contexts (Holzhauser and Schalla, 2017). The consistent collection of an enormous amount of data coming from the increasing intelligence of manufacturing plants is in fact enabling different decision-making paths within the entire process of developing, producing, and maintaining products and services (Rimmy and Sharma, 2016).

As the entire manufacturing environment is changing, methods and approaches used for supporting companies during product development processes are changing too. In this context, the activity of cost analysis has also been affected by this big-data revolution.

As aforementioned, the way data is handled and collected is generally a challenge in this field. However, requirements have been ever changing, due to the new opportunities provided by the massive amount of information and data available nowadays. A report provided by General Electric (Annunziata and Evans, 2012) shows how manufacturing companies gather on average over 13 billion data samples per day. Tangible information (from operations) and intangible information (design choices from PLM systems) is embedded in this data (Ma et al., 2014). Therefore, the effective extraction and use of this "hidden" information represents the next frontier to drive innovation, and growth in manufacturing (Chandrasegaran et al., 2013). In this new environment, the opportunities for PLC, and also cost-driven decision-making multiply.

The methods that are the most appropriate in these contexts are currently being discussed in the literature (Altavilla et al., 2017, Chandrasegaran et al., 2013) and are a future step of my research.

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