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A Method for Forecasting Design Requirements Based on Experts' Knowledge and Logistic Growth Model.

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Table of Content:

List of Figures:

List of Tables:

Chapter 1

[1] Introduction

The rate of technological innovation increased considerably in the last years. This situation forced companies to quickly adapt their organization, processes and products to better answer the emerging demands from the society. In such a continuous fight to survive the market competition, companies need to anticipate the main features of future products and related manufacturing processes as essential mechanisms to keep their market position, competitiveness, and moreover to support the innovation process. Consequently, companies that were once dominant but failed to anticipate the appropriate information have discovered their vulnerability to the changes (Christensen, 2013; Roper et al., 2011). According to Roper et al. (2011), some changes that can affect companies emerge from technology development, market directions, while others will arise from social changes and related political decisions. Christensen (2013) highlighted that the strengths that make an organization successful could become obstacles if it is not prepared to new changes, as for example, the inability to quickly and smoothly adapt organization skills.

From system engineering viewpoint, the rate of changes is increasing for both products and processes, essentially motivated by improvements to better satisfy the different customer's requirements. On the one hand, changes for product and process should fulfill requirements emerged from market needs (Regnell et al., 1998). On the other hand, it should also deal with company's requirements (i.e. reduce resource consumption and cost). In this dynamic scenario, the constant evolution of products and processes create emerging and non-obvious problems challenging those who conceptualize, develop and implement the new solutions known as design engineers i.e multiple engineering disciplines as mechanical, designer, electric engineers and others (Robinson et al., 2005). Frequently, design engineers address at the conception of a new product by using product design phases (Cross, 2008). These phases allow to keep controlled and organized the design engineering tasks and related activities. Among the different phases, the early design phases are considered the most critical and relevant for the product development (Nguyen et al., 2012). The early design process phases aim at defining and extracting the different requirements of a product or process (Eppinger et al., 1994). Furthermore, a poor definition of requirements during its early phases can dramatically influence the results of the latter phases, causing several losses in terms of effort and time for companies. Consequently, design engineers need to properly understand the company and customers' requirements to provide solutions that can be developed and implemented, but not only considering a day-by-day perspective, but also a long-term perspective (Cascini, 2013). Moreover, design engineers should anticipate information about product and process requirements to exploit as much as possible their experience and knowledge to address emerging problems and changes. Indeed, the anticipation of information about requirements during the early design process phases should aim at: First, support company's decision makers, as for example R&D managers or CEO; Second, exploit the knowledge of design engineers in order to better accomplish the later design process phases.

In this scenario, the definition of reliable practices and supporting tools having an anticipatory perspective allows at driving with better effectiveness and efficiency the decision making processes. In practice, the process for the anticipation of information is known as *forecasting*. The forecasting methods are used to anticipate information about future and mainly applied by those who have to assign rights to make decisions, as for example, economists and managers. The results reported by the application of a forecasting method allow deciding on investments for making and implementing good decisions and implement ways to evaluate the business results (Lawrence & Klimberg, 2009). Indeed, the forecasting results and their synthesis provide strategic directions for the decision makers to follow, which support them to effectively manage the companies' resources.

From technology viewpoint, the anticipation of information about how a technology will change and what features will characterize the next generation of products or services is known as *technology forecasting (TF)*. The Technology future analysis working group (2004) highlighted that TF can be defined as a systematic processes that aims at producing valuable predictions for "describing the emergence, performance, features or impacts of a technology at some time in the future" However, even from a technology standpoint TF remains being closer to economists and managers than to those who are facing and solving the emerging problems as design engineers. In some research domains as economic and statistic have been created and developed different complex models of extrapolation and prediction, however, TF is much more than that. Certainly, TF should use quantitative regression, but also has to support at creating reasonable views of the future and bringing new knowledge to users and beneficiaries (Kucharavy and De Guio, 2008).

A relevant research goal in the engineering design domain is the definition and identification of suitable methods and tools to anticipate main features of products and processes, which have to be capable of driving with more efficiency the design process and also support decision makers about technology. This mentioned need is pushing design engineers for looking methods, models, and tools to better answer emerging demands and changes by exploring Technology Forecasting (TF) methods. However, this field of research is in an initial stage (Cascini, 2013).

In this scenario, a current research opportunity in the design domain is emerged at understanding which forecasting methods, techniques and tools can be suitable introduced at general design process. In specific, which are the forecasting methods suitable to be used and adopted by design engineers, by taking into account their skills, knowledge and background. So this PhD thesis attempts to exploit this research opportunity.

Accepting the hypothesis that **early design phases are critical stages for the product development process, and forecasting methods are useful to anticipate relevant information about requirements to support the design**

process and decision makers about technology. Therefore, the main research question is the following:

- How to systematically anticipate information about requirements during the early design process stage?

This research question can be further split in three sub-questions that will be faced in the present doctoral dissertation:

- How a design engineer can be guided into use forecasting methods in order to anticipate information about product and process?
- How a method for forecasting can be introduced systematically into the product development process?
- Which is the industrial and academic applicability of a method for forecasting in the design domain?

In order to answer these questions, the present thesis is divided in four chapters. Chapter one presents the state of the art of this research considering two viewpoints. From a design engineer perspective, the state of the art introduces a brief description of different product development processes to understand the common phases, which characterize a general design process. These descriptions clarify why the anticipation of information, particularly for requirements, is crucial at early design phase. From forecasting viewpoint, the state of the art presents particular attention in the definition about what technology forecasting really means in order to harmonize the common knowledge from literature. The different forecasting methods and related classifications are described as well. The last section presents the role of software tools to support the forecasting analysis, with specific attention to those users without experiences in forecasting.

Chapter two presents the original contribution of the present research. The first contribution of this research is the formalization of knowledge among different domains. However, the major contribution of the present research is the consequent introduction of a method for forecasting design requirements usable by design engineers without previous experience in forecasting. This chapter has been structured in three sections.

- **First, a formalization of the semantic of the requirements**. This will allow keeping a structured and systematic description of the requirements during the elicitation process, simplifying the transfer of knowledge.
- **Second, a formalization of forecasting methods compatible with design engineers' knowledge is provided. Furthermore, this subsection will linger on the background useful to understand the main traits in the application of the adopted forecasting techniques and models for this research**. This section will offer a frame useful to synthesize and create recommendations for design

engineers bringing the knowledge from forecasting experts to the design users.

- Finally, in the last section, **a method for forecasting design requirements is proposed as the main contribution of this research capable to support design engineers to anticipate information about design requirements; moreover, it can be useful to drive R&D strategies and related investment.**

Chapter three presents the results of this research by considering both applications, from an industrial and an academic perspective. From an industrial perspective, some research results are obtained based on the real application of the proposed method for products and processes, which allows understanding the benefits and limitations of the method proposal. From an academic perspective, tests to students were developed to understand and observe the learning process related to the proposed method and also to get new insights that the method provides through the test's participants. At the end of the section 4 three main validation criteria are described. Those criteria are used to validate the current research, and are based on:

A. Theoretical structural validity (Pedersen et al., 2000):
   i. Individual constructs constituting the method.
   ii. Internal consistency of the way the constructs are put together in the method.

B. Empirical performance validity (Pedersen et al., 2000):
   i. Capability to clarify the directions for product and process development and driving related strategic decisions.

C. Capability of the method to guide the design engineers without experience in forecasting:
   i. Usability of the time perspective to forecast requirements.
   ii. Capability of the method to provide new insights and conclusions about product/process requirements.
   iii. Effectiveness of the method to be transferable to design engineers independently from the adopted product development process.

Finally, the conclusions and further development section is presented as the fifth and last one. The outcomes of this research activity are discussed, highlighting to what extent the objectives have been satisfied, which limits have emerged during the application and testing phase, as well as the further opportunities originated from these activities.

Chapter 2

[2] State of the Art

This chapter defines the context on which the whole research focuses. Furthermore, this chapter presents some considerations about the limitations emerged from the state of the art analysis in the different science domains.

In the first section, a brief description of the design phases and related features is presented, together with an overview of Product Development Process (PDP). Moreover, this section describes the need of anticipating the requirement information during the early design phases. The second section introduces briefly what technological forecasting (TF) means, as well as an overview of current TF methods available on literature. In the third section is presented the conclusion of the state of the art analysis. Finally, the hypothesis and research questions are presented as well, which will be addressed through the development of this PhD dissertation.

2.1 The Product Design and Development Process

This section introduces a set of different Product Development Process (PDP) as initial understanding about how time-perspective approaches (i.e. anticipation of information) should be introduced into the design process. The different PDP are presented with a general description of their essential design phases, which are required to develop a product. Furthermore, this section defines the phases and features among different PDP, allowing to understand common knowledge of design engineers.

From the perspective of a design engineer, Cross (2008), carried out a meaningful review of different available approaches for product design. According to his analysis, it is possible to resume the different activities performed by designers during the PDP in four different phases: Exploration, generation, evaluation, and communication. These phases are organized in sequences, and iterations and loops are allowed and expected according to the heuristic of the design process. Also the model proposed by French (1985) is articulated into four phases: Analysis of the problem, conceptual design, embodiment of schemes and detailing. By comparing both the mentioned models, it is clear that every time a design proposal is developed, it requires the generation of solution concepts in order to address a need. Jones (1984), focuses on the same phases, although articulating those concepts in only three steps: Analysis, Synthesis and Evaluation, even if they plainly have a similar meaning to what Cross (2008) has proposed. The objective of these phases is more structured and systematic analysis, as it can be understood from the work proposed on Becattini (2013), where the *Analysis* stage prescribes to list all the requirements in order to produce a meaningful and complete design specification. During the stage of s*ynthesis*, each characteristic of the design specification is singularly addressed to devise solution concepts. The *evaluation* phase, in turn, specifies that the decision on the final design proposal must be taken into account by considering the capability of the design concepts to match the various requirements.

In this context, it is important to note how Pahl et al. (2007) improved the characterization of the design process by prescriptive models for design, identifying four phases along the PDP (Figure 1). In particular, in Pahl's model, the *Clarification of Task and Plan* phase collects information about the requirements to be embodied in the solution and also about constraints. *Conceptual Design* establishes function structures, searches for suitable solution principles, and combines these elements into concept variants. In the phase of *Embodiment Design*, starting from the concept the designer determines the layout and forms to create a technical product or system in accordance to technical and economic considerations. Finally, *Detail Design* describes the arrangement of form, dimensions, and surface properties of all the individual parts laid down, together with the materials specified, technical and economic feasibility re-checked; all drawings and other production documents as well. With a similar logic, Ulrich and Eppinger (2012), proposed a PDP based on six phases: *i) Planning, ii) Concept Development, iii) System-Level Design, iv) Detail Design, v) Testing and Refinement, vi) Production Ramp-Up.*

Baldussu (2014) noted how apart from the differences in the third phase's names, these two approaches, Pahl et al. (2007) and Ulrich & Eppinger(2011), share a common perspective for at least the first 4 steps. Moreover, Baldussu (2014) pointed out how most of the times companies specifically develop their own PDP approach, often as an adaptation of one of the standard approaches listed so far (e.g. Cross, 2008; Pahl et al., 2007; Ulrich and Eppinger, 2011). In fact, examples of PDP proposed by Pahl et al. (2007) and Ulrich and Eppinger (2011), are mostly diffused in industries and thought at universities. One common feature among them was observed by comparing all these above-mentioned approaches. All the mentioned PDP models start with an analytical phase to understand the problems to address and the requirements that should be met to obtain a valuable solution.

From this state of the art, it is important to note that requirements analysis seems to be a common step among different PDP models. Therefore, requirements analysis is an essential as well as an elementary step, and it deserves to be a central issue in the design research (Chakrabarti, 1994). Consequently, it is important to note that design engineers have to understand company's and customers' requirements to provide solutions that can be developed and implemented, but not only considering a day-by-day perspective, but also a long-term perspective (Cascini, 2013).

Consequently, a research proposal that considers a time-perspective approach has to be introduced at an early design phase, allowing design engineers to bring new knowledge about future of product and process. As a consequence, this research is going to focus the attention on the analysis of design requirements and their potential evolution for both product and process. The following subsection allows at understanding how design engineers deal with design requirements in practice.

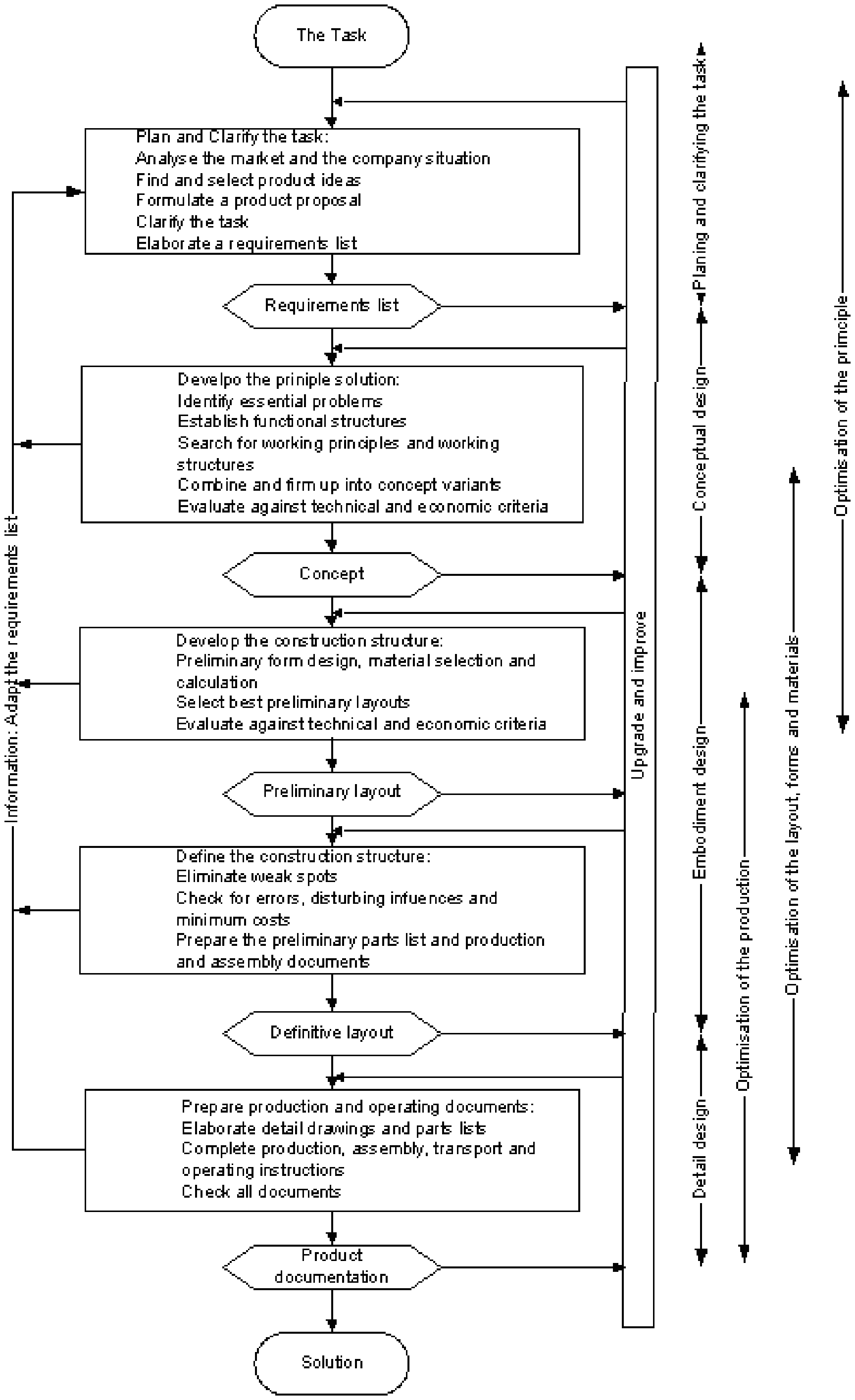


Figure 1: The phases describing the systematic Product Development Process according to Pahl et al. (2007).

2.1.1 Design specification and requirements for product and process

This subsection presents a literature review about the management of requirements during the early design process, with deep attention on the elicitation of requirements. The PDP model developed by Pahl et al. (2007), in specific the first phase model, has been adopted as the reference model for this subsection

According to Pahl et al. (2007), *the task clarification* phase is characterized by activities which help to identify, collect, transform into a suitable form, and store the requirements and associated information that the design must satisfy to be used during subsequent design phases. The goal of this phase is, basically, to identify and transform information residing in the assignment and other associated documentation into the designer's own language. At the same time, the definition of the design specification is a task that requires designers to formalize their or others' knowledge in order to make it manageable, understandable and, most of all, usable to drive the whole product development process with criteria for supporting both the exploration of new solutions and their evaluation (Cross, 2008). Indeed, the satisfaction of requirements influences the decision-making process for both the choice of best alternatives and the search of new solutions. However, it is important to clarify what requirement means, for instance, IEEE's (1998) defines requirements as:

"A statement that identifies a product or process operational, functional, or design characteristic or constraint, which is unambiguous, testable or measurable, and necessary for product or process acceptability" (by consumers or internal quality assurance guidelines)(IEEE, 1998)

The definition, organization, and management of the system's requirements are challenging especially for those situations characterized by high complexity. The NASA Systems Engineering Handbook (Kapurch, 2010) and the INCOSE textbook are two examples of Systems Engineering approaches for the management of a complex system development. Both of these texts show that the identification of requirements is as relevant as their proper management in appropriate clusters, which are organized hierarchically.

From the Systems Engineering perspective, Bijan et al. (2013) has reviewed the state of the art concerning approaches dealing with system requirements. They characterized them by similarity, considering three relevant categories. A first category focuses on facilitation methods and approaches, collecting those that aim at understanding and acquiring customers' needs (e.g.: Use Cases, QFD, and The Five Whys). Another category concerns the prioritization methods that collect approaches like the Analytic Hierarchy Process (AHP) in order to distinguish requirements according to their importance for customers along the product development process. The third category, the transformation of requirements, in turn, considers approaches whose purposes are to switch data, information, and knowledge into requirements after the application of facilitation techniques. Moreover, Bijan and colleagues also add a further category of approaches (i.e. “standalone”), for which a common characterization is not viable.

It is interesting to note that, despite the already mentioned approaches, the majority of those methods were built in order to support the definition of hierarchical relationships between systems and subsystems. The Agile manifesto (Beck, 2001) is the only alternative which allows considering requirements as dynamically changeable during the development process, due to the active presence of the customers as participants to the designing activities. However, it is important to mention that none of the cited approaches addresses at the understanding of the dynamics of requirements of a product beyond the product development process, on a longer time perspective.

However, what emerges from the above-presented analysis of the state of the art, as well as from the mentioned textbooks by NASA and INCOSE, confirms that the importance of knowledge is an essential element of the system development to clearly define targets and objectives so as to drive and check what is generated during the design process. Consequently, this research proposal aims at understanding how to exploit the knowledge design engineers by using time-perspective approach to support the design process.

2.1.2 Role of knowledge during the early design process phase

From the design perspective, the definition of requirements is a cognitive process that deals with the transformation of tacit into explicit knowledge (knowledge externalization). The definition of requirements is one of the most critical cognitive processes to be carried out (Civi, 2000), especially because it is necessary to state in advance what to capture during such knowledge formalization (Hicks et al., 2002). In other words, it is necessary to consider both the sources of knowledge and the content to be formalized inside the design specification. However, it is important to understand which source of *knowledge*, *information*, and *data* are plausible to exploit during the product development. According to Rowley (2007) *Data* is an unorganized and unprocessed set of discrete units that collects objective facts or observation whose meaning is null until it is not considered within an appropriate context. *Information,* in turn, collects processed and organized data that is meaningful and relevant within the context in which it has been considered or examined. Finally, *Knowledge* pertains to the individuals and several processes can breed it, such as the synthesis of multiple sources of information over time as well as study, learning, and experiences. For what concerns the sources of knowledge that may play a relevant role in the design processes, Allen and colleagues (2000) presented a classification of the different sources of knowledge, both explicit (e.g. libraries, patent offices, advertising, journals, standards, etc.) and tacit (e.g. customers, suppliers, colleagues, in a single word, the stakeholders)(Figure 2). In particular, while the formers require, in case, the interpretation of what is already made explicit, the latters are those sources for which the externalization becomes relevant (Becattini, 2013).

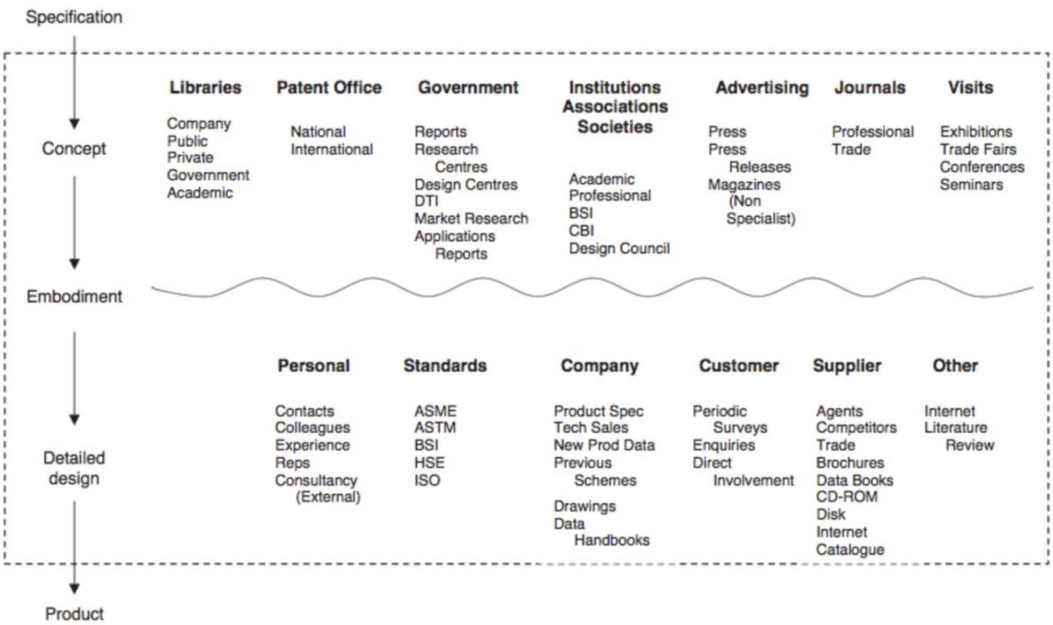


Figure 2: Sources of information and knowledge along the different phases of the design process according to Allen et al. (2002).

The stakeholders of a product, a process, or a service (i.e., something that has been somehow designed) are defined as those "who will have an interest in the system throughout its entire life cycle" (Haskins et al., 2006) or "The organization or individual who has requested the product(s) and those who are affected by or are in some way accountable for the product's outcome" (Kapurch, 2010).

The second definition is also followed by the distinction of stakeholders in customers and its category. The definition of customers is uniform in literature. Customers are those who can be considered as the final beneficiaries of the design outcome. What vary in literature are the categories to be included into the customers. Some authors include designers and engineers (Kapurch, 2010); some others are mostly focusing on the final beneficiaries of mass products (Bijan et al., 2013). From the systems engineering perspective, however, this is perfectly consistent, showing the need of developing instruments which are sufficiently versatile to address the different stakes, whatever is the source they come from.

Considering customers as the first beneficiaries of products (e.g. the purchasers of goods) their opinion about needs, expectations and, eventually, requirements is the content to be considered crucial for a successful design process (Clausing, 1994). The so-called “Voice of the Customer” (VoC) plays a relevant role whether the product development process is carried out for the customer (customer outside the design process), with the customer (co-design with the customer as a solution evaluator) or by the customer (co-design with the customer as a solution generator) (Kaulio, 1998). Questionnaires capture the VoC and design experts formulate questions according to customers' requirements defined in advance. Several approaches are available to support the formulation of questions such as, for example, the “quality dimension development process” (Hayes, 2008) and the “critical incident approach” (Flanagan, 1954). Considering a long time perspective, it is worth mentioning that the people involved in these surveys are usually asked to express their opinions about the experiences they already have had with existing products, or after the interaction with already developed prototypes in one of their common usage scenarios. It follows that those answers can poorly drive designers in better understanding customers’ future needs, which are beyond the short term.

For what concerns the other stakeholders involved at different extents in the design process (e.g. designers, procurement and organization departments, as well as manufacturers, suppliers, decision makers, etc.), there exist a wider number of design tools or approaches for the elicitation and the management of requirements. Among those, it is worth mentioning technical standards (e.g. those released by entities like ISO). Technical standards are sets of design requirements (both as definitions and range of values) for specific product or process categories. They are very focused on specific fields of techniques and, as a consequence, the more detailed they are, the higher is the degree of complexity of the subject of the standard. This makes them poorly adaptable to a various range of fields of applications. Fulfilling a standard cannot be considered as a real knowledge elicitation, since they just make explicit what was tacit for others. On the contrary, Checklist tries to address this issue with a broader perspective, being more general and by taking into account different issues concerning the development of a product. Several checklists are available through scientific literature. For instance, the textbooks by Pahl et al. (2007); by Roozenburg and Eeekels (1995) as well as the one by Hales and Gooch (2004) present checklists for supporting the identification of the requirements by the stakeholders involved in the product development. They usually address different concepts by following taxonomies that are based on the product lifecycle stages (e.g. such as maintenance, disposal) or on geometry and material issues (e.g. size and weight).

From a different perspective, the “Design for X” (Pahl et al., 2007) guidelines address the needs of a wide range of technological domains. However, they are mostly focused on the definition of best practices to design products so as to satisfy a meta-requirement at a time, rather than a wide range of requirements, as necessary in the development of artificial products that have to interact with a complex environment (Simon, 1981).

With the purpose of combining the versatility of the Design for X approach and the capability to cover a wide set of requirements as for standards and checklists, a recent proposal focuses on the development of a more versatile approach for populating a design specification (Becattini, 2013). It introduces a general-purpose checklist based on abstract criteria for the elicitation of requirements. Its taxonomy should allow an investigation of relevant knowledge by considering abstract categories such as performances, harmful effects and consumed resources (Becattini et al., 2011) that are further detailed in sublevels. All the above approaches are capable of triggering reflections in the stakeholders of the development process, so as to generate requirements that are not yet usually considered, but that may become potentially relevant in the future. Noteworthy, they do not provide any contribution in understanding what could be their value for the achievement of satisfaction.

It is worth considering the method to carry out the externalization process, being it directly responsible of the effectiveness and the efficiency of the definition of the design specification. The *human-human approach* involves a methodological facilitator (Fellers, 1987), which is skilled in the procedure for acquiring new knowledge and transfer it to an explicit format. This person (the facilitator) must coordinate the activities in order to keep a clear understanding of what is the content to be externalized, so that it is possible, in turn, to organize it in an appropriate way to make it reusable in the future. These approaches are often based on the interaction through Questions and Answers (Q&A) among different participants. The logic of interviews has been also duplicated in the forms of written questionnaires, so as to start releasing from the need of a facilitator. On the other hand, questionnaires with predefined questions cannot adapt the sequence of Q&A according to the answers the person participating in the survey is writing.

Surveys and interviews, however, are not the only methods capable of carrying out the externalization processes. Several examples demonstrate that this issue can be also addressed through the use *of Relation Tables:* insert the elicited knowledge in a well-structured framework that is easy to update and that holds a well-defined hierarchical structure. Nevertheless, it is also worth noticing that this highly hierarchical way to represent information dramatically increases the efforts in cases where complex phenomena and systems, as occurs in design for technical systems, should be codified (Martin et al. , 2012).

Noteworthy, several contributions try to exploit the use of computer tools so as to mimic the behaviour of a methodological facilitator. Wang and Zeng, for instance, presented a prototype capable of asking questions in order to capture product requirements from customers' answers (Wang and Zeng, 2009). Both Shneidermann (2006) and Andersson (2004) proposed computer-based tools exploiting the sequences of questions and answers for the verification of product requirements downwards the development process. From a more problem-based perspective, Becattini et al. (2012) proposed a model and an algorithm that has been implemented in a prototype web application that aims at highlighting the conflicting requirements underlying a design problem.

For what concerns the computer mediated communication approaches for improving the knowledge about the future, some applications based on the Delphi-method, e.g.: (Garcia-Magariño et al., 2009) and (Turoff et al.; 1999), show that Q&A is a suitable technique in order to leverage qualitative knowledge. Other instruments, requiring a stronger background in statistics, support the definition of fact-based predictions by means of the regressions of quantitative data (e.g. LSM2 by IIASA and Loglet).

Finally, the organization of knowledge about requirements should be easily understandable and sharable among the different subjects involved at various extents in the development and design processes. Moreover, the anticipation of information for requirements have to be capable of dealing with the externalization of tacit into explicit knowledge, as well as with its quantitative and qualitative aspects, in order to exploit the experience of the different stakeholders involved in the design process.

The following section presents the state of the art related to Technology Forecasting (TF) methods, which deals with the anticipation of data and information about future.

2.2 Technology forecasting

> *"Technology forecasting purpose's is to provide timely insight into the prospects for significant technological change"*
>
> *(et al., 1997)*

How technology change and what features will characterize the next generation of products or services required by the market constitutes strategic information for companies, and represents a shared dilemma among innovators. The research community has tried to address these needs through technology forecasting (TF) methods. However, the definition of what technology forecasting method means in literature is quite fuzzy, and it can be interpreted in different ways depending on the specific research community e.g. economy and statistic. From prescribed language definition, the meaning of method is rather intuitive (*"an ordered systematic arrangement of..."*) (Oxford English Dictionary, 2014)), however, the meaning of "technology" and "forecasting" are worth of some more explanation.

As first, the Oxford English Dictionary (2014) defines technology as: "*the branch of knowledge dealing with the mechanical arts and applied sciences*" and "the *application of such knowledge for practical purposes, esp. in industry, manufacturing*". With similar perspective, the American Heritage Dictionary (2014) reports: "[technology is] *the application of science, especially to industrial or commercial objectives"; "the scientific method and material used to achieve a commercial or industrial objective".* Both of these definitions seem to be adequate for this research since both, product and process, are included in the objectives to be achieved in the definition.

Secondly, the Oxford English Dictionary (2014) defines forecasting as: *"to consider or think of beforehand*"; "*to estimate, conjecture, or imagine beforehand (the course of event or future condition of things)".* On the other hand, the American Heritage Dictionary (2014) defines it as: *"To serve as an advance indication of..."; "to estimate or predict in advance, especially to predict".* Both of these definitions fitting the meaning adopted for the term in the present dissertation: both of them deal with the meaning of anticipation regardless of the object of the anticipation itself (i.e. data, information or knowledge.)

Even considering the previous clarifications, the definition of the TF methods in the current vocabulary is rather fuzzy (Porter et al., 2011). In fact, TF is understood differently depending on the field of research. For instance, economy and other fields such as statistics and management rely on forecasting based on statistical/probabilistic prediction (i.e. anticipation of quantitative values), building complex models of extrapolation; as a consequence, their perception about TF is mainly related to data prediction by using those complex models without so much attention on the forecasting users (Porter et al., 2011). On the contrary, Armstrong (2001) highlighted that a suitable forecasting method certainty should use extrapolation techniques to create an accurate future prediction, but in practice the forecasting is more than that. Armstrong (2001) described the "forecasting" as a need to anticipate uncertainty information about the future, highlighting the fact that its usefulness largely depends on the initial user's knowledge. With similar view, Kucharavy and De Guio (2005) emphasized that a suitable and reliable TF should bring, at least, new knowledge to users and related beneficiaries. On the one hand, the users are essential for the application of the forecasting analysis. On the other hand, the forecasting beneficiaries are important to evaluate the forecasting results (FORMAT-deliverable 2.1, 2013).

Other author as Martino (1993) proposed the TF as "*a prediction of characteristics of useful machine, process or techniques*", highlighting three main points in his proposal: i) TF deals with characteristics, such as levels of performance (i.e. speed, power, or temperature, etc.), and it does not have to state how these characteristics are achieved; ii) TF deals with useful machines, excluding those items which depend more on the popular tests than on technological capability; and iii) TF needs four essential elements in order to bring useful knowledge to decision maker. These four elements are: *the technology being forecast, related characteristics statement, time for forecast and probability.* From similar perspective, the Technology Future Analysis Working Group (2004) proposed that TF as a systematic processes which aims at producing valuable predictions by "*describing the emergence, performance, features or impacts of a technology at some time in the future*", where its usefulness is conditional to the final decision maker (i.e. economist, managers and others)

Combining the ideas of TF, the author of this dissertation defines a common viewpoint on what TF means i.e. a systematic process capable of anticipating data and information about technology in order to bring new and useful knowledge to users and related decision makers. This meaning allows understanding that technology forecasting is more than predicting data by using extrapolation models; it has to bring also new knowledge about the future for users and beneficiaries.

The next subsection presents the different forecasting methods available on literature to understand methods' features, benefits and limitations to support design engineers during the design process.

2.2.1 Forecasting methods and related characterization

In literature, several methods and tools are available with different features and characteristic to support decision makers with information about the possible and probable future scenarios of a technology. Since many types of forecasting methods are available in literature, several attempts have been made in the research community to integrate and cluster this wide variety of technology oriented approaches (e.g. Gordon and Glenn (2003); Technology Future Analysis Working Group, 2004). The need to organize the different methods emerged since the forecasting is not a simple and single phenomenon, but it is a rather complex process of analysis and synthesis of data and information. As stated in the FORMAT methodology (2013), the forecasting involves people, processes as well as science and sources of information. Moreover, there are no universal forecasting methods and, in fact, more than one hundred are available in literature (FORMAT deliverable 2.3, 2013). Actually, despite this abundance of technology forecasting methods and techniques, it seems that to come up with a reliable forecasting is still rather difficult. On the one hand, the capability to create a reliable and accurate forecast analysis depends on the techniques and the experience of the analyst using that given forecasting method to understand the technology future. On the other hand, the novelty of the results is a critical feature about what should be forecasted (Armstrong, 2001), even if it is from a relative and not absolute point of view. According to Armstrong (2001), forecasters recognize a useful forecasting method when it is easy to use and when it brings to non-obvious conclusions. With similar view, Kucharavy et al. (2007) point out that there is a need of providing to “final users” usable and reliable forecasting techniques to enable the retrieval of useful indications when setting company's priorities and structuring the design activity. Consequently, it seems that appropriate forecasting methods are those that stem from the specific knowledge of the users providing new insight about the future that the method can provide them. From this perspective, probably the forecasting methods created with a specific scope and purpose represent the most widely acknowledged solution to accept the reliability, usability and accuracy of a method by different users.

Among the different available forecasting methods, Technology Future Analysis Working Group (TFAWG) (2004) presented one of the most recognized classifications of TF methods; in their proposal the technology forecasting method are presented in 9 forecasting families (i.e. groups of different forecasting methods organized according their characteristics). In TFAWG’s classification is possible to distinguish among both Soft (Qualitative) and Hard (Quantitative) forecasting methods. On the one hand, qualitative methods correspond to those methods that create a future scenario based on users’ knowledge and judgment. On the other hand, quantitative methods are those that use quantitative regression and, in some cases, a set of rigorous rules to envisioning the future. Furthermore, TFAWG (2004) proposed a secondary classification about how the forecasting is developed as: i) Exploratory methods which begin from the present, and see where events and trends might take us; ii) Normative methods that begin from the future, asking what trends and events would take us there. However, many methods can be considered normative or extrapolative, quantitative or qualitative, depending on how they are applied. For instance, TFAWG (2004) pointed out that each method can be useful by itself or by a combination of them. In table 1 is presented the classification proposed by the TFAWG (2014).

Table 1: Forecasting families and related methods according to TFAWG (2004).

Family	Forecasting method	Hard/Soft	Expl/ Norm
Expert Opinion	Delphi (iterative survey)	S-Ql	N-E
	Focus Groups [panels, workshops]	S-Ql	N-E
	Interviews	S-Ql	N-E
	Participatory techniques	S-Ql	N
Trend Analysis	Trend Extrapolation [Growth Curve Fitting]	H-Qt	E
	Trend Impact Analysis	H-Qt	N-E
	Precursor Analysis	H-Qt	E
	Long Wave Analysis	H-Qt	E
Monitoring and Intelligence	Monitoring [environmental scanning, technology watch]	S-Ql	E
	Bibliometrics [research profiling; patent analysis, text mining]	H/S-Ql/Qt	E
Statistical	Correlation Analysis	H-Qt	E
	Demographics	H-Qt	E
	Cross Impact Analysis	H/S-Ql/Qt	E
	Risk Analysis	H/S-Ql/Qt	N-E
	Bibliometrics [research profiling; patent analysis, text mining]	H/S-Ql/Qt	E
Modelling and Simulation	Agent Modelling	H-Qt	E
	Cross Impact Analysis	H/S-Ql/Qt	E
	Sustainability Analysis [life cycle analysis]	H-Qt	E
	Causal Models	H/S-Ql/Qt	E
	Diffusion Modelling	H-Qt	E
	Complex Adaptive System Modelling (CAS) [Chaos]	H-Qt	E
	Systems Simulation [System Dynamics, KSIM]	H-Qt	E
	Technological Substitution	H-Qt	E
	Scenario-simulation [gaming; interactive scenarios]	H-Qt	E
	Economic based modelling [input-output analysis]	H-Qt	E
	Technology Assessment	H/S-Ql/Qt	E
Scenarios	Scenarios [scenarios with consistency checks; scenario management; concept scenario]	H/S-Ql/Qt	N-E
	Scenario-simulation [gaming; interactive scenarios]	H-Qt	E
	Field Anomaly Relaxation Method [FAR]	S-Ql	N-E
Valuing/ Decision/ Economics	Relevance Trees [futures wheel]	S-Ql	N-E
	Action [options] Analysis	S-Ql	N-E
	Cost-benefit Analysis	H-Qt	E
	Decision Analysis [utility analyses]	S-Ql	N-E
	Economic based Modelling [input-output analysis]	H-Qt	E
Descriptive and Matrices	Analogies	H/S-Ql/Qt	E
	Backcasting	S-Ql	N
	Checklist for Impact Identification	S-Ql	E
	Innovation System Modeling	S-Ql	E
	Institutional Analysis	S-Ql	E
	Mitigation Analysis	S-Ql	N
	Morphological Analysis	S-Ql	N-E
	Roadmapping [product-technology roadmapping]	H/S-Ql/Qt	N-E
	Social Impact Assessment	S-Ql	N-E
	Multiple Perspectives Assessment	S-Ql	N-E

	Organizational Analysis	S-Ql	E
	Requirements Analysis [needs analysis]	H/S-Ql/Qt	N
Creativity	Brainstorming [brainwriting; nominal group process (NGP), SCAMPER]	S-Ql	N-E
	Creativity Workshops [future workshops]	S-Ql	N-E
	TRIZ	H-Qt	N-E
	Vision Generation	S-Ql	N-E
	Science Fiction Analysis	S-Ql	N

Given the over-mentioned scenario, an important activity for this research is at least recognizing which are the methods suitable to support the different PDP. Furthermore, recognize which methods are compatible with design engineers' knowledge. Consequently, a detailed explanation is required to understand their suitability for this research. According to Roper et al. (2011), there are only five families considered frequently used by practitioners:

i) Methods constituted by the ones who have the knowledge, well known as **"***Expert Opinion***",** where the opinion of the expert is obtained and analysed. The main assumption of these methods is that *"some individuals know a lot about some topic than others, their forecast will be substantially better"* (Roper et al., 2011). However, a limitation of the method is the identification of the appropriate expert for the forecast. Moreover, if the interaction among experts is allowed, the forecast may be affected by several social and psychological factors (Levary et al.,1995);
ii) Methods that rely only in prediction of future values, also known as *"Trend analysis":* Mathematical and statistical techniques used to extend the time series data into the future. The main assumption for this family is *"past conditions and trends will continue in the future more or less unchanged*". The limitations of these methods are availability and goodness of the data (Phillips et al., 2007).
iii) Methods focused on collecting data and process them to find relevant patterns and trends recognized as *"Monitoring"*. Actually, strictly speaking this is not considered as a forecasting method; however, it is used to gather data and in some cases information. The main assumption is "*there is information useful for a forecast, and it can be obtained"*; the main limitation emerged from the quality of the data and their results, because several times it is performed without adequate selectivity and filtering (Coates et al., 2001);
iv) Methods that try to represent the reality by models, well known as **"***Modelling"*, the main assumption is *"the basic structure and important aspects of part of the world can be captured by simplified representations"*. However, a limitation emerges from the sophisticated techniques that may drive to faulty assumptions, giving a poor credibility to the forecasting results (Armstrong, 1985). In particular, models usually favour on quantifiable over no-quantifiable parameters, thereby neglecting potentially important factors (TFAWG, 2004);

v) Finally, those methods that create "*Scenarios*" about the future**,** corresponding to a set of scenarios that can encompass a plausible range of possibilities for some aspects of the future. The main assumption is "*The richness of future possibilities can be incorporated in a set of imaginative descriptions. Usable forecasts can be constructed from a very narrow database or structural base*"; a limitation emerged from the practice, in many cases, the forecast might be more a fantasy rather than a forecast unless a strong basis in reality is maintained (TFAWG, 2004).

It is worth noticing that TFAWG's classification focuses his attention on describing methods and techniques without deep references to the forecasting users. As a consequence, in TFAWG's classification, the selection of a forecasting method is suggested mainly by the data availability rather users knowledge.

On the contrary, the classification proposed by Armstrong (2001) presents features nearby to forecasting users. Indeed, Armstrong (2001) highlights that the usefulness and accuracy of a method are strongly influenced by users. In his book "*Principle of forecasting",* Armstrong (2001), defines a classification of forecasting methods based on knowledge sources. In specific, the methods classified by Armstrong (2001) are divided into those methods based primarily on judgments and those methods based on statistical sources. On the one hand, judgemental methods are those based on qualitative analysis, allowing exploiting the user's knowledge and experiences about the subject to forecast. On the other hand, statistics methods exploit the data available to predict future values. It is important to note that the two classes of methods display an increasing amount of integration of, respectively, judgmental and statistical procedures.

In more detail, judgmental methods are split into those that predict one's own behaviour, versus those in which experts predict how others will behave. The statistical methods are divided into univariate branch and multivariate branch (Figure 3). The univariate methods are those methods that use time series data to predict other values and the multivariate methods are those that use models with multiple time series to predict future values.

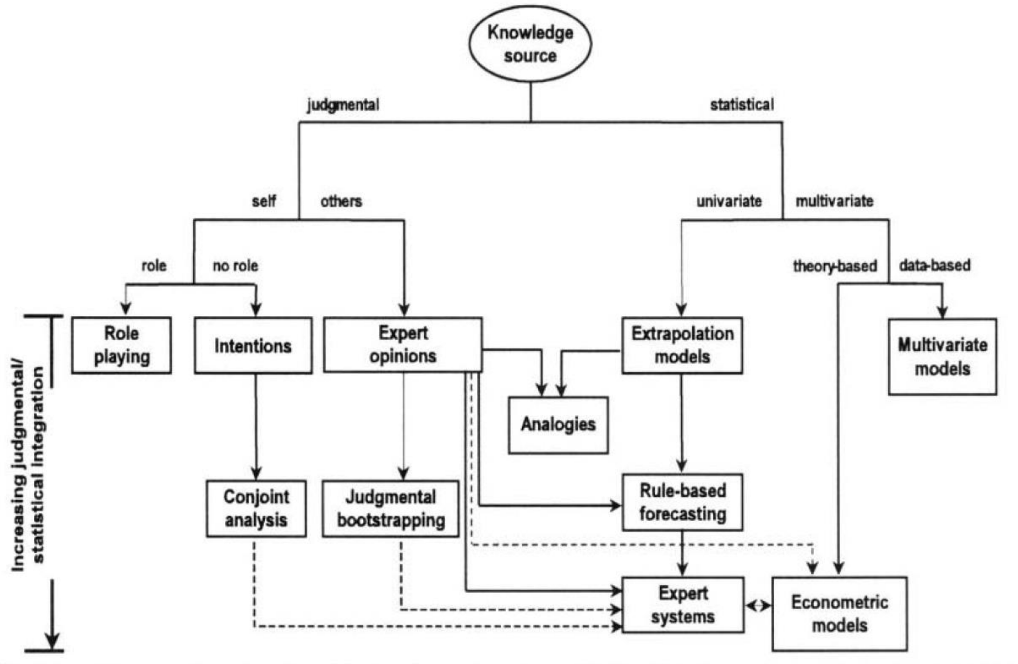


Figure 3: Characteristics of the forecasting methods and their relationships according to Armstrong (2002).

For what concerns the ambiguity in determining the right forecasting methods for this research, the comparison between TFAWG (2004) and Armstrong (2001) allows to understand the required aspects to consider for the anticipation of design requirements. On the one hand, the time-perspective approach has to allow exploiting judgment and knowledge from design engineers (i.e. as forecasting users). On the other hand, it has to be suitable to manage the different type of requirement by considering both qualitative and quantitative requirements. Consequently, the introduction of a time-perspective to the design process has to be, at least, based on the combination of quantitative and qualitative methods capable to be used by design engineers.

With a broader perspective, the FORMAT Consortium (2013) developed an exhaustive literature review to understand the overall framework of forecasting methods. The classification developed by FORMAT Consortium was constituted by more than two hundred methods available on literature (Table 2). The classification of the methods was based on the classes proposed by Kucharavy (2013), but formalized by Slupinski (2013). The usefulness of this classification emerged from the need to understand the purpose of the forecasting methods and, furthermore, to be of a practical use given the large number of method available literature review. In detail, Kucharavy's classification grouped all the techniques in a manageable number of classes: i) *Causal models* (e.g. analogy, morphological analysis, laws and patterns of system evolution); ii) *Phenomenological models* (e.g. extrapolations of time series data, regressions); iii) *Intuitive models* (e.g. Delphi surveys, structured and unstructured interviews); iv) Monitoring *and mapping* (e.g. scanning of literature and published sources, scenarios, mapping existing information). Table 2 illustrates the accounted methods and related number of categories proposed by different authors. References, meanings and more detailed descriptions are available in (FORMAT deliverable, 2013).

Table 2: Number of methods extracted by different authors in the forecasting field (FORMAT deliverable, 2013).

#	Name of the source	Method.	Categ ories
1	A.L. Porter *et al*. "Technology futures analysis: Toward integration of the field and new methods" 2004.	51	9
2	Makridakis *et al.* "Forecasting methods and applications", 1998.	19	19
3	J.Scott Armstrong *et al.*"Principles of forecasting", 2002.	10	10
4	Vanston, "Technology futures", 2005 .	28	11
5	FOR-LEARN	26	9
4	J.P. Martino "Technological forecasting for decision making", 1993.	39	11
7	Futures Research Methodology Version 2.0, Millenium Project, 2002.	27	-
8	Futures Research Methodology Version 3.0, Millenium Project, 2011.	35	-
9	Technological Forecasting and Social Change, Special issues since 2004.	9	-
10	International Journal of Forecasting, Special issues and sections since 2000.	4	-
11	M3 competition	24	6
12	A.L. Porter – presentation, 2005.	19	13

The analysis proposed in FORMAT-deliverable 2.3 (2013) highlighted the multiplicity of methods, in fact; there are significant overlaps between methods, moreover, some of them are entitled to different authors and named differently in the diverse sources.

Concluding, it is interesting to notice that forecasting methods are not mutually exclusive. Moreover, according to the over-mentioned authors' classifications during the state of the art analysis, it is possible to state that a general criteria to select a forecasting method should be at least consider three elements: i) users (i.e who is going to use the method); ii) sources of data, information and knowledge (i.e. where to obtain data, information and knowledge), iii) forecasting purpose (i.e. what we need to know about the future).

With a complementary view, Martino (1993) highlighted that independently from the adopted method (i.e. expert opinion, trend analysis, modelling, monitoring, scenario or others) at least four essential elements should be followed to develop an appropriate and structured forecasting analysis. These elements will be widely explained in the following subsection.

2.2.2 Elements for a structured and systematic forecasting analysis

A well-structured forecasting analysis is critical to exploit as much as possible the user's capabilities and knowledge. On this basis, Martino (1993) defines four elements which can be considered as step-by-step instructions to follow in order to develop a structured and systematic forecasting analysis, without regard on the adopted forecasting method. In Martino's view, the time perspective of the study is irrelevant at an initial stage. The first mandatory action is to properly define the context of the analysis (i.e., the specific area to be observed and the research questions to be answered) so as to perform reliable estimations about the future and to correctly assess the technological feasibility of the emerging solutions (Martino, 1993; Cuhls, 2003). Martino (1993) emphasizes that forecasting analysis can be divided into four main elements (Figure 4). In particular, these elements are known as: *The technology being forecast,* focusing on the object of the forecasting (i.e. the technology under analysis); *the statement of the characteristics of the technology* which should be given in terms of the characteristics of the functional capability of the technology (i.e., a measurable information about the functional capability of a technology in carrying out the function); *the time of forecast* (i.e., the time when the technology is going to be executed); *the statement of the probability associated with the forecast* (i.e., the probability of reaching a specific functional capability over time).

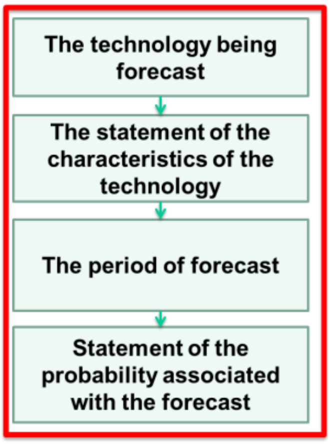


Figure 4: Elements of a structured and forecasting analysis proposed by Martino (1993), ordered as sequential phases to follow.

Given the sequential nature of the elements, it is important to define the role of the users in the choice of the different techniques; due that users are an essential part of forecasting analysis and play a relevant role in the forecasting results (Armstrong, 2001), so the adoption of different techniques and models should be compatible with their related knowledge and experiences. Moreover, the mentioned Martino's elements may help to focus on the conception starting from scratch of a new forecasting method or by integrating the current and existing techniques in order to build new ones. Consequently, a structured and systematic time-perspective method to support design process should be developed by adopting Martino's (1993) elements. For instance, the adoptions of these elements have been already investigated by the author in Nikulin et al. (2013) and Nikulin et al. (2014).

It is important to note how the action of combining different existing techniques can be also considered as a new method, and it is a common practice in the current forecasting research field. For example, System archetype (Senge and Suzuki, 1994) implies the recognition behaviour of a system in order to develop a better understanding of the overall forecasting context, to later on develop the regression analysis. As was previously introduced, the usability of specific forecasting methods can be enriched by using different software tools to support users (Edmundson, 1990). With this in mind, the following subsection describes the role of forecasting software tools, which are essential to support forecasting users. A distinction will be made between those software tools created for general and specific purposes.

2.2.3 Role of forecasting software tools in the forecasting analysis

Researchers have established that judgmental (Armstrong, 1985) and expert methods (Porter et al., 2004) are ubiquitous in practical situations and requires new tools to face this subject (e.g., Fildes and Hastings 1994; Mentzer and Kahn 1995; Sparkes and McHugh 1984). It seems likely, however, that the increasing availability, affordability, and usability of forecasting software tools (e.g software packages and applications to develop a forecast) will soon lead to some positive changes in this situation (Armstrong, 2001). The combination of qualitative forecasting (e.g., based on judgment and knowledge) and quantitative forecasting (e.g., trend analysis and statistics) will then become more relevant. It is important to know how the forecasting software tools can give a strong support to the forecasting analysis; moreover, it can help to the action of transferring knowledge carried out by users. For instance, the potential benefits deriving from the implementation and utilization of automatic regressions allows to reduce the time of the forecasting analysis to those methods based on extrapolation (Armstrong, 2001; Roper et al., 2011). Indeed, Edmundson (1990) highlighted that the time series forecasting analysis can be dramatically improved by using forecasting software tools. In fact, economists now have software tools to enable the forecast and trade on the basis of real-time data and information. However, economists also have to use their knowledge to respond quickly to profit from this anticipated information.

With the previous mentioned scenario, Armstrong (1995) divided the forecasting analysis in three time dimensions to facilitate the comprehension of the forecasting analysis: Short, period of time to forecast the effect of small changes (i.e., seasonal changes); medium and long**,** period of time to forecast the effect of considerable or large changes (i.e., understand historical changes and main trends). Similarly, Edmundson (1990) emphasizes that there are three essential components that simplify the synthesis of the regression results, for instance: trend (i.e. future values), cycle (i.e. stage where the trend is) and noise (i.e. residual error). However, it is important to remember the identification of an appropriate software tool within the time series and statistical analyses depend on the knowledge of users carrying out the analysis (Simon, 1957; Armstrong, 2001). With this respect, many software tools are capable of describing very specific details of statistic results and in many cases researchers seem to be blind with complex formulations. However, as Meade and Islam (2001) showed, various sophisticated and well-thought-out formulations often do not improve accuracy.

Some scholars have investigated the possibility of creating a universal environment for different types of software with different scopes where the forecast is included as well, as for example Minitab and R. Indeed, regression analysis is nowadays widely used and constitutes a reliable way to correlate data to a specific assumption and predict future values. However, it is important to clarify what regression analysis is, in detail, a statistical technique that aims at validating specific hypothesis under observation according to:

- An *assumption to characterize the data i.e.* the statistical relationships among data are often modelled by equating one variable to a function.
- An *equation related to the assumption that aims at fitting the data*, i.e. equation to represent the data behaviour based on specific assumption; recurrent equations in practice are linear, exponential, logarithmic and logistic.
- A *set of variables meaningful for the analysis, i.e.* reported parameters of the regression affecting the equation, which defines the behaviour of the fit.

Regression analysis finds values of parameters that characterize an equation and related assumption, to validate a specific hypothesis (Longnecker & Ott, 2001). In practice, the reliability of the regression has to be confirmed by using several statistic indicators (Lemeshow & Hosmer, 1982). For instance, the r-squared and r-squared adjusted are indicators that usually support the result of the fit. Moreover, the assumption about the behaviour of the trend can accepted or refused by means of the statistical significance (i.e. p-value) (Kendall, 1946¸Longnecker & Ott, 2001). The overall regression quality can be also checked by looking regression errors values as: Mean Absolute Error (MAE); Mean Absolute Percentage Error (MAPE); Mean Square Error (MSE) or Root Mean Squared Error (RMSE). If exist consistency between the initial hypothesis, assumption and statistic results the potential trend is suitable and appropriate (Longnecker & Ott, 2001).

In the forecasting context, several regressions can be used to extrapolate data with an anticipatory perspective. However, the selection of a suitable function to fit the data (regress the data) to understand a given behaviour is not trivial; the results of this activity largely depend on the assumption and the equation used to model its evolution (Johnson, 2009). In this context, it is critical to organize, represent and highlight the relevant features concerning the specific software capable at least of developing a regression in general. On the one hand, diverse software applications which contain several forecasting tools are nowadays available (for example Minitab, STATA, Mplus and R). These software demand an initial statistical knowledge for beginners. On the other hand, there are software tools created with only a specific technique which is a positive answer to facilitate the forecasting analysis as Logistic Substitution Model Software II developed by International Institute for Applied System Analysis (IIASA) and Loglet Lab developed by the Rockefeller University. Moreover, there are specific forecasting software tools as ForecastingPro and Vanguard Sales Forecasting capable of simplifying the regression analysis for beginners. However, these software tools continue been more economic and management oriented.

With specific attention on quantitative trend extrapolation analysis,

Table 3 collects a non-exhaustive set of software tools and their related applications, commonly used by scholars to develop a forecasting analysis. Table 3 focuses on the following set of software tools, which cover the most common type of analysis used by practitioners. Moreover,

Table 3 also describes a set of limitations exposed by the author for understanding the suitable of these tools in the context of this research. Moreover, some of these software tools were tested by the author (Appendix-A).

Table 3: Software tools that can be used to develop a regression analysis with a forecasting purpose.

Software tools	What it is for	Regression analysis used in forecasting research field.	Potential limitation for this research (i.e. none of them was conceived to provide recommendations to users)
Minitab	Statistic with general purpose in the engineering domain	• Time series • Trend analysis • Moving average • Exponential smoothing • Trend analysis • Winter's method • cross-correlation functions • ARIMA	Requires specific knowledge on statistics, it can be time consuming to learn the overall set of regression analysis.
STATA 12.0	Regression analysis with general purpose in the management and economic field	• Time series • Trend analysis • Moving average • Exponential smoothing • Trend analysis •Vector and vector error correlation • ARIMA	Requires specific knowledge on statistics, it can be time consuming to learn the overall set of regression analysis.
Mplus	Regression analysis with general purpose in the economic field	• Time series • Trend analysis • Moving average • Exponential smoothing • Trend analysis •Vector and vector error correlation • ARIMA	Requires specific knowledge on statistics and programming, it can be time consuming to learn the overall set of regression analysis. Moreover, it is not so versatile and flexible for beginners.
R	Statistic software with general purpose in multidisciplinary domain	• Capable to develop all the different types of forecasting techniques by programming	Requires a high level of programming and statistic knowledge, it can be time consuming to learn the overall set of regression analysis. Moreover, it is not so versatile and flexible for beginners.
Matlab	Software with general purpose and used in multidisciplinary domain	• Capable to develop all the different types of forecasting techniques by programming	Requires high level of programming and statistic knowledge. Moreover, it is not so versatile and flexible for beginners.
Logistic Substitution Model Software (IIASA)	Software with specific purpose and used for forecasting based on logistic growth curve.	• Logistic growth curve analysis • Bi-Logistic • Substitution mode(Fisher-Pry) • Gompertz • Exponential • Linear Regression	There is not enough statistic information to understand the forecasting result, for instance, the reliability can be questionable (Appendix).
Log Lab 2.0 (Loglet)	Software with specific purpose and used for forecasting based on logistic growth curve.	• Logistic growth curve analysis • Bi-Logistic • Substitution mode(Fisher-Pry)	There is not enough statistic information to understand the forecasting results. Software with specific purpose and used for forecasting based on logistic growth curve (Appendix).

From the previous table and thinking for the potential application of these tools by design engineers, the described software tools presented some limitations mainly by lacks of information and meaning, which is required to exploit as much as possible the users' knowledge. It is interesting to note that ForecastingPro software has some flexible features capable to suggest the selection of the best fit according different regression models. Nevertheless, other aspect to consider for this research is the time consumption to learn how to use a forecasting method and related software tool, which have be taken also into account for the usability of them. In other words, the selection of a forecast method and software tool largely depends on the forecasting users and his affinity with it. In addition, the research developed by Simon (1957) suggested that people looks for satisfaction rather than optimization, when users need to make a decision about the adoption of a software tool.

The following section summarize the main conclusions emerged from the state of the art analysis to clarify how support properly the design process with a time-perspective approach.

2.3 Conclusions of the state of art

The rate of changes is increasing for both products and processes, essentially motivated by improvements to better satisfy the different requirements. Frequently, design engineers address the conception of a new product by using product design phases and related PDP. However, design engineers approach considers mainly a day-by-day perspective, when a longer time-perspective seems to be a more interesting alternative to anticipate product and process changes.

From the state of the art analysis and by comparing the different PDP approaches, it emerged that different PDP share similar initial design phases, related goals, and objectives. Moreover, the elicitation and identification of appropriate requirements at early design phases is crucial for the overall design process. However, none of the existing methods for elicitation of requirements has been conceived to support the early design process phases by taking into consideration long time-perspective, beyond the specific PDP. From a time-perspective viewpoint, TF methods try to understand how the characteristic and features of technologies will be into the future. During the state of the art analysis, TF methods have been presented in different categories by following different logics and perspectives from several authors.. Some researchers have emphasized the relevance of the final user and beneficiary in accepting the suitability of forecasting results (Armstrong, 2001; Kucharavy, 2007). The application of software tools allow to simply the efforts to use and adopt a forecasting method, which is essential for methods acceptability.

Concluding, forecasting methods depend on largely from the users, as well as the meaningful insights and knowledge that the methods provide them. On this basis, a method for forecasting design requirements has been proposed which need to be compatible with the knowledge of the design engineers, allowing them to exploit as much as possible their experiences. Given the structure of design requirements the proposed method has to be capable of analysing both qualitative and quantitative requirements, enabling to cover the nature of the different requirements that can emerge during the early design process phases.

2.4 Hypothesis and research questions

In order to start working on a method for forecasting design requirements it has to be accepted and highlighted the main research motivation:

The early design phases are critical stages for the product development process, and forecasting methods are useful to anticipate relevant information about requirements to support the design process and the related decision making process. Therefore the main research question is the following:

- How to systematically anticipate information about requirements during the early design process stage?

The aim of this research is the integration of a proper technology forecasting method and related tools into a new method for forecasting design requirements usable by design engineers and with specific attention on those without forecasting experience.

In order to achieve these results it is necessary to answer the following research questions:

- How a design engineer can be guided into use a method for forecasting in order to anticipate information about product and process?
- How a method for forecasting can be introduced systematically into the product development process?
- Which is the industrial and academic applicability of a method for forecasting in the design domain?

Answering the first research question will allow individuating the correct methods and techniques to guide the design engineer in the elicitation of requirements, organization, and the proper forecast for the both qualitative and quantitative requirements. Answering the second research question allows introducing the proposed method at different PDP available on literature. The third research question allows understanding the usability and suitability of the proposed method from an industrial perspective.

Research results will be also obtained from a real application of the proposed method for both products and processes. This will allow to test and to understand the benefits and limitations of the method proposal. From an academic perspective, tests with students will be developed in order to understand and observe the learning process related to the proposed method and also to get new insights that the method provides through the test's participants. Finally the complete research will be validated with three main approaches:

A. Theoretical structural validity (Pedersen et al., 2000):
   i. Individual constructs constituting the method.
   ii. Internal consistency of the way the constructs are put together in the method.
B. Empirical performance validity (Pedersen et al., 2000):
   i. Capability to clarify the directions for product and process development and driving related strategic decisions.
C. Capability of the method to guide the design engineers without experience in forecasting:
   i. Usability of the time perspective to forecast requirements.
   ii. Capability of the method to provide new insights and conclusions about product/process requirements.
   iii. Effectiveness of the method to be transferable to design engineers independently from the adopted product development process.

Chapter 3

[3] Methodological proposal and research contribution

This chapter presents the original contribution of this work. In particular, it deals with correlated activities that have been carried out in order to answer the main research questions. This chapter is structured into four sections.

The first section clarifies the overall goal of this research by recalling the current limitations emerged from the analysis of the state of the art. The second one clarifies which model/methods have been selected from literature and adopte. When necessary, those models and methods have been modified in order to accomplish the overall research goals.

The third section describes the main contribution of this research work, in specifically, this research work has developed a method for forecasting design requirements, which is usable by design engineers. The method is organized in seven steps, which have been developed following the four elements identified by Martino’s works that have been explained in the previous chapter. Moreover, the steps of the proposed method have been clustered into these four groups (Martino's elements), allowing to guide the user during the forecasting analysis. Moreover, the adoption of Martino’s elements is useful to develop a more structured analysis to follow, when forecasting is required.

Finally section four describes the development of a new software tool for supporting the regression analysis usable by both, forecasters and non-forecasters. The new software tool integrates some features of the current software tools that have been reviewed for this work; moreover, other features have been added to make it suitable to support the required knowledge for the method application, with specific attention to users without deep and extensive statistics knowledge.

3.1 Overall goal of the activity

The anticipation of information is relevant for companies at different organizational levels (Armstrong, 2001). From the analysis of the state of the art, the need to provide design engineers with a proper method for forecasting emerges. This method should be capable of anticipating information of requirements at the early design phases. Moreover, the method has also to help them to properly exploit their experience and knowledge about design requirements in order to make consistent contributions to the product development process.

Usually forecasting methods were developed in order to support economists and managers. The main reason for using forecasting methods is to drive strategic decisions about economy and management. Nevertheless, considering the emerging changes in the design field as Design Driven Approach, the design engineers have been taking a more strategic company role (Verganti, 2013), thus confirming the need of forecasting methods usable by designers engineers as well. In other words, according to this view, design engineers should not just provide specific solutions; they also have to be capable of suggesting direction of product development or support companies decision makers. Consequently, design engineers need to understand what will be the evolution of products and processes (Cascini, 2011).

Unfortunately, forecasting analysis is mainly applied to understand market trend and production planning in companies. However, the emerging need for understanding the evolution of products requires knowledge and experience, which go beyond the management; for example, a reasonable amount of technical knowledge and experiences about the product is also required. Nevertheless, the forecasting analysis is less likely to be used by people with technical knowledge, as design engineers, for at least two reasons. First, the number of forecasting methods available in literature are incredible large. As a consequence, recognizing an appropriate forecasting method to be applied is time consuming. Second, specific knowledge and experience to apply the selected method can be hard without previous method experiences for example knowledge about model assumptions and regression results is required as well. With this view, to consulting a forecasting expert could be a reasonable alternative, when companies need to understand the future. However, a forecasting expert cannot be affordable for all companies. Moreover, forecasting experts do not necessarily know about features and characteristics of the technology to be forecast.

Given the overall context of the research, the selection or creation of a forecasting method should at least consider three elements: i) data and information available, which are a necessary resource to develop a forecasting method; ii) forecasting users, which are those that are going to use the forecasting method; iii) forecasting purpose, what is necessary to understand about the future.

These considerations drive the presented research to develop a method for forecasting design requirements that allows guiding design engineers without specific statistical knowledge, to anticipate information about design requirements. The proposed method is based on different forecasting and engineering models. The method, in addition, fits the different phases that Martino (1993) proposed to build an appropriate forecasting analysis. In addition, the author recognized the opportunity to create the method based on freely available resources, thus allowing it to be used by different companies without extra costs at least for what concerns the early design phases. The following bullet points list summarizes the required features that a method for forecasting design requirements should be capable of addressing so as to be suitable at early design phases. The method has to be capable of:

- Keeping an organized structure of the requirements, so that it is possible to classify requirements according to a hierarchy by distinguishing from where requirements emerged and showing relationships between them.

- Introducing instruments to practically deal with the time dimension beyond the very short-term perspective of the sole product development process. The introduction of the time dimension should be shaped in order to generally support the decision-making processes, i.e. the ones characterizing the design rationale, at various levels, in order to allow its versatile application in different contexts.
- Dealing with the externalization of tacit into explicit knowledge, as well as with its quantitative and qualitative aspects, in order to exploit both the experience of the different stakeholders involved in the design process and the fact-based forecasting capabilities of statistical approaches.
- Using an organization of knowledge that is easily understandable and sharable among the different subjects involved at various extents in the development or design processes, so as to also improve the versatility of the instrument for the wide range of interested stakeholders.

Stemming from these bases, this research has defined a set of existing models and tools, which are expected to address these needs. The dissertation will also be focused on the harmonization of the tools as well as the content that design engineers have to manage, in order to define an effective method to drive the choices behind the design processes with a time-perspective. The next sections will clarify the logic behind the choice of the different tools and the challenges faced for their integration in a single framework having the above-described characteristics.

3.2 Definition of a reference framework for a method for forecasting design requirements

This section defines the reference framework adopted to develop a method for forecasting design requirements. Such section is divided into three subsections. The first subsection provides a way to organize the knowledge elicited from experts, which plays a paramount role for carrying out the various cognitive-demanding activities during design process. The second subsection introduces a framework for capturing the knowledge from design requirements by considering both qualitative and quantitative requirements. In particular, this framework attempts to capture the technical and customers knowledge from the product and process. Moreover, it helps to determine which are the requirements to be met. Since, many times these knowledge elements are often not clearly expressed, the description of requirements has to be transferable in practice to different company levels and it has to be analysed as well, characterizing a semantic structure of both, quantitative and qualitative requirements. The third subsection focuses on a framework for forecasting methods suitable to extrapolate quantitative requirements. The selection of the regression model is based on the concept of technical system evolution which is closer to the design engineers than economic and management trend analysis.

3.2.1 Definition of a reference framework for organizing knowledge according to the time dynamics and system hierarchy

The first challenge for this dissertation is related to the organization of the knowledge of the requirements according to time-perspective approach. This subsection aims at organizing and exploiting the knowledge elicitation, as well as, monitoring the evolution of the requirements through time.

With this perspective, the selection of a suitable model capable of dealing with the organization of requirements is relevant, and more critical, when a new perspective as system evolution is added to support the design process. With this in mind, this research has recognized in the TRIZ body of knowledge (Altshuller, 1984), and specifically in the System Operator, a good opportunity to organize and exploit the knowledge elicitation about requirements. Noteworthy, the characterization of the requirements on a TRIZ perspective has been explored by Becattini (2013a). In his works, Becattini (2013a) proposed a suitable characterization of requirements based on the Law of Ideality Increase of technical systems. Becattini's proposal helps to elicit an extensive and complete list of requirements to support the design process. Nevertheless, the proposal developed by Becattini (2013a) has not considered the evolution of the requirements from past to present systems, neither the potential future of requirements beyond the specific PDP analysis.

In more details, the System Operator was created by G. Altshuller as a tool that allows modelling knowledge consistently with the system-based logic of creative problem solvers, to support the replication of their effective way of thinking (Altshuller, 1984). The System Operator is typically depicted as 3x3 matrix of "screens", but it is freely expandable in more columns or rows according to various exigencies. It organizes knowledge according to two main dimensions (Figure 5).

The vertical axis represents the level of detail of the space dimension; the system is composed by several entities called sub-system, the system is also included in a high system level, called super-system. In other words, a super-system is a parent system for the examined system; consequently, a super-system is needed for the existence of the system.

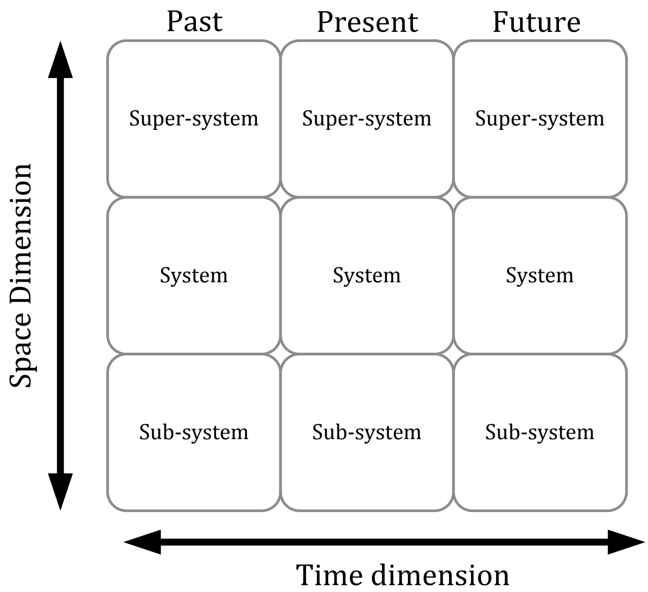


Figure 5: The System Operator; the most common schema to stimulate an effective way of thinking (Altshuller, 1984).

The horizontal axis represents the time dimension (i.e., past, present and future), which is useful to stimulate the thinking capability of problem solvers about technology changes. The versatility of entities possible to include at System Operator's screen is quite large in literature, for instance, prescriptive ideas, process description, part descriptions and requirements as well (Becattini et al, 2013; Nikulin et al., 2013b). This versatility make it suitable to be adopted as a reference model to elicit requirements as proposed by Becattini (2013a). Furthermore, other features of the System Operator as space dimension allows to understand the causal-and-effect relationship between system levels, which is useful for this research as well. In more details, the space dimension of the System Operator seems likely to be a reasonable alternative to categorize the requirements at different hierarchical levels, typical of system engineering. The analysis of causal relationships by using System Operator has been explored by the author in Nikulin et al. (2013b). Moreover, novelties and opportunities to represent the dynamic of product and process requirements have been already published by the author in Becattini et al. (2013). Furthermore, the adoption of the System Operator is emphasized by this research because the time dimension of the System Operator may be considered as the initial step to start understanding how requirements change and eventually, harmonizing both qualitative and quantitative requirements. Moreover, description of requirements and related time-dimensions can be also included in the System Operator's screens, implying a holistic view of a requirements list. Nevertheless, the use of System Operator model should also allow satisfying the following set of necessities in the context of this research proposal:

- Versatility and ease of application to different industrial products and processes.
- Scalability to different detail levels, so as to map the knowledge of different experts and stakeholders of the industrial product and process.
- Capability to represent time dynamics with an evolutionary perspective on design requirements

Moreover, the System Operator can be considered as flexible enough to be combined with different requirement elicitation methods as interviews, checklists and VoC, which are already familiar for companies (Becattini, 2013a). However, a mapping of evolution of requirements is needed in order to understand how to capture qualitative and quantitative knowledge from design engineers. Remarking that knowledge, information and data are crucial for producing a reliable vision of the future.

3.2.2 Definition of a reference framework for capturing qualitative and quantitative knowledge about design requirements

During the state of the art (Chapter 2) a review of several approaches for the retrieval of knowledge about design requirements has been presented. In chapter 2 it has been clarified also that requirements formulation is crucial to address the demands emerging from different stakeholders. A design method owning an anticipatory design perspective should, therefore, be based on a requirements elicitation method that both supports the requirements analysis and synthesis. Interviews, checklists and other design approaches can be conveniently used to trigger reflections about requirements. With this perspective, also the System Operator by itself can be used as a stimulus to capture requirements as proposed by Becattini (2013a). Nevertheless, the selection of suitable methods for the elicitation of requirements is beyond the overall goal of this research, in other words, this research is concerned to how manage the captured knowledge from those methods.

The technological aspect of this research requires a formalization of requirements based on technical viewpoint rather than management and economic. For this research, the requirement formalization is mainly focused on the evolutionary perspective of products and processes by considering two mutually correlated concepts for the evolution of technical systems.

- The improvement of system performances. According to Marchetti & Nakicenovic (1979), the technology evolution is based on improvements on different technology features and characteristics, which can be measured in terms of performances;

- Law of Ideality Increase (Altshuller, 1984), which highlights that improving the "useful function", intended as desired outcomes, allows increasing the ideality of the technological system; on the other hand the reduction of “harmful function” and “resource” constitutes an alternative to increase system ideality as well. The resources are expressed in terms of space, time, information, material and energy, according to the TRIZ body of knowledge.

Nevertheless, other types of requirements as social and economic cannot be neglected if it is required to understand the evolution of the system. Threfore a suitable model for this research should be capable to integrate this perspective as well.

The above-mentioned concepts are intended as a direction to emphasize the elicitation of requirements for products and processes. However, the collected requirements need to be organized by using simple semantic structure, which allows to reduce as much as possible the experts’ knowledge bias produced by long and extensive sentences. Given this reason, the System Operator by itself is not enough to satisfy the overall research goal. Consequently, for this research is also required a model capable of describing requirements keeping a simple structure of them. With this in mind, the ENV model (Cavallucci & Khomenko, 2007) describes system or elements by using three complementary entities, thus the system can be characterized by the following description:

- the material or immaterial element (E) pertains to; and
- its name (N);
- the value (V) that should get in order to achieve the satisfaction threshold.

This generic framework of system description entities of the ENV model seems to be appropriate for detailing the different types of requirements. The ENV model seems to satisfy the need to keep knowledge and information traceable and transferable to different stakeholders given its simplicity. Moreover, the ENV (value) could be used to simplify the identification of qualitative and quantitative requirements during the forecasting analysis, through the description of value units. On the one hand, qualitative requirements can be just forecasted on a knowledge-based perspective, thus leveraging processes as knowledge acquisition and knowledge exchange. On the other hand, quantitative requirements could be conveniently used to exploit the forecasting methods based on regression and statistical approaches.

With reference to the necessity of producing measurable requirements, it is proposed -for this research- to define the requirements by adopting the logic of the ENV in a system description. The ENV model will be used to classify both quantitative and qualitative requirements. This classification has to support also the initial identification of the forecasting approach to follow, as for instance based on expert knowledge or trend analysis.

In order to make the ENV model suitable for this research, partial amendments are required. In this context, the ENV model has been enriched with different sets of descriptions (Table 4), which allows simplifying the characterization of requirements for time-perspective analysis. Moreover, the different sets of descriptions have been created in accordance with the System Operator logic, exploiting as much as possible the current features of the two already selected models. Descriptions of proposed amendments are presented below:

- The ENV (Element) is related to the forecasting object/element, in specific, the different levels of system operator.
- The ENV (Name) is split into three descriptions capable of capturing both qualitative and quantitative requirements: i) requirement name, ii) categorization of quantitative and qualitative requirements and; iii) requirement unit.
- The ENV (Value) is linked to the requirements at different time periods (past, present and future), which can be used as an initial step to identify requirements changes.

Table 4 shows the formalization of the dynamic for both qualitative and quantitative requirements based on ENV logic. According to such description, it is evident that a requirement can be measured in terms of at least, dichotomous variables, allowing a comprehensive understanding of the system.

Table 4: Definition of requirements based on enriched ENV logic by considering time perspective approach.

Element	**Name**			**Values**		
System levels	**Requirement**	**Quantitative/ Qualitative**	**Units**	**Past (Value)**	**Present (Value)**	**Future (Value)**
Refrigerator	Capacity	Quantitative	[liters]	200	600	750
	Complexity of the 3D polymer form surface	Qualitative	[Forms and shape]	Low number of forms and shapes	Number of forms and shapes	High number of forms and shapes

In this section it has been highlighted the need for a model capable of capturing the quantitative and qualitative knowledge from design engineers. Given the technology aspects of this research, the elicitation of requirements has been proposed by looking at two mutually correlated concepts as improvement of system performance (Marchetti & Nakicenovic, 1979) and Law of Ideality Increase (Altshuller, 1984). The ENV model has been enriched so as to make it suitable for this research proposal. The proposed amendments of the ENV model have been proposed with the logic of integrating it with the System Operator in order to understand the evolution of the design requirements. The categorization of both quantitative and qualitative requirements would help to identify, at least initially, the potential forecasting method to follow (i.e., qualitative or quantitative method).

With regards to the quantitative requirements, the next subsection presents a theoretical framework for quantitative trend extrapolation models usable for searching which model can be used in the context of this research.

3.2.3 Definition of a reference framework for regression analysis to forecast quantitative requirements evolution

As mentioned during the previous sections, the forecasting users play a relevant role when choosing a forecasting method. In this case, the experience of the forecasting user is critical; even more when knowledge beyond the technical system is required (for example, statistic knowledge). From a design perspective, the process to select a regression model has to be able to extrapolate future values of quantitative requirements. At the same time, the understanding of regression results has to bring new insight and knowledge to those that use the regression model, implying a more meaningful forecasting analysis. With this in mind, regression models need to be, for the aim of this research, close to the already known concepts that design engineers manage. In the state-of-the-art analysis about forecasting methods, several regressions have been presented and these can be used to extrapolate data with an anticipatory perspective: for example ARIMA, linear, exponential, logistic extrapolations and others. However, the selection of a suitable regression model to understand unknown trend behaviours is not trivial. The selection largely depends on the assumption and the equation used to model that trend (Johnson, 2009).

There are several kinds of regressions for modelling different types of trends; however, some models are more suitable than others in practice. According to the different models, it is necessary to find an affinity between different aspects that influence the suitability of the method. For instance, in this research it is necessary to harmonize aspects concerning: i) the assumptions that relate the regression models with the evolution of technical systems and; ii) the new insight and knowledge with which the model can provide to design engineers in order to support the design process. On this basis, one of the plausible assumptions that characterizes the evolution of technical systems is known as s-curve, and it is widely applied and discussed in literature. Several authors proposed the s-curve to understand the evolution of the technical system, as example, Altshuller (1984) proposed the Law Increased Ideality, which represents an experimental and qualitative s-curve characterizing the evolution. Furthermore, Marchetti & Nakicenovic (1979) proposed the concept of s-curve to understand the technology substitution based on the concepts of "technology improvements". Moreover, Salamatov (1991) presented the system evolution as a sequence of stages as infancy, growth, maturity and decline. In others words, the s-curve seems to be more plausible, at least, to represent the evolution of technical system.

Regarding the regression model capable of representing the s-curve behaviour, it is known as logistic growth curve or logistic regression. Nevertheless, the initial use of the logistic growth was not necessary to understand the evolution of technical systems. In detail, the logistic growth curve was introduced by Verhulst in 1838, but popularized by Lotka (1925) as a means for forecasting the saturation of natural ecosystems. In his works Lotka (1925) tried to predict and understand how the population grows inside a particular ecosystem over the time (i.e, geographical region).

The results related to the application of the logistic regression not only allow of predicting trends and related future values for prediction, but also to stimulate the seeking of reasons explaining why the system/ecosystem will be saturated or why a maximum will be reached. The possibility of representing both the evolution of technical system and stimulate the thinking capability beyond the specific prediction values, makes the logistic growth curve an interesting model to investigate. Given the capability of logistic growth curve to represent the s-curve, it has been selected as model proposal to introduce the time-dimension approach at early design phases rather than others regression models.

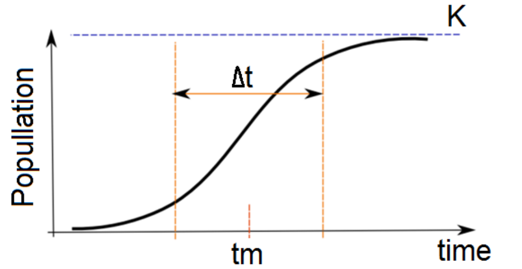
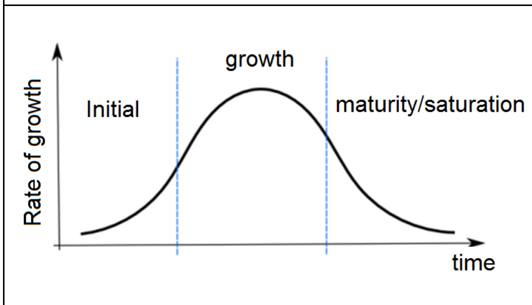
In literature, Marchetti & Nakicenovic (1979) and also Modis (1992) proposed the logistic growth assumption as an elementary brick, which allows predicting ecosystem/system evolution that follows a natural law of growth independently from the context (e.g., biological, economic and technological). Moreover, Marchetti(1985;1986) used this forecasting model and showed that the logistic growth curve was an appropriate construct for forecasting technological changes. Currently, the logistic growth curve is understood as a regression model capable of modelling technology evolution as well as other behaviours as social and economics behaviours. Technically, the equations characterizing the logistic growth behaviour are proposed with several variants. Indeed, the term “logistic” describes different curves of the same family rather than a single function. The most common curve within this family is the “generalized logistic curve” or “Richard’s curve”, characterized by seven different parameters (Fekedulegn et al., 1999) (Marinakis, 2012). It is important to note that “Richard’s curve” can be considered as the “Ideal” logistic growth curve representing all the variants that this model can represent. However, the validation of the equation parameters behind this equation can be questionable, mainly because of the complex interpretation of them.

At this point, it is important to recall that the selection of a specific logistic growth curve for this research has to be compatible with the knowledge of design engineers as much as possible. With this in mind, the equations proposed by Meyer et al. (1999) and the equations adopted by Marchetti (1986) are easier to perform than the Richard's one and the related parameters can be understood by both practitioners and beginners. Moreover, Meyer et al. (1999) and Marchetti (1986) are widely applied by researchers and professionals in literature. Furthermore, there are free software tools which include these equations. Consequently, they are more accessible to be used (IIASA and Loglet). The author has been developed different tests to compare the characteristics of Meyer's and Marchetti's equations to understand their suitability for this research. The results of these tests are presented in appendix-A.

From the presented logistic growth curves (both Meyer's and Marchetti's equation) and regarding the need of producing at least a comprehensive regression analysis to support design engineers, logistic growth curve proposed by Meyer (1999) seems to be the most suitable and comprehensible equation to understand the evolution of products and processes requirements. Graphically, the logistic growth curve adopts an s-curve shape (Figure 6). Generally, the population (according to the logistic first applications) starts to grow slowly (e.g. initial stage), but then, after a while, this growth starts accelerating (e.g. growth stage) until it achieves a saturation point (e.g. saturated stage). Meyer's equation uses three parameters to represent the s-shape. These parameters are described below.

- K: this parameter represents the saturation capacity of the defined ecosystem/system.
- Tm: this parameter represents the middle time of growth, where s-curve achieves the 50% of growth.
- Δt: this parameter represents the time of growth from 10% to 90% of the s-curve.

Figure 6: Graphical description of Meyer's logistic growth curve and its equations.

	$N(t) = \frac{K}{1+e^{-\frac{\ln(81)}{\Delta t}(t-t_m)}}$ (1)
	$\frac{dN}{dt} = \frac{\ln(81)}{\Delta t} * N(t)\left(1 - \frac{N(t)}{K}\right)$ (2)

On the one hand, the K parameter points out the limit of the growth of the system under investigation, so that it is possible to understand what its remaining potential is. On the other hand, the time-related parameters (Δt and Tm) of the regression allow understanding if the trend is at the end of its lifecycle or just at the beginning (Marchetti, 1986). At the same time, the rate of growth is represented by the derivative of the Meyer's equation (Figure 6), which represents the speed at which the system grows during its life. It is worth recalling that these three parameters (K, Δt and Tm) can significantly improve the analysts' knowledge exploitation, and their related meaning can bring a simplified understanding of the process analysis, as proposed by Edmundson (1990).

Moreover, the s-shape can be split into different stages as initial, growth and maturity/saturation. These stages can be useful not only to understand the technology statement, but also to stimulate the thinking capability of design engineers to search for new alternatives solutions or resources. For example, if one variable is close to reach the saturation, it is important to know which are the reasons behind this saturation (e.g., why is the technology going to reach the maximum performance?, is there any resources that limits growth?, others).

In literature, there are plenty of examples about the application of logistic growth model in different contexts. However, these examples mostly rely in the assumption developed by the author (i.e. mainly experts) to apply the logistic regression. In this framework, it is important to remark that design engineers are not necessarily experts developing forecasting analysis. Furthermore, the characterizations of variables with logistic growth curve behaviour are still not formalized on the available literature. Consequently, the definition of guidelines for supporting this kind of regression analysis cannot be avoided. On this basis, the introduction of recommendations for the identification of variables that can behave logistically should be addressed to achieve the research goal of this PhD dissertation.

A tailored analysis has been carried out by the author to exploit the already available information in technological forecasting studies, where logistic growth model was applied. The analysis was performed considering as reference the main Journal in the field, i.e. "Technological Forecasting and Social Change". More than 48 papers, published in the years 2008 - 2013, were therefore collected and in particular, the papers where logistic growth analysis was used to understand the evolution on different systems/ecosystems have been selected. More than 60 cases studies are included in those papers considering both a theoretical and a more practical point of view. The overall classification developed by the author is presented in the appendix-B. The formalization of existing knowledge was addressed taking into account the different classifications, which are described below:

- System level where logistic growth curve was studied; it includes a more detailed system description as well.
- Parameters used to develop the regression analysis, allowing to understand which variables are used for forecasting.
- Characteristics of the parameters; it considers both, logistic growth curve and rate of growth if is presented. The time-period and number of data points used to develop the forecast were included as well.

Table 5 collects examples of classification for variables used by scholars in order to extract a small set of rules for supporting the application of logistic growth behaviour for requirements (More details are available in appendix-B).

Table 5: Classification used in order to address the formalization of knowledge from technological forecasting to engineering-design field, papers between 2008-2013.

Paper Author	Decomposition of the logistic growth variable from papers							
	System		Parameter	Characteristic of the parameter				
	system/ ecosystem	Detail of system/ ecosystem	Name	Parameter S-curve	Parameter rate of growth	Initial observ ation	last observ ation	Nº of observ ations
Boretos (2009).	World	Economy	GDP	GDP/year	(GDP/year) /year	1948	2008	60
	World	Geographic al	Population	Population/ year	(Population /year)/year	1948	2008	60
	World	Economic	GDP per capita	GDP per capita/ year	(GDP per capita/year)/year	1948	2008	60

Given the wider range of cases studies is quite fuzzy to distinguish the logic for selecting variables which behave logistically. However, an analysis based on analogies and abstraction levels from previous classifications is useful to retrieve the main traits among all the collected papers. For what concerns the system, the logistic growth curves are applied to boundaries of large geographical regions as countries, continents and also world. For what concerns the detail level of the system, the cases studies are mostly focused on economic rather than technology aspects, thus confirming that also logistic growth curves are mainly used in economic and management. Moreover, parameters are frequently referred to economic ratios, indicators and indexes. On the contrary, parameters referred to technology are always related with performances. According to the characteristics of the parameters, both cumulative and non-cumulative parameters are used to develop logistic growth curve regressions. However, the logic of selecting those parameters (cumulative or non-cumulative) is quite fuzzy to distinguish. The selection of cumulative or non-cumulative depends mainly by the author assumption and what he would like to understand about the future.

According to the time-period proposed by Fye et al. (2013), it is possible to infer that logistic growth curves are mostly used from medium (i.e., between 6 and 10 years) and long-time periods (i.e., more than 11 years) rather than short periods. It is important to mention here that most of the quantitative case studies are supported by at least three statistics indicators as r-squared, p-value and residual error indicator.

From the knowledge obtain from paper classifications and synthetizing the potential behaviour that parameters can have in practice, it has been defined common traits through which the parameters can be organized by affinity. The proposed classifications are a small number in order to improve their easy management and cover an almost complete set of domains without overlooking something particularly meaningful. These traits are summarized into the two main categories:

- **Context:** Characteristics concerning the domain in which the data is particularly relevant. The distinctions between domains are sometimes fuzzy, due to the highly complex relationships that a single system may have with other systems in different domains: (i) *Economic*, (ii) *social*, (iii) *technological*, and (iv) *environmental* contexts have been chosen for classifying variables on the experiences and the knowledge exchanges with other researchers addressing the same kind of researches.

- **Parameter growth:** Characterizations focusing on how the parameter has already changed from the past to the current moment. They have been organized into four mutually exclusive variables: (i) *increasing;* (ii) *decreasing,* (iii) *constant, and* (iv) *fluctuating.*

In the case studies, the parameters that have presented an increasing behaviour are frequently used to develop a forecasting analysis based on logistic growth curve. Nevertheless, transformation and combination of parameters is also allowed to obtain an increasing behaviour, when required (e.g. performances, indicators and indexes). However, this transformation or combination does not confirm that assumption of logistic growth will be fully validated. To develop a plausible validation, it is required a reasonable understanding of the variable and their meaning. Moreover, the statistic results have to be checked as well. The prescriptive traits and recommendations for the management of the logistic growth curve are included in the next section, and specifically in the prescriptive method description. (Section 3.4).

3.3 A new software tool to support regression analysis based

As shown by the review of the software tools for supporting the forecasting analysis, (see section 2.2.3), software tools can provide a strong support to the overall forecasting analysis. Moreover, software tools are useful in transfers the knowledgeable actions that have to be performed by users.

As proposed by Edmundson (1990), the potential benefits deriving from the implementation and utilization of automatic regressions reduce the knowledge demand of quantitative forecasting methods. Currently, several software tools are capable to deliver an appropriate regression analysis to be used in the forecasting field. However, the adoption of these software tools can suffer some deficiencies. For instance, some limitations in their adoption by design engineers, specifically if unexperienced, can emerge from a lack of knowledge in statistics. Such issue will be used as inspiration for the development of a new software tool capable to provide recommendations about regressions.

Currently, two popular software tools used in the forecasting practice have a specific scope on logistic growth curve (i.e. IIASA and Loglet). Both software tools allow to develop other different types of analysis (i.e., bi-logistic and fisher-pry transform) (Marchetti, 1986; Meyer, 1994; Meyer, 1999), but none of them has been conceived with the aim of supporting users by providing recommendations about the interpretation of their results. Moreover, their accuracy and regression method can be considered questionable during the practice in some cases; more details about issue see appendix-A. On the contrary, there are other software tools as ForecastingPro(2014) capable to provide suggestions to select the best regression model to represent the data under analysis. Nevertheless, this type of software continues been economic and management oriented (ForecastingPro, 2014).

Given the adoption of the logistic growth curve for this research proposal, the development of a software tool for logistic growth analysis has been considered as a good opportunity, to verify whether to provide inexperienced design engineers with a software helping them performing and interpreting can provide fruitful results in terms of technology forecasting. In fact the tool should be able to assist design engineers through the use of recommendations in order to facilitate the adoption of the proposed method and exploit in a better way the knowledge for quantitative forecast. On the one hand, a new software tool should develop an accurate and reliable analysis in order to provide trustworthy results. Even more, it should provide suggestions for the interpretation of the results making them understandable for both, practitioners and beginners. On the other hand, the new software tool has to be capable to support the users as much as possible in order to trigger them and facilitate the adoption of the proposed method.

A first step towards the development of a software tool to support the design engineers is the definition its own the essential feature. In this research, these features were obtained by analysing current software tools used to develop forecasting analysis based on logistic growth model as IIASA and Loglet, and also looking the feature provided by ForecatingPro. The elicitation of software features included several interviews, discussions and workshops with practitioners, during the development of the FORMAT-project. As results, Table 6 collects a non-exhaustive set of features required for the new software tool acquired by the previous mentioned activities and also by comparing with the two already available on literature (i.e. IIASA and Loglet).

From Table 6, it is possible to observe how some of the most pertinent features are not currently fulfilled by the software tools (IIASA and Loglet) available nowadays on the market. Such features are considered valuable to support design engineers through the quantitative analysis, as well as the most established and diffused instrument for prediction purpose based on logistic growth curve. Therefore these particular features have been added to the software developed and discussed in this doctoral dissertation. Noteworthy, the set of useful features listed in the Table 6, even if not complete, covers almost all the constructs and analysis required for an appropriate regression analysis for beginners in the forecasting knowledge domain as design engineers. More details among software tools and their specific regression results are presented in the appendix-I.

Table 6: Summary (partial) features required to support design engineers during the regression analysis based on logistic growth curve. Colour represents the current fulfilment of the features; Red-not satisfied, Yellow-partially satisfied and Green-satisfied.

ID	Required features to support design engineers with lacks of statistical knowledge	Logistic Substitution Model (IIASA)	The Loglet lab software	Need of the feature for the research proposal
1	Capable to develop different types of regressions based on logistic growth curve	Logistic growth curve, Multiple logistic growth curves, Fisher-Pry Transform	Logistic growth curve, Multiple logistic growth curves, Fisher-Pry Transform	Must Have
2	Capable to show residual and regression graphs	Only regression graph	Regression and Residual graphs	Must Have
3	Provide indicators to understand the goodness of the fit and regression results	R-square	Without indicators	Must Have
4	Provide indicators to understand goodness of fit by using residual error	Without indicators	Without indicators	Must Have
5	Provide a Confidence Interval to understand the accuracy of the regression	Without Confidence Interval	With Confident Interval	Must Have
6	Provide values of the regression parameter in a simple way.	Parameters based on Meyer (1999) (K, tm, ΔT) and Marchetti (1980) (α,β and time- constant)	Parameters based on Meyer (1999) (K, tm, ΔT)	Must Have
7	Capable to compare logistic growth curve developed by user assumption and regression.	It is possible	It is possible	Must Have
8	Provide recommendations and suggestion about statistic results	Without recommendation and suggestions	Without recommendation and suggestions	Must Have
9	Capable to be installed in different Operative system (standalone installer)	It is possible	It is possible	Must Have
10	Capable to handle data from user interface	Copy, paste, delete and modify data	Copy, paste, delete and modify data	Should Have
11	Capable to save project and recall project	It is possible	It is possible	Should Have

From the analysis of Table 6, it clearly appears that there exist several features that are satisfied by the current software tools. However, the current software tools do not provide explanation concerning the meaning and significance of the output results (Table 6-ID8). On the one hand, some of them are just sufficient to graph the logistic growth results. On the other hand, the features that have a clarification purpose for regression results suffer from different lacks of meaning, as for example the error and confidence interval data interpretation. These necessary features to support design engineers are completely missing from some of the mentioned software tools, as example, IIASA doesn't include the error distribution and confidence, with the same viewpoint, Loglet doesn't include statistic indicators to understand the goodness of the fit and regression results.

A new software tool should be intended as an opportunity to fulfil the previous mentioned lacks of feature from current available software tools (IIASA and Loglet). In the context of this research, a new software tool has been developed by adopting some of the current software features and by adding new ones. In order to improve the readability of this part, the tests developed to explore the software tools features and logistic growth equations are presented in the appendix. The first test aimed to compare the different software tools and some regression packages (i.e. Loglet, IIASA, Minitab and Matlab) by using experimental data extended to different period of time with the purpose to recognize their related over-fitting (i.e. the phenomena according to which the non-linear regression loses its ability to predict data series). The second test has been developed in order to reveal the most promising logistic growth equation. Indeed, Meyer equation and simple logistic growth curve, also known and Marchetti's equation, were proposed for this test by means of their simplicity. The test aimed to compare the meaningful of their related regression parameters by using experimental data and different period of time, the test allowed to evaluate their regression quality and related accuracy (details about mentioned tests are presented in the appendix-A). As results of the over-mentioned tests, from statistic viewpoint, a new software tool employs to carry out the logistic growth curve based on Meyer equation, and supplies relevant indications about the reliability of the results. Furthermore, the Levenberg-Marquardt algorithm has been employed for the new software tool given its capability to fit non-linear regression and related data series (Alper et. al, 1990). The hypotheses assessing all regression parameters are based on the Log-Likelihood test, which can be rejected with a greater confidence based on p-value. Such indicator provides evidence about the statistical significance of the regression parameters in explaining the reliability of the logistic growth model. Furthermore, the outcomes of additional indicators are offered in order to discuss the goodness of the fit regression. In order to measure the accuracy of the model with respect to the introduced data, the Root Mean Squared Error (RMSE) aims at measuring the difference between the actual target and the value predicted by the model. The correlation coefficient R-adjusted is a statistical measure of the strength of the relationship between the actual versus the predicted outputs. The R coefficient can range from +1 to -1. The closer is R-adjusted to 1, the stronger is the positive relationship.

This research has identified the need to adopt the good aspect of the previous software tools in order to enable an increasing usability by design engineers. Consequently, by integrating the software tools features and by adding new ones, in figure 7 it is presented the graphical interface of the new software tool known as

FORMAT-prototype. In detail, two screen graphs are presented in the new software tools in order to display the regression results and residual errors; the users also have the possibility to add their parameters. For instance, they can compare their personal judgment with the regression results (Figure 7). Moreover, a statistic table was included to simplify the interpretation of the regression results. Finally, the new software tool is capable of developing different regression analyses as simple as logistic growth curve, bi-logistic growth curve, rate of growth and fisher-pry transform (Meyer, 1994; Meyer, 1999). If that the statistic results are not appropriate several screens emerge to support the reasoning process of the user. Finally, the software can be installed alone in any window operative system. Figure 7 shows the user interface and the general features of the developed software tool.

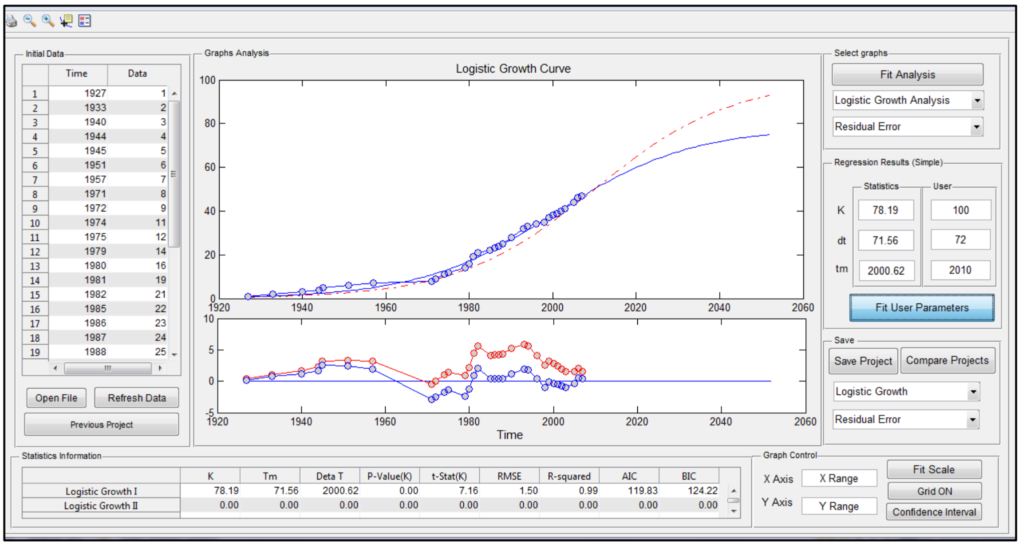


Figure 7: User interface of a new software tool to support regression analysis based on logistic growth curve, in specific for those with lack of statistical knowledge as design engineers

More detailed explanation about software tool features is available on appendix-I in order to improve the readability of this thesis. Furthermore, the proposed software tool was conceived on the boundaries of FORMAT-project (http://www.format-project.eu/). FORMAT is a project funded by the European Commission under the 7th Framework programme-IAPP Marie Curie Actions (PIAP-GA-2011-286305). The FORMAT project has been a good opportunity to test this new software tool in real industrial cases studies.

3.4 Step by Step Method for Forecasting design requirements

This section describes the proposed method for forecasting design requirements, which was developed by integrating model/methods that were discussed and described during the previous sections. A method for supporting design engineers in the analysis of requirements with an evolutionary perspective has been proposed and it should be intended as a contribution to the design theory and practice to generate solutions that are capable of having a more resilient response to the product changes.

The method was created by using seven sequential steps, which have to be capable to guide design engineers to forecast both quantitative and qualitative requirements. The proposed method is organized according to the elements proposed by Martino (1993), allowing us to keep a more structured and systematic approach to develop a forecasting analysis. In Figure 8 the steps of the method are presented according to the essential elements proposed by Martino (1993) (i.e. the technology being forecasted, the statement of the characteristics of the technology, the time of forecast and the statement of the probability associated with the forecast).

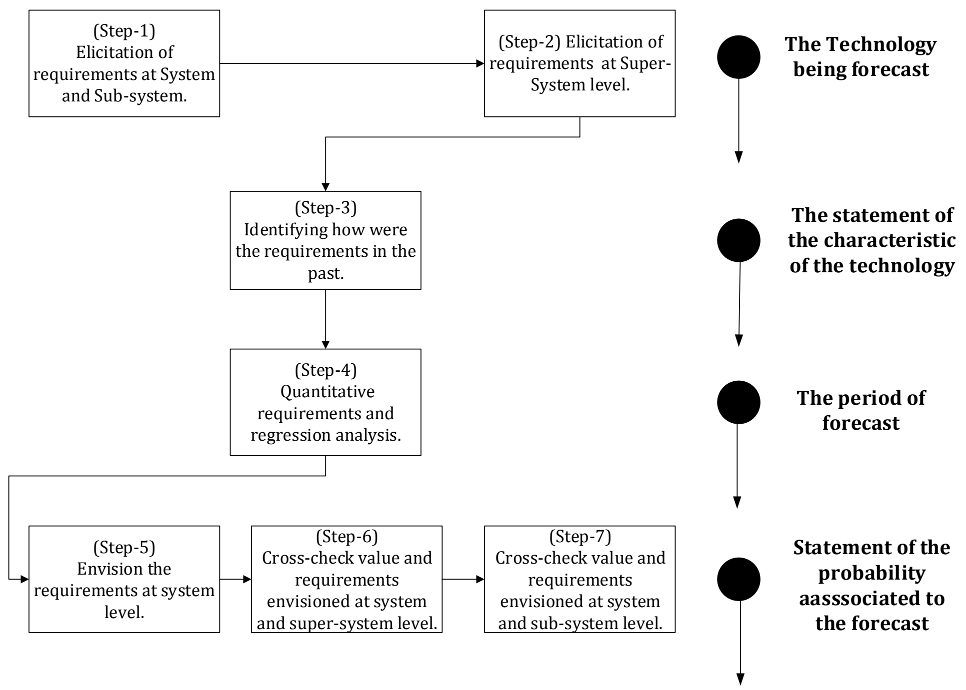


Figure 8: Description of the method's steps and their relation with the stages proposed by Martino (1993).

At the same time, the System Operator model was used to represent the overall framework for the proposed method. With this model framework, the different sources of knowledge can be organized in terms of requirements by using the logic of the ENV model and System Operator levels.

In Figure 9, the steps of the method are presented at the System Operator screen. The numbers and the related arrows refer to the movement from one screen to another for the method accomplishment.

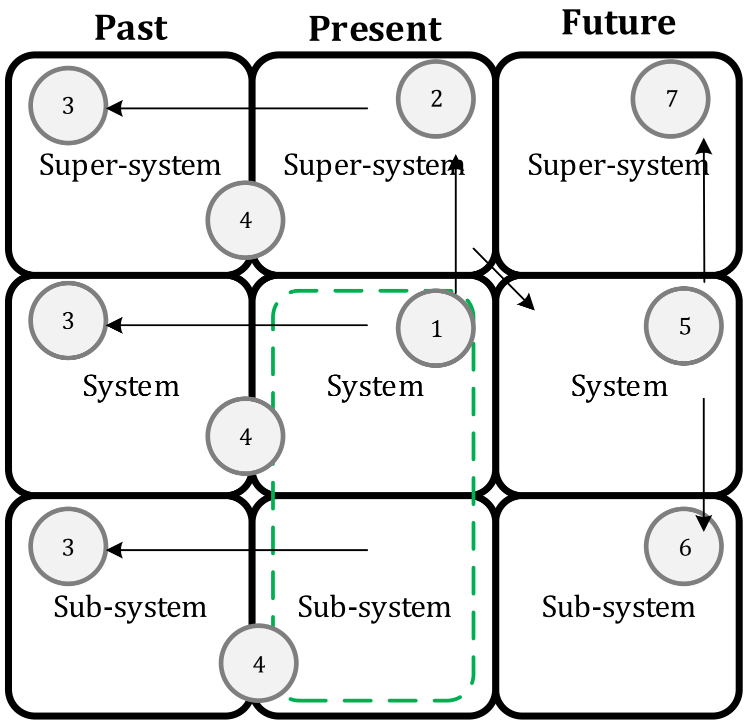


Figure 9: Management of knowledge for design requirements in the framework of the system operator. Circled numbers refer to the steps of the procedure of the method, and the arrow represents the direction of movement from one screen to the other.

According to the description of the steps inside of the System Operator, the STEP-1 and STEP-2 deal with the identification and/or characterization of requirements at the current situation (central column of the system operator). The current situation is considered as the starting point to update knowledge about the requirements. STEP-1 and STEP-2 are proposed as separate steps in Figure 9 to simplify the method's understanding for engineering stakeholders, in specific to those that are not familiarized with System Operator. A general recommendation is to address at the definition of requirements from the system level (to set a reference point for the analysis), but the choice between what characterize first between the super or the sub-system is free to the user.

The following STEP-3 considers the history of the elicited requirements during the STEP-1 and STEP-2. The STEP-3 allows focusing the attention to understand what has changed from both qualitative and quantitative requirements. Firstly, the design engineers need to look from the past to the present in order to understand the main requirements changes at least for what concerns the requirements values. The identification of changes among requirements should stimulate the design engineers' knowledge at understanding what has been changed for products/process requirements; and they also should recognize the main reason/causes for those changes. It is important to mention that the definition of the past time in this step (System Operator past column) is strictly related to the time period to forecast, consequently, a definition of a reasonable past period needs to be at least the same future time (System Operator future column), i.e., if it is required to forecast a period of 10 years, design engineers should at least consider 10 years or more into the past.

In general terms, STEP-1, STEP-2 and STEP-3 were created to support design engineers in recognizing the current state of the art of the requirements, allowing them to obtain a more comprehensive and holistic view about requirements changes from past to present. With this previous requirements analysis, the anticipation of the future situation of requirements starts to be feasible (STEP-4). On the one hand, qualitative requirements can be forecasted on the basis of the experts' knowledge projections. On the other hand, quantitative requirements can be forecasted on the basis of quantitative regressions, as was proposed for this research; the logistic growth model is the reference model to understand the future of products/processes requirements.

To simply the regression analysis based on a logistic growth model, a classification of quantitative requirements has been proposed. The proposed classifications are a small number to improve their easy management and cover an almost complete set of behaviours without overlooking something particularly meaningful. In detail, the classification should be intended as a contribution to recognize quantitative requirements that potentially behave logistically. Moreover, recommendations about how to manage requirements to obtain a logistic behaviour are presented as well. More details about the classification and recommendations will be presented in the prescriptive method description.

During the previous steps analysis has been analysed individually, the next steps of the method aim at supporting the consistency among the different hierarchical levels involved in the System Operator (STEP-5, STEP-6 and STEP-7). The final projections and cross-checks aim at envisioning the evolution of the system, its subparts and the different contexts that they are immersed. Finally, the overall System Operator framework needs to be consistent and harmonized, since it is possible that the fast development of a specific system can trigger big changes at both, the super- and sub-system level and vice versa.

The next subsection presents a more prescriptive description of the different method's steps as well as the recommendations emerged from the different analysis presented on the methodological proposal this research.

3.4.1 Elicitation of requirements at system, sub-system and super-system level (STEP-1 and STEP-2)

In general, the development of these steps are related to the first stage of the analysis proposed by Martino (1993), where the product/process to forecast has to be defined properly. These steps attempt to organize and characterize the elicited requirements by the analyst in a hierarchical way.

According to the objectives of this research, STEP-1 and STEP-2 are considered as separate steps due to the design engineers' tendency of generally focus their analysis considering the system and its parts, initially neglecting the characteristics of the context. Furthermore, the choice of considering the two steps as separate emerged from the need of properly guiding design engineers during the application of the method.

3.4.1.1 STEP-1: Elicitation of requirements at system and sub-system level.

The main goal of the first step is the identification of design requirements, which will be forecasted at system and sub-system level. Additionally, during this step it is necessary to define the boundaries of the analysis (i.e. limits of the system to analyse). In fact, in this step, design engineers need to focus their efforts on the description of the product/process in terms of requirements. Moreover, the description of those requirements has to be structured according to the ENV logic and proposed amendments, allowing them to be manageable for their use in the next steps of the method.

Different models/methods can be adopted to elicit requirements to describe product/process; nevertheless, those methods have to be suitable to fulfil the System Operator at system and sub-system level. For example, the Energy-Material-Signal (EMS) (Pahl and Beitz, 1996) model can be used as the initial model to start fulfilling the System Operator screen. However, this does not exclude the use of other models to obtain a more comprehensive set of requirements (such as IDEF0, BPMN 2.0, etc).

It is important to mention that the EMS model is widely applied in the creation of a common language between designers and engineers (Pahl and Beitz, 1996; Cross, 2008). Consequently, its model decomposition aims at supporting the elicitation of requirements related to the product and/or process for the system by describing their Useful Function and related sub-functions (Becattini, 2013). More details for producing criteria for the definition of the system requirements having the characteristic of completeness, non-redundancy and conciseness can be found in Becattini (2013). Nevertheless, the repeatability of the model decomposition can be improved through combined adoption of the NIST functional basis (Cascini et al., 2009), which is a formal function representation to support functional modelling, and standardized set of function-related terminology. Furthermore, the adoption of the TRIZ-body of knowledge as a classification of resources and its related application can stimulate in a more effective way the elicitation of requirements, as suggested in (Becattini, 2013).

As final remark, it is important to point out that the description of the design requirements has to be clear and simple, independently of the method adopted, to make them easily transferable to different stakeholders. Consequently, the use of the Element-Name-Value (ENV) model with proposed amendments is needed (section 3.2.2). In this first step, the tasks to be performed are then the following:

i) Define the system and sub-system; function description can be used to identify the main function of the system (e.g. EMS), the repeatability of this decomposition can be improved through a combined adoption of the NIST functional basis (Cascini et al., 2009). Note that this does not exclude the usage of other alternative models for the definition of the system and elicitation of requirements.

ii) Prepare the requirements list for both, the system and sub-system(s); it has to establish a consistent relation between the System Operator levels. Moreover, it has to be understandable and measurable according to the ENV logic.
   a. Elicit requirements by using tools and methods defined at the state of the art section with the purpose to exploit as much as possible the knowledge from different stakeholders (e.g. Interview or checklists).
   b. Describe the requirement's list according to the constructs of the ENV model with the proposed amendments for system and subsystem.

iii) Identify qualitative and quantitative requirements at system and sub system levels on the basis of the requirements units from the ENV description.

In Figure 10 it is presented a schema of where design engineers have to focus their attention for the elicitation of requirements according to the System Operator structure.

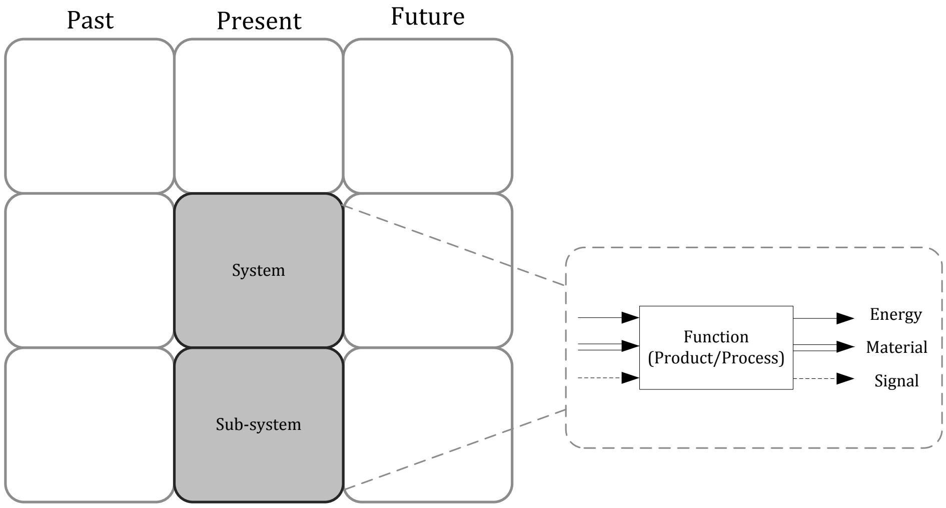


Figure 10: Diagram used for STEP-1 related the System Operator model and the logic to elicit design requirements at system and sub-system.

According to this step, the output is a list of requirements obtained by using simple description for both the system and sub-system under investigation. Nevertheless, the number of elicited requirements can be quite large in practice (Becattini, 2013b). Consequently, it is recommendable focuses the attention in a small set of requirements capable to be managed by the design engineers. Nevertheless, this recommendation not restricts the usage of the proposed method to forecast all the design requirements.

Finally, this step is the initial point to understand which requirements drive the product/process evolution.

3.4.1.2 STEP-2: Elicitation of requirements at super-system level.

The STEP-2 is related to the elicitation of requirements at super-system level. The main goal of this step is to identify requirements at super system level which may potentially influence the future of the system. With this in mind, the technological context, at least, has to be explored to identify new requirements at super-system, especially if the product/process is a part of a larger one. However a complete framework of requirements cannot remain only in the technological aspect. Indeed, the super-system also has to be consistent with essential concepts and contexts related to the Sustainable Development (SD) (World Commission on Environment and Development, 1987), which is increasing its influence in different subjects such as policies, laws and regulations. In details, three main pillars provide the direction for the SD such as: Social, Economic and Environment. Consequently, these contexts need to be added to the technological aspect for a more resilient and holistic understanding about product/process requirements. The combination of these four contexts allows obtaining a more comprehensive and complete framework of the evolution of the technical system based on requirements. Some works related to this topic have been already presented by the author in (Becattini, Nikulin and Cascini, 2013).

In this scenario, the role of the analyst is to explore these four contexts (i.e. technological, social, economic and environmental) to enlarge his/her thinking capabilities during the requirements elicitation process, without losing something really meaningful which can influence the product/process future. In this first step, the tasks to perform are the following:

i) Define the super-system and related boundaries.
ii) Elicit requirements from super-system levels by considering different contexts such as technology, social, economic and environmental.
iii) Describe the requirements list related to the super-system by using the ENV model with the proposed amendments.
iv) Identify qualitative and quantitative requirements at super-system basing on the requirements units derived from the ENV description.

It is important to mention that, if it is required, the previous tasks-steps do not exclude the elicitation of new requirements from system and sub-system levels according to the above-mentioned contexts. Moreover, to enrich the elicitation of requirements, the hierarchical relations between the requirements at different system-screen can be identified (Becattini, Nikulin and Cascini, 2013). Figure 11 shows a diagram representing the logic for the elicitation of requirements and its relation according to different contexts and System Operator levels.

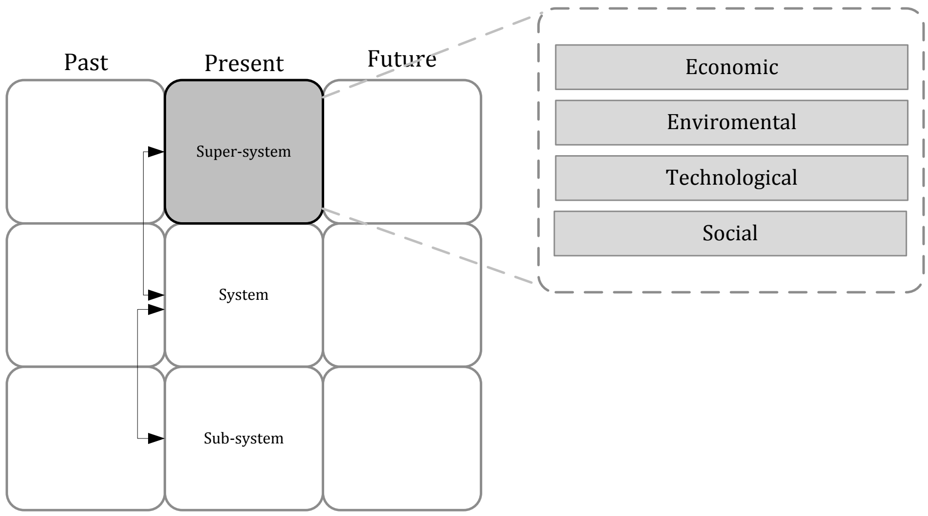


Figure 11: Diagram used for STEP-2 related to the System Operator model and the logic to identify design requirements at super-system. It can also be used at system and sub-system if it is necessary to elicit new requirements.

Finally, from the application of STEP-3, a list of requirements is obtained for the product/process at super-system level which considers four contexts: technological, social, economic and environmental.

3.4.2 Identifying how were the requirements in the past (STEP-3)

The STEP-3 allows understanding how the requirements values have been changing from the past to present. In other words, it allows understanding the dynamics of the design requirements. In depth, STEP-3 is related to the second phase proposed by Martino (1993) concerning the understanding of "the statement of the characteristics of the technology" (Martino, 1993). During the application of STEP-3, it is possible to recognize the changes occurred in the system, by identifying how the requirements were in the past. It is important to highlight that this opportunity is frequently neglected from current methods for the elicitation of requirements (e.g. VoC, Checklist, QFD and others).

It is important to remark here that the definition of the past-time is strictly related to the time to forecast. As previously mentioned, the definition of a reasonable period for past time needs to be at least equal (or larger) than the future time to forecast.

In this step, a qualitative estimation has been proposed to recognize requirement changes from past to present. The qualitative estimation should be intended as an easier and comprehensible assessment, which is independent from the System Operator level and context. The qualitative estimation has been proposed by using three classes, listed as follows:

- **Higher:** requirements that have been having a higher, bigger or larger value in the past, so the statement of improvement for these type of requirements are mainly by decreasing the units' values from past to present.
- **Stable:** requirements that have been having a same or similar value in the past, so the statement of the requirements has remained stable from past to present, consequently, the units' value of these requirements have remained stable.
- **Lower:** requirements that have been having a lower and/or smaller value in the past, so the statement of improvement for these requirements are mainly by increasing the units' values from past to present.

To simplify the understanding for users, the classes are presented graphically in Figure 12. In this step, the tasks to perform are then the following:

i) Define the elapsed time of the forecasting analysis considering both future screen and past-screen of the system operator.

ii) Estimate the requirements past-value for both qualitative and quantitative requirements by using the proposed classes (higher, stable, and lower).

iii) Identify the available sources of data and knowledge for qualitative and quantitative requirements. One the one hand, qualitative requirements deal with expert opinion and related knowledge. On the other hand, quantitative requirements, if data is available, deal with extrapolation analysis to obtain future values based on predictions.

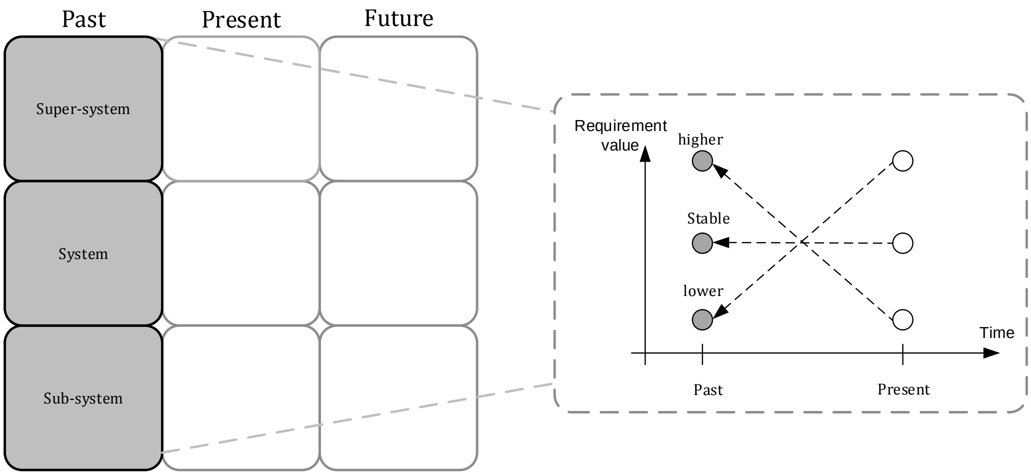


Figure 12: Diagram used for STEP-3 related to the System Operator model and diagram to support the requirements estimation process in the past.

During the estimation process, the previous classes should facilitate the identification of the knowledge sources by considering if design engineers are dealing with quantitative and qualitative requirements. As an output for this third step, a qualitative estimation of the requirements in the past is obtained for both qualitative and quantitative requirements. Moreover, the sources of data and knowledge are identified as well.

3.4.3 Quantitative requirements and regression analysis (STEP-4)

This step aims at exploiting the regression analysis for quantitative requirements. Moreover, this step is related to the third phase proposed by Martino (1993) according to his "period of forecast", which refers to trend extrapolation and its time period of forecast.

Given the technological aspect of this research, the s-curve model has been adopted to forecast requirements changes according to the considerations highlighted on the section 3.2.3, such as: First, the s-curve seems to be a suitable model to represent the evolution of technical system (Altshuller, 1984). Second, the s-curve can be characterized by a logistic growth models (Marchetti, 1985; Marcheti; 1986). Third, logistic growth model (Meyer's equation) and its related parameters seem to be closer to concepts already known by design engineers as technological stages (initial, growth and maturity/saturation).As a consequence, this model seems to be more suitable than others to be understood by design engineers. Four, given the popularity of the logistic growth model for understanding the technology evolution, it is interesting for this research to explore the benefits and limitations to be adopted in a method for forecasting design requirements, at least, as a referential regression model. Actually, this step not restrict the use of other regression models, nevertheless, given the research goal the author has decided to explore the boundaries for the application of the logistic growth model to understand the evolution of the technical systems, in specific design requirements.

As mentioned on section3.2.3, the identification of variables suitable to be forecasted by logistic growth model is an open issue. From the previous classification of papers in section 3.X, recommendations and suggestions were created in this step to characterize the behaviour of requirements by analysing those requirements that potentially can behave logistically.

In this scenario, the four proposed classes allow characterizing the potential behaviour that requirements can have during the forecasting time period. In other words, the classes allow identifying in an easier and comprehensible manner the potential qualitative trends among the elicited requirements. These classes can be understood as an initial attempt to recognize variables that behave logistically as well, such classes are described below:

- **Increasing:** a requirement that has presented an evident increasing value during the forecasting period.
- **Decreasing**: a requirement that has presented an evident decreasing value during the forecasting period.
- **Stable:** a requirement that has remained almost without changes during the forecasting period.
- **Fluctuating:** a requirement that has changed cyclically during the period of forecasting.

As mentioned in section 3.2.3, the variables with an “increasing” behaviour seem to be more suitable to behave logistically than the others. However, to fully validate the usability of the logistic growth model it is necessary to check at least two mutually correlated analysis. First, design engineers have to identify if the logistic growth model is meaningful and reasonable in reality for the selected variable. Second, design engineers have to check if the logistic growth model is supported by appropriate statistical results to confirm its acceptability as well.

To simplify the understanding of the proposed classes, they are presented graphically in Figure 13. Nevertheless, it is important to note that behaviours of requirements can be influenced by perturbation or noise, thus hindering the classification process. So the capability of the users' judgment to understand the behaviour of the requirements plays a relevant role to overcome this possible limitation.

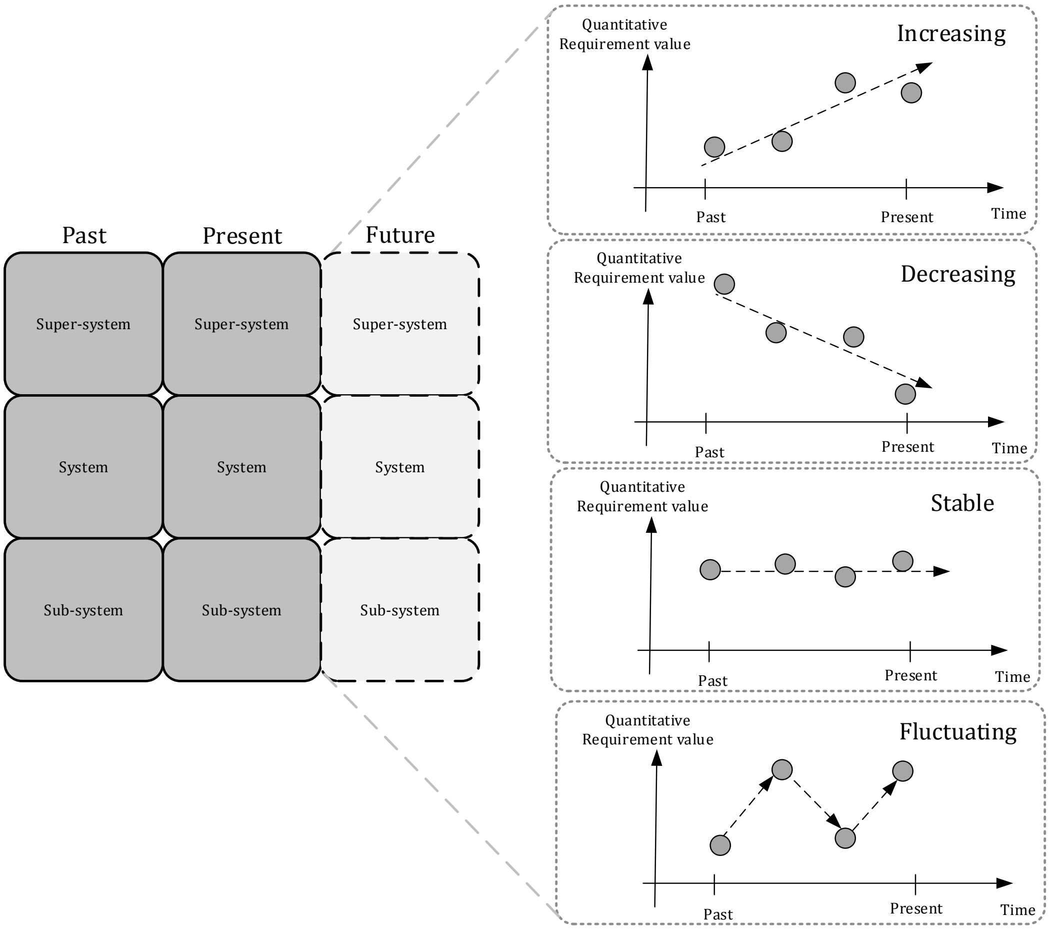


Figure 13: System Operator screen and the requirements classification according to the proposed classes. Future SO-screen is in dotted line as initial envisioning knowledge projections.

It is important to mention that the proposed classification allow forecasting requirements that only have presented an "increasing" behaviour. However, it is also important also to forecast the remaining requirements as well. From a literature review, several authors have pointed out the possibility to create indicators/ratios to represent the s-curves. For example, Altshuller (1984) proposed the Law of Ideality Increase as a combination of the Useful Function, Harmful Function and resources, which is represented by an s-curve. Moreover, in appendix-B it is possible recognize that some authors create indicators/ratios to exploit the logistic growth model as well (Miranda et al., 2010; Sneddon et al., 2011). Nevertheless, there are lacks of information about how create this indexes properly in practice. With this in mind, additional recommendations for the combination of requirements have been created to exploit as much as possible the logistic growth as a reference model for this research. The proposed requirement combination allows obtaining an "increasing" behaviour by using simple mathematical transformation, allowing us to exploit in a better way the remaining requirements. In this context, the combination of requirements will be called "Performance indexes".

In Figure 14 a set of the proposed combinations capable of delivering an "increasing" behaviour from the previous classification is presented. As an example of the proposed approach, the combination of "stable" and "decreasing" requirement behaviours (e.g. in Figure 14-leftside B and C) should allow to create an "increasing" behaviour performance (e.g. in Figure 14-rightside, combination (B/C)). More examples of possible combinations are included in Figure 14. However, the number of combinations between requirements can be large, therefor it is important to define a manageable number of performances taking into consideration the meaning of the performance, for example, according to the "limits of growth" assumption (Kucharavy, 2007). Furthermore, the created performance also needs to be supported by statistical results to confirm its acceptability.

It is worth noticing that requirements with "fluctuating"" behaviour were excluded from the proposal, given the uncertainty of the final performance behaviour. Nevertheless, the use of requirements with "fluctuating" behaviour to create performances cannot be neglected from the practice, even if the final results largely depend on the combined requirements and related meaning, data available and statistic results. As a consequence, "fluctuating" requirements are more difficult to model.

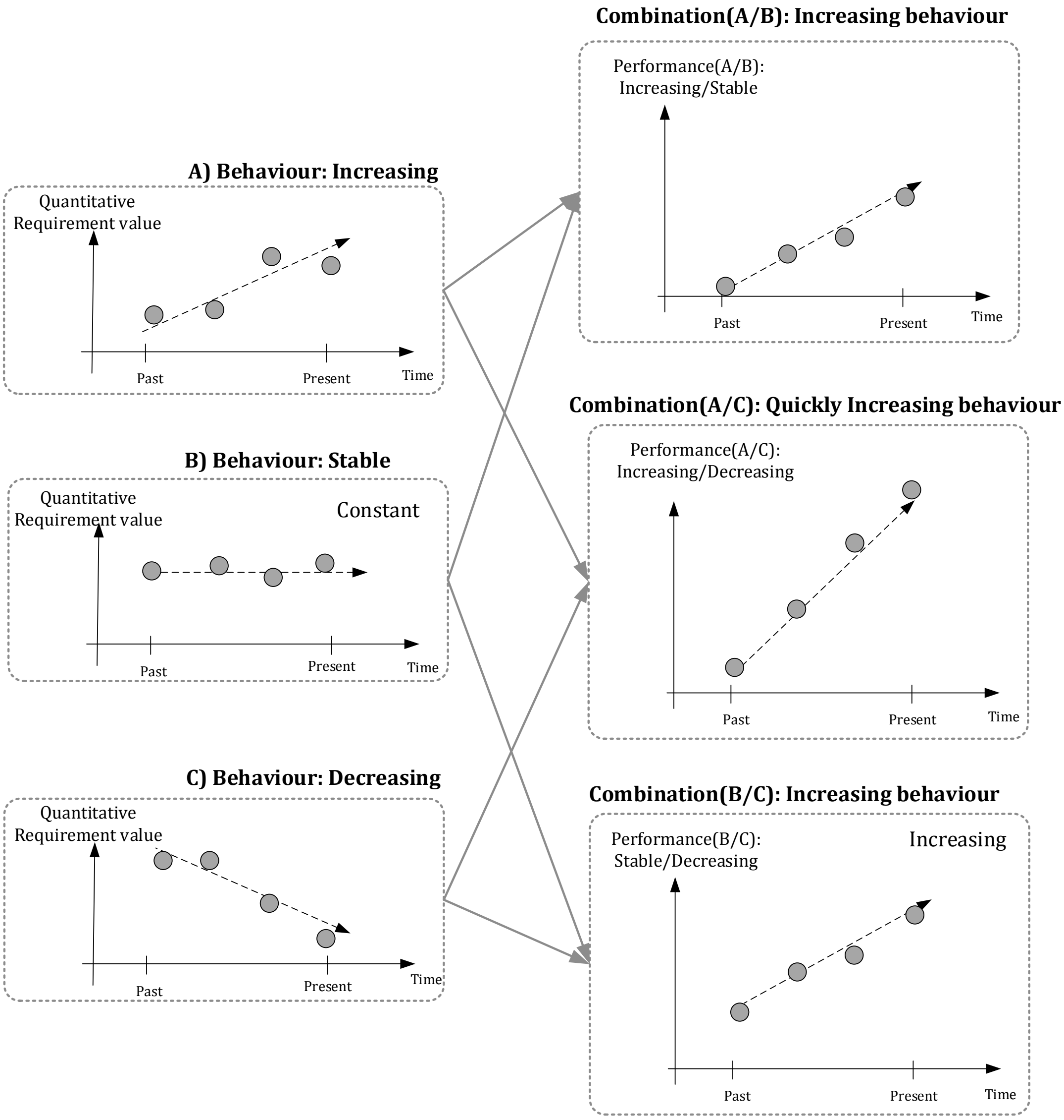


Figure 14: Graphic representation of performances based on the combination of the behaviour of requirements; Left-side describes requirements behaviours from System Operator screens, the right-side represents the expected trend of combining them; requirements with "fluctuating" behaviour were excluded from the proposal given the uncertainty of the behaviour of the performance delivered.

Moreover, in this step it is required a certain level of knowledge in statistics to understand the regression results. Due to this need a software tool has been developed to specifically support those users who do not have a deep knowledge in statistics (section 3.3). According to the above-mentioned suggestions, the tasks to develop in the current step are the following:

i) Classify requirements according to the proposed classes (i.e. increasing, decreasing, stable and fluctuating). Starting from requirements with "increasing" behaviour, develop the following sub-steps:

   a. Check consistency among the "increasing" requirement and their meaning, for example, by "limits of growth" assumption.
   b. Develop a regression analysis for "increasing" requirements based on logistic growth model.
   c. Check statistic indicators of the regression (e.g. r-squared; p-value and some residual indicator as MSE or RMSE).

ii) With the remaining requirements, create performances based on the proposed combinations (Figure 14).
   a. Check consistency among the "increasing" performance and their meaning.
   b. Develop a regression analysis for "increasing" performance based on logistic growth model.
   c. Check statistic indicators of the regression (e.g. r-squared; p-value and some residual indicator as MSE or RMSE).

As an output for this step, it is possible to obtain different regressions based on logistic growth model for requirements and/or created performances. It is important to remark that this step is focused on the exploitation of the logistic growth model. However, from a practical viewpoint, the analysis of more complex regression analyses during this step cannot be neglected. Nevertheless, their application, in practice, largely depends on the specific user knowledge (well skilled on statistic). In detail, this type of analysis requires larger statistic knowledge and the topic span beyond this PhD dissertation.

3.4.4 Envision of the requirements at system level and cross-check value at system and sub and super system levels (STEP-5, STEP-6 and STEP-7)

The developments of these steps are related to the last element proposed by Martino (1993), which corresponds to the "probability statement of the forecast". On the one hand, these steps aim at envisioning the System Operator future-screen, for both quantitative and qualitative requirements, and for performances as well. On the other hand, these steps aim at understanding the hierarchical relations among the different system levels with time perspective view.

Moreover, these steps are essential to exploit as much as possible the knowledge emerged from previous steps analyses, by creating an educative reflection about plausible future for the product/process under investigation. Finally, the overall forecasting has to be based on the combination of quantitative and qualitative projections, which should be in accordance with reliable source of knowledge and information, such as the experts' knowledge and statistic information.

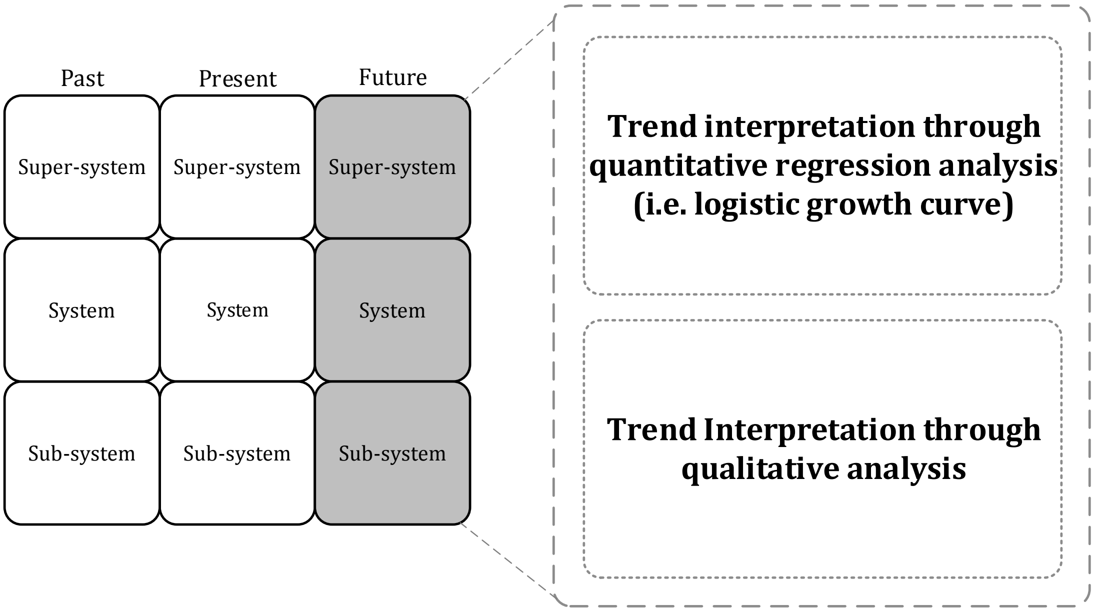


Figure 15: Schemes used in STEP-5, STEP-6 and STEP-7 show the System Operator model and the logic to envision requirements by considering both quantitative and qualitative interpretations.

During the development of the steps, quantitative and qualitative requirements should be envisioned (Figure 15). Firstly, regressions based on logistic growth model are interpreted according to the requirement/performance stage (Figure 16). With this in mind, the identification of the appropriate stage for requirements should help to simplify the understanding of potential future changes and also stimulate the thinking capability of the design engineers by looking for reasons/causes beyond the specific stage (Meyer et al., 1999; Marchetti , 1985; Modis, 2000). In detail, the three main stages are presented as initial, growth and maturity/saturation stages in Figure 16.

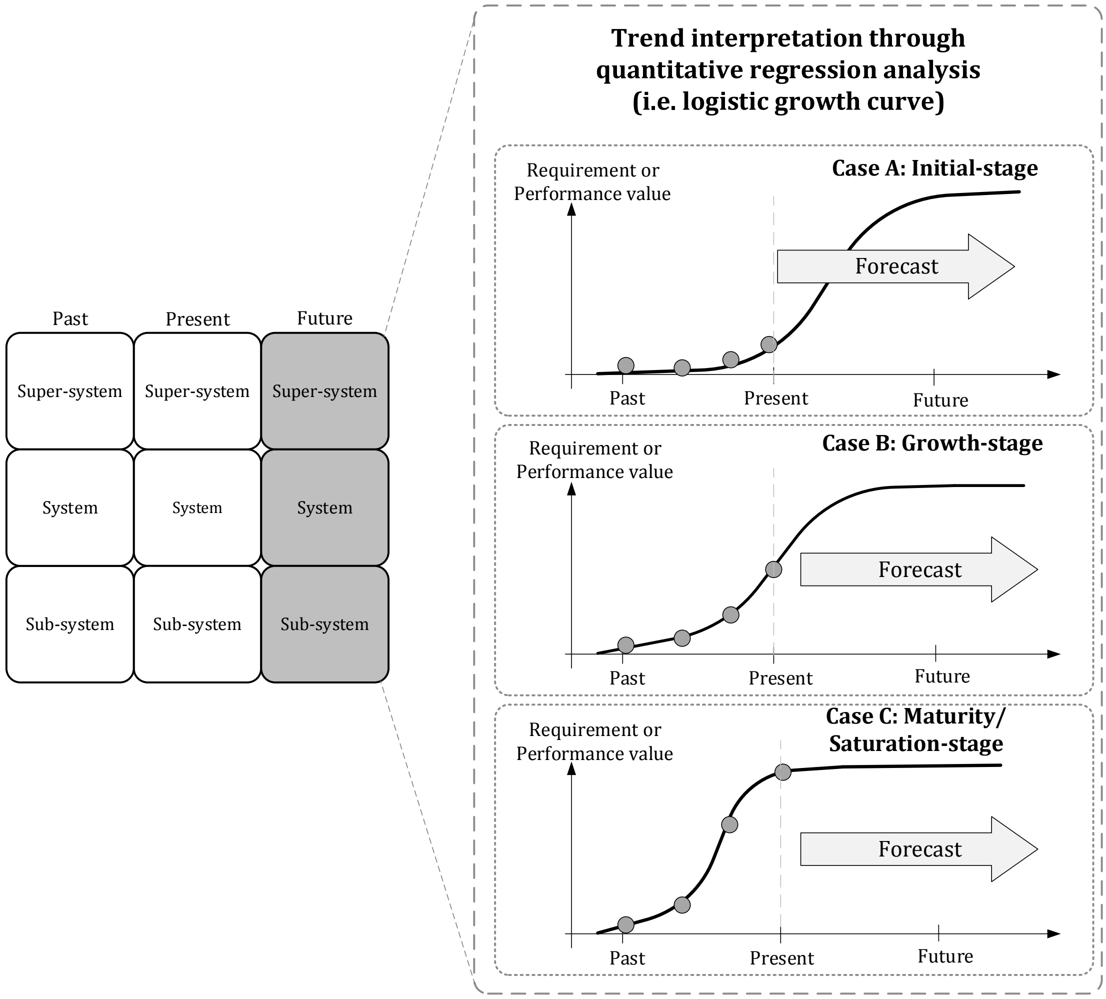


Figure 16: Diagram for the interpretation and envisioning for quantitative requirements or performances (quantitative projections).

Secondly, qualitative projections take into account the perception/opinion on requirements values under the expert's knowledge, by identifying their potential future behaviour (Figure 17). In this case, the qualitative trends are proposed in three main categories: i) increasing; ii) stable; and iii) decreasing. With this in mind, the proposed approach is focused on exploiting the capability of the expert to produce a meaningful and understandable output regarding the previously mentioned classes. In this case, it is relevant also to understand the reasons behind the potential trend to stimulate the thinking capabilities of design engineers. At the end, quantitative and qualitative projections for requirements need to be checked and harmonized at different System Operator levels to be consistent with the overall forecasting analysis.

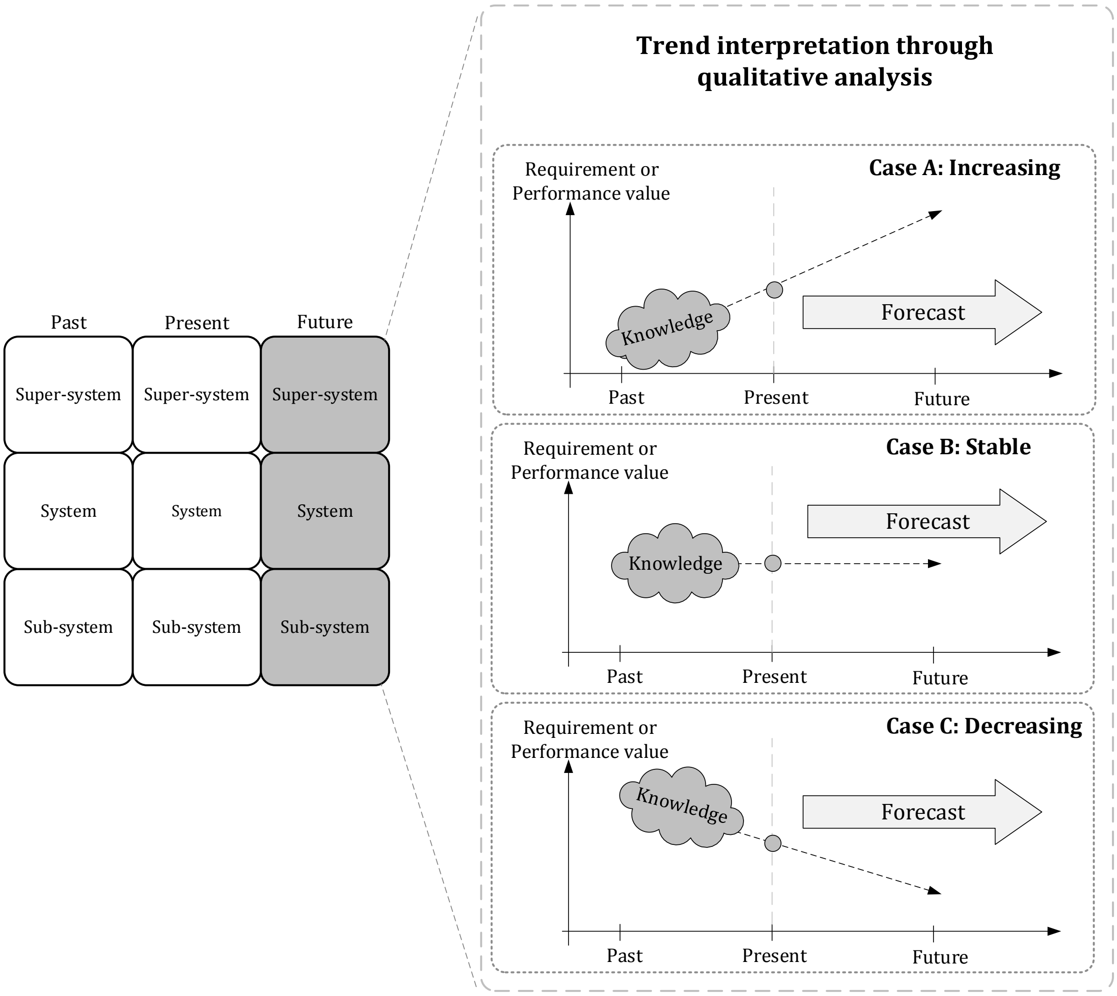


Figure 17: Diagram for the interpretation and envisioning for qualitative requirements or performances (qualitative projections). In this case the dotted lines are used to illustrate the direction of change, but not necessarily mean that this direction will be linear.

Finally, design engineers need to check the requirements changes to create a coherent knowledge projection (qualitative and quantitative projections) to understand the system evolution, its subparts, and the different contexts they are immersed in. For what concerns the probability statement, on the one hand, the quantitative projections can be checked by the statistic results that the regression analysis provide. On the other hand, the qualitative projections can be checked by the perception of usefulness and final assessment by experts' opinion and related beneficiaries. With this premises, expert's involvement is relevant to create a consistent consensus about the future by setting directions about requirements and its related system.

Finally, it is recommendable to addresses the forecasting of requirements from the super-system present screen to system future screen (to set a reference point for the knowledge projection), mainly because requirements at higher level are more likely to influence the requirements at lower level (Becattini, Nikulin, Cascini, 2013). In detail, the next steps have been proposed sequentially separated to simplify the knowledge projection at the different system levels. Eventually, the envisioned System Operator future-screen corresponds to the main output of the overall forecasting analysis.

3.4.4.1 STEP-5: Envision of the requirements at system level.

This step has been previously introduced as an overall framework of the System Operator future-screen. During this step, each requirement has to be envisioned according to the quantitative and qualitative projections proposed on Figure 16 and Figure 17. On the one hand, quantitative projections based on logistic growth model have to bring assessable statements about the requirements changes. On the other hand, qualitative projections based on experts' knowledge have to bring a better understanding about how the future of requirements will be. Nevertheless, the combination of qualitative and quantitative projections has to be consistent in bringing new insight and knowledge for design engineers and related decision makers. In this step, the tasks to perform are the following:

i) Create quantitative projections for requirements and performance based on logistic growth curve model at system level.
   a. Identify the logistic growth stage (initial, growth and maturity/saturation).
   b. Identify the reasons why the logistic growth stage is in a specific stage. For example if it is in a maturity stage, are there some limiting resources? Why has been reached a maximum?

ii) Create qualitative projections for requirements based on the proposed classification at system level (Figure 17).

iii) Cross-check and harmonize the qualitative and quantitative projections for requirements, and performances as well.
   a. Identify if there exists a causal-relationship between qualitative and quantitative projections at system level.

iv) If it is possible, provide new insight and conclusions that the knowledge projections bring out about the requirements at system level.

The main result of this step is a description of the knowledge projection from both, quantitative and qualitative requirements at system levels.

3.4.4.2 STEP-6: Cross-check value and requirements envision at system and super-system level.

At this time, it is necessary to envision the super-system level. The knowledge projections related to the super-system level needs to be in accordance with the previous step. In this step, the tasks to perform are the following:

i) Create quantitative projections for requirements and performances based on logistic growth curve model at super-system level.
   a. Identify the logistic growth stage (initial, growth and maturity/saturation.)
   b. Identify the reasons why the logistic growth stage is in a specific stage. For example if it is in saturation stage, are there some limiting resources? Why has been reached a maximum?

ii) Create qualitative projections for requirements based on the proposed classification at super-system level (Figure 16 17).

iii) Cross-check and harmonize the qualitative and quantitative projections for requirements, and performances as well.
   a. Identify if there exists a causal-relationship between qualitative and quantitative projections at super-system level.
   b. Identify if there exists a causal-relationship between qualitative and quantitative projections between the system and super-system level

iv) Provide a description of the new insight and conclusions that the knowledge projections bring out about the requirements at super-system level.

v) If it is possible provide new insight and conclusions that the knowledge projections bring out about the requirements at super-system level as well.

vi) Cross-check the new insights and conclusions between the system and super-system about requirements.

The main output of this step corresponds to the description of the knowledge projections at super-system level, and it has to be in accordance with the knowledge projection at system level.

3.4.4.3 STEP-7: Cross-check value and requirements envision at system and sub-system level.

With the knowledge projection created from STEP-5 and STEP-6, it is necessary to end the forecasting analysis by envisioning the sub-system level. The envisioning process uses the same logic of the previous mentioned steps. However, a new task is added to summaries the whole forecasting process. In this step, the tasks to perform are the following:

i) Repeat STEP-6, but considering the super-system as sub-system.
ii) Cross-check the new insights and conclusions between the overall System Operator.
iii) Provide suggestions and recommendations about how the new knowledge can support the design process and related decision makers.
   a. Check and confirm the insights and conclusions with related experts and stakeholders.

Given the interaction with experts some amendments can emerge, consequently, the iterations to improve the final results are allowed. Finally, the outcome of this step is a knowledge projection by each design requirements at different System Operator levels. Moreover, the projections include directions and recommendations to support the design process and related decision makers.

Chapter 4

[4] Application of the proposed method for forecasting design requirements, cases studies and tests

This section collects and discusses the results obtained by the application of the method for forecasting design requirements and the software tool developed to support design engineers. The related activities have been carried out by the author in an industrial and an academic context.

The first section of this chapter presents two different cases studies, to which the proposed method has been applied. The first case study is related to the manufacturing industry, in particular to the white good industry, characterized by changes for both product and process. Such activity has been conducted individually and together with the members of the Process Technology R&D team of Whirlpool in the context of the FORMAT-project. The second case study is related to the mining industry. This case study is framed in an industry where the process changes to tackle new challenges and demands, but the product does not change, for instance a commodity product as copper. The mining case study has been conducted together with members of the Technological Centre of Valparaíso and its partners in the context of the Cluster Mining Project, which is constituted by different mining companies from the North of Chile.

The second section collects a case study to be used for two testing activities in an educative context. The tests have been performed with students of the School of Mechanical Engineering at Politecnico di Milano and Product Design Engineer students at Universidad Técnica Federico Santa María.

For each experimental activity, the objectives have been pointed out at the very beginning in order to clarify which was the purpose of the case study and testing activity in relation with the above-mentioned objectives. Each section presents the experimental activities, and then concludes with a discussion about the actual validation of the objectives. The case studies and tests have been organized to validate the research proposal according to the following criteria: i) theoretical structural validity (Pedersen et al., 2000); ii) empirical performance validity (Pedersen et al., 2000); iii) Capability of the method to guide design engineers in order to forecast design requirements. In Figure 18 the structure of this chapter is presented according to the validation criteria:

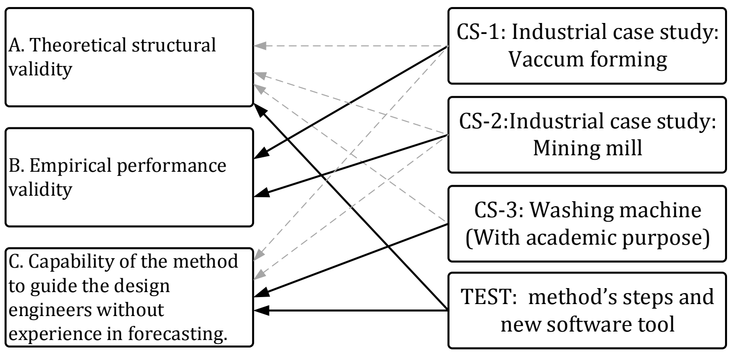


Figure 18: Organization of the chapter and related activities; black arrows are activities directly related to the validation criteria and doted arrows are activities partially related to the validation of the criteria.

4.1 Case study in the context of FORMAT Project: Vacuum forming case study

A real case study is presented as an empirical application to understand and estimate the applicability and viability of the proposed method in an industrial context. This case study has been developed within the FORMAT Project (http://www.format-project.eu/), a Marie Curie IAPP EU funded project that aims at developing of a forecasting methodology able to support decision makers in their strategic decisions. Both, academic organizations and industries are partners of the project consortium. The case study hereby exposed was considered as interesting for one of the project partners that operate in the business of white goods production. Particularly, the partner was interested in the forming technologies for the inner liners of domestic refrigerators.

The application of the method for forecasting design requirements was developed within the FORMAT-project, and specifically for what concerns the vacuum forming case study. The dynamic of the case study was the following: the author was a participant of the core-team for the vacuum forming case study in the FORMAT-project. During the case study the author applied the proposed method to enrich the FORMAT-methodology with data and information related to the system requirements. The contribution of the method results was shared among the different FORMAT meetings performed and reported at the end of the case study. Figure 19 illustrates the dynamic of the case study for the method application during the FORMAT-project.

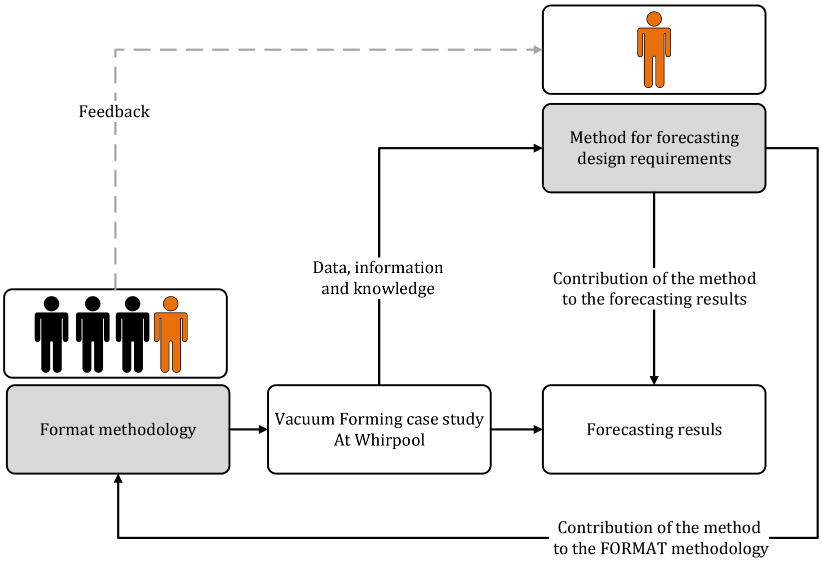


Figure 19: The dynamic of the case study within the FORMAT-project.

The first application of the method has been carried out as a complementary analysis with the support of experts of Whirlpool Europe (from now on WH), and regarded the vacuum forming process. Noteworthy, this case study aimed at understanding how the method works in an industry where products change constantly to improve their performance. In fact, manufacturing technologies have to adapt themselves to the evolving features of products or processes. For more information and details of the study beyond the method proposal see deliverable D4.5 of the FORMAT Project (www.format-project.eu/).

This application devotes particular attention to the capabilities of the method to clarify the directions for product and process development for both FORMAT-teamwork and decision makers. Moreover, it is interesting also to underline the efforts required by the analyst in the fulfilment of the different method steps to understand the potential limitation, which will be reported in the discussion and conclusion of this case study.

4.1.1 Elicitation of requirements at system, sub-system and super-system (STEP-1 and STEP-2)

The method was applied as a complementary study during the development of the FORMAT methodology by reusing the data and information captured during FORMAT sessions for the vacuum forming case study. The FORMAT-methodology is constituted by stages which are split according to the FORMAT acronym: FORmulate, Model, Act and Transfer. (More details about FORMAT methodology are available in http://www.format-project.eu/)

During the FOR Stage of the FORMAT-methodology, the analysts (FORMAT) and Whirlpool's experts agreed on a set of questions (WHAT do we need to know about future?) whose answers may be conveniently used in order to plan future R&D strategies (WHY do we need to know the future?) in the selected context (time span 20 years, 2013-2033; location, factories of Europe, Middle East and Africa): i) Will vacuum forming (VF) technologies be needed in the future? ii) What will be the most available forming technologies in the future? iii) What will be the evolution of the main parameters of vacuum forming technologies? These questions are interesting to know in order to have a complete evolution framework of the vacuum forming technologies. Nevertheless, these questions are beyond the author's method proposal, because the method attempts to forecast design requirements rather than develop a complete forecasting analysis of technologies. However, it is interesting to identify the boundaries and limitations of the method to support these forecasting questions about vacuum forming technologies.

During stage M of the FORMAT methodology, the analysts (of the FORMAT team) described the current technological situation. In this case, the current inner-liner manufacturing process was modelled by using a functional description: <to make><open polymer 3D-form (box-form)><from granules>. The current process phases were described by using an adapted BPMN, considering polystyrene granules as the input flow. A sequence of functions were elicited to further characterize the process of transforming granules into a 2D polymer sheet (melt, form, size and quality check, stabilize and store) and its final transformation into an open 3D plastic form (soften, shape, size and quality check).

To obtain a complete overview of the manufacturing process, the main function of the production process was analysed by using the System Operator considering a period of time of ±20 years from present. As a result, it produced a list of features, requirements, drivers and barriers from the present at the different System Operator levels: super-system (e.g. refrigerator and company context), system (e.g. current process), and sub-systems (e.g. sub-process or process phases). The items defined by the FORMAT-team during the description of the technology were elicited by interviews with experts from WH and collecting information from different internal/external data sources, with special attention paid to collect information which might potentially have an impact on (or impacted by) the plastic liner of fridges (e.g.: beyond technology, the environment, and also the social and economic side have been considered in the analysis).

In details with respect to the author's method, the elicitation of requirements (STEP-1 and STEP-2) was collected from the items characterizing the System Operator developed by the FORMAT-team. Then, the items were modified according to the ENV logic and related amendments from section (3.2.2). Moreover, some fuzzy items were also transformed into requirements as well. The overall list of requirements is presented in appendix-C. According to the proposed STEP-1 and STEP-2, the requirements were classified by the author into quantitative and qualitative requirements. Also the units for each requirement were identified. Nevertheless, to be practical in use, the overall list of requirements presented in appendix-C has been chunked according to the theory proposed by Miller (1956) about the limits of capacity for processing information well known as "The Magical Number Seven, Plus or Minus Two". The selection of the requirements according the Miller's theory was based on two aspects: i) requirements considered relevant for the product/process improvement; and ii) the hierarchical relation among the elicited requirements. Moreover, this choice was also compliant with the need of the industrial partner of the FORMAT project of not fully disclosing the results of the study. The selected requirements were distributed equally at the different System Operator levels. Table 7 presents the different requirements to forecast and related classification after the chunking process.

The three main rows characterize the hierarchical levels of description: the refrigerator as the context into which the inner liner (final outcome of the forming process) is exploited, the forming process as the main system, and its phases as the sub-system level of description. According to the proposed classes from STEP-1 and STEP-2 in section 3.3, the column with the header "Present (2013)" collects elements and names for design requirements while, on its right, their units of measurement are presented as well by following the logic from the ENV model, so as to directly suggest if the requirements are qualitatively or quantitatively measurable. Furthermore, the present requirements (Table 7-"Present (2013) Requirements") have been chosen to stress the concept of the mutual relationships between different System Operator levels. For instance, the bigger the volume of the refrigerator (super-system level) is, the larger should be the size of the 3D polymer form that is produced at the system level. Moreover, the quantity of polymer used for the process (sub-system level) is directly related to the size and the complexity of the 3D polymer form. Bigger sizes correspond to an increased need of polymer material. Energy consumptions as well, are partially related to the characteristic of 3D polymer form as size and complexity.

Table 7: Requirements list of vacuum forming organized according to system operator framework after the chunking process.

	Past (1993)	**Present (2013) Requirements**	**Units**	**Qualitative/ Quantitative**	**Requirement behaviour (1993-2013)**
Super-System (refrigerator)	Lower	Refrigerator volume	[m^3][litres][ft^3]	Quantitative	Increasing
	Higher	Energy consumption	[kilowatts/year]	Quantitative	Decreasing
	Higher	Material quantity	[kg]	Quantitative	Decreasing
System (Vacuum Forming process)	Lower	Process production	[number of pieces/hour]	Quantitative	Increasing
	Lower	Complexity of 3D polymer form shape	Number of [Form],[Curves]	Qualitative	Increasing
	Lower	Size of 3D polymer form	[m^3]	Quantitative	Increasing
Sub-System (Process stages)	Lower	Extruder production	[number of pieces/hour], [pcs/shift]	Quantitative	Increasing
	Higher	Thickness of polymer	[mm], [cm], [m]	Quantitative	Decreasing
	Higher	Maintenance time	[min], [hr], [days]	Quantitative	Decreasing

4.1.2 Identifying how were the requirements in the past (STEP-3)

All the above mentioned requirements (Table 7) were assessed according to the proposed classes in STEP-3 by estimating a past value for them. During the FORMAT case study, it was defined a period of time of ±20 years from present to develop the forecasting. The author has followed the same period of time to develop the forecasting analysis to be compliant with the FORMAT-project activities as well. The estimation about how the requirements values were in the past was based on the information gathered by the FORMAT-teamwork and also on historical tendencies that the requirements themselves have presented through the elapsed time. The column on the left side of Table 7("Past (1993)"), in fact, conveniently shows how the requirements were in the past by using the qualitative classes proposed in section 3.4.2 (lower, stable, higher). In detail, the qualitative estimation of the requirements from STEP-3 allowed establishing and understanding better the requirements behaviour from the past to the present, making it easier to synthesize the upcoming steps of the method. Most of the requirements values were lower in the past, for example, the maintenance time was lower in the past, the thickness of the polymers to form pieces was higher, the number of pieces produced by the extruder was lower (from 660 [pcs/shift] in 1999 to 1100 [pcs/shift] in 2013).

According to STEP-3 (iii), during this step different data sources were explored by the author. On the one hand, the internal data source available from FORMAT-beneficiaries was mainly related to the production; moreover, the data available was mostly for specific years (sporadic) rather than a complete data series. On the other hand, external data sources were explored as well. Several data sources provide data about the refrigerator (super-system) in particular for refrigerator volume and energy consumption. The data sources were the Association of Home Appliance Manufactures (AHAM) and Appliance Standards Awareness Project (ASAP).

4.1.3 Quantitative requirements and regression analysis (STEP-4)

In this step all the requirements (Table 7) were classified according to the behaviours proposed in STEP-4 (Section 4.1.4) by using the historical tendencies that the requirements themselves have presented through the elapsed time. During this step most of the requirements showed an "increasing" behaviour. From the previous step, the energy consumption and the refrigerator volume were the requirements with the highest data availability (complete data series) which were collected from external data sources.

Given the recommendation provided for exploitation of the logistic growth model in section 4.1.4, the refrigerator volume corresponds to the initial candidate to behave logistically (increasing behaviour) if compared to the other elements in the restricted set of presented requirements. Nevertheless, according to STEP-4 (ii-a) a clarification of the meaning is required before providing a logistic growth curve analysis. In fact, considering the three dimensions of the refrigerator, it is straightforward that it cannot grow unlimitedly in height and depth because of potential problems of users in reaching the contents. The growth in width is the least constrained, even if the size for domestic appliances in kitchens can be considered as restricted (true for the built-in devices, false for stand-alone ones). On this basis, a regression analysis was performed for interior refrigerator volume with data coming from the Association of Home Appliance Manufactures (AHAM) and Appliance Standards Awareness Project (ASAP).

Figure 20 presents the average value of the internal volume of refrigerators. Given the fact that data was obtained from external data sources, the volume of the refrigerator come from United State, nevertheless, the data base include refrigerator branches for all around the world, independently from the kind of refrigerator or geographical region it has been manufactured in.

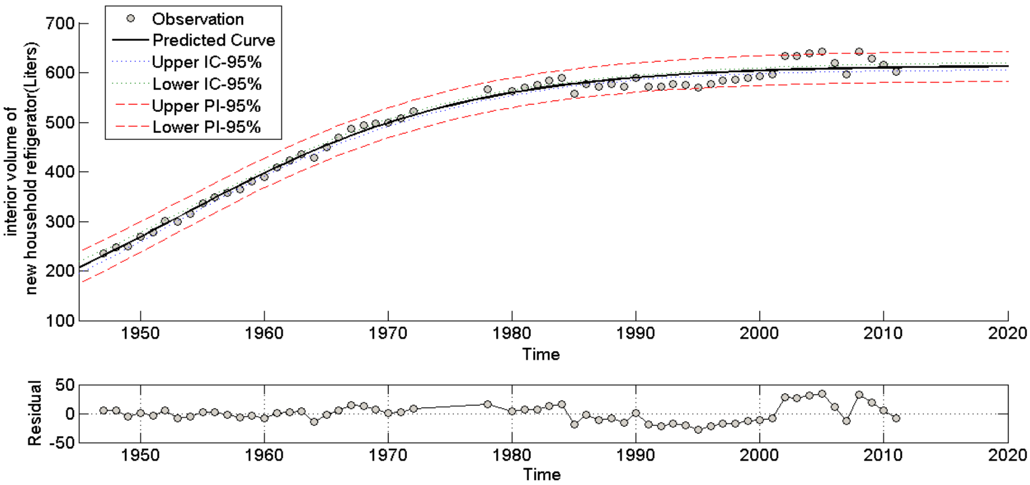


Figure 20: Average of interior volume of new household refrigerator; Data source: Association of Home Appliance Manufactures (AHAM) and Appliance Standards Awareness Project (ASAP).

In this case, the statistical analysis through which the regression analysis was carried out used data from the last 60 years to improve the quality of the regression results (as demonstrated in Appendix-A). As results of this analysis, all the statistic results are appropriate to validate the use of the logistic growth model to represent the interior volume refrigerator trend. In detail, Table 8 shows the goodness of the fit and the regression parameters. For this case all the regression parameters are significant (p-value<0,01), which is a positive indication for the acceptability of the logistic growth model. Moreover, the r-adjusted is 98,5% supporting the regression quality as well.

It is interesting to note that in this case the logistic growth model begins from a minimum that is not necessarily equal to zero (Figure 20). According to Chang & Baek (2010), the logistic growth model does not necessarily begin from zero, because technologies are set up with a minimum performance level in order to begin growing. With another view, Modis (2002) defined the remaining parts of the logistic growth curve as "backcasting" and they can be used to stimulate the insight about the variable under investigation. More details about "backasting" can be obtained from Modis (1992) and Modis (2002).

According to trend results, the maximum capacity that the interior refrigerator volume going to reach corresponds to 614,47 [Litres]. This statement can be considered as partially true, because companies seems to be capable to develop bigger refrigerator, but in practice, it is interesting to understand why the refrigerator volume is saturated. Some potential insights might be referred, for example, to limitation of space, human size and/or quantity of food that people is capable to eat and save in the refrigerator. As a consequence, the size of refrigerator seems to remains in a saturated volume.

Table 8: Statistic results for regression analysis for refrigerator volume.

Parameter	**Value**	**Statistical significance (p)**
Parameter of the regression		
Maximum for average of interior volume of new household refrigerator [litres]	614,47[Litres]	p<0,01
Period of time for 80% of the cycle [years]	52 years	p<0,01
Middle time when interior volume growth achieves his 50% [years]	1953 years	p<0,01
Results of the fit		
R-Adjusted [%]	98,5%	-

Given the recommendation to exploit the logistic growth model presented in section 4.2.4, a performance has been created by combining two requirements the refrigerator volume and the energy consumption. The combination used to create this performance index is shown in Figure 14 (Combination A/C) where an "increasing" requirement is divided by a "decreasing" requirement. For this case study, the refrigerator volume requirement was divided by the energy consumption requirement allowing obtaining an "increasing" performance by the combination of them. Nevertheless, a clarification of the meaning is required before providing a logistic growth curve analysis. In fact, the refrigerator volume cannot unlimitedly grow as presented in Figure 20. Moreover, the energy consumption cannot be reduced beyond a minimum level to maintain the refrigeration process. Consequently, the performance index cannot grow unlimitedly because is limited by resources. With this in mind, the logistic growth model seems to be an interesting analysis to explore the potential trend for this performance.

In this case, the number of data points for energy consumption was lower than the refrigerator volume, consequently, the regression analysis was developed taking into account the common years between them (Figure 21).

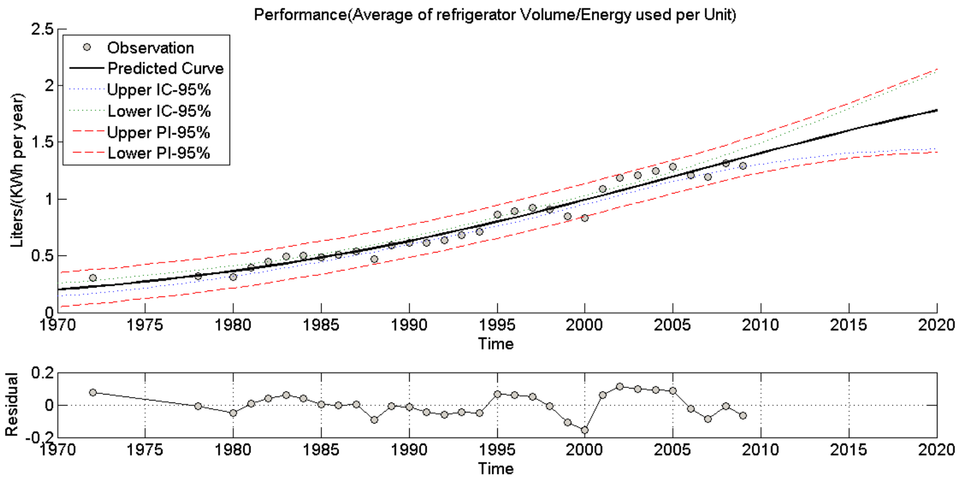


Figure 21: Created performance for refrigerator (Effective volume/Energy consumption); Data source: Association of Home Appliance Manufactures (AHAM) and Appliance Standards Awareness Project (ASAP).

Also in this case, the regression parameters are appropriate to validate the logistic growth model, at least, in terms of statistic results. In Table 9 the regressions results are presented. In particular, the goodness of the fit and the regression parameters are showed. Moreover, the regression parameters are significant (p-value<0,01) and the r-adjusted is 95,6%.

Table 9: Statistic results for created performance index (volume refrigerator/energy consumption)

Parameter	Value	Statistical significance (p)
Parameter of the regression		
Maximum value expected for the index [Volume of refrigerator/ Energy consumption]	2,23 [Litres/(KWh per year)]	p<0,01
Period of time for 80% of the cycle [years]	60 years	p<0,01
Middle time when indicator achieves his 50% [years]	2003	p<0,01
Results of the fit		
R-Adjusted [%]	95,6%	-

At the end of this step, two logistic growth curves were developed. According to the internal data source, the FORMAT-beneficiary did not provide enough data to carry out an appropriate quantitative analysis, Due to the lack of data, there were sporadic observations rather than a complete data series

4.1.4 Envision of the requirements at system level and cross-check value at system and sub and super system levels (STEP-5, STEP-6 and STEP-7)

In the last steps all the requirements were projected according to the criteria proposed in STEP-5, STEP-6 and STEP-7. According to the availability of data and information retrieved from FORMAT-case study, each requirement was projected by the author one by one starting from system-level, but then the projections were confirmed by the FORMAT-teamwork. At system level, the knowledge projections were developed only by a qualitative viewpoint based on the criteria proposed on Section 3.4.4. At super system level, the knowledge projections were developed by quantitative projections (refrigerator volume and performance) and qualitative projections. Finally at sub-system level, the knowledge projections were developed based on the proposed criteria as well (section 3.4.4). Finally, the cross-check analysis conciliates and harmonizes the quantitative and qualitative projections between analyst, FORMAT-teamwork and beneficiary. Table 10 provides the complete knowledge projection about the future for the design requirements already collected in Table 7. The results have been included in the final report of the case study.

Table 10: System Operator (future screens) envision according to the different requirements and their relations for vacuum forming case study.

	Present	**Future knowledge projection (Envision)**
Super system (refrigerator)	Refrigerator volume	Interior refrigerator volume should not increase in the future; the saturation capacity is achieved.
	Energy consumption	Energy consumption has been decreasing in the last years. Energy consumption depends on governmental regulations and standards which relate the refrigerator volume to the energy consumption. According to this regulation, the energy consumption cannot exceed a specific volume.(Energy Star, 2014)
	Material quantity	Material quantity should continue with a slightly decreasing in the next years, but it can't increase the energy consumption.
	Performance: Volume of refrigerator/ Energy consumption.	This performance will continue to grow in the upcoming years, not because of the growing volume but because of the decrease in the energy consumption, which is forced by legal policies
System (Vacuum Forming process)	Production of process 3D polymer form shape is complex	This is a critical requirement, because it can influence the customer's decision. Moreover, the company should put additional R & D effort, not in terms of studying the process capable to increase the 3D volume form, but in terms of studying the process or alternative technologies capable to increase the flexibility of the process to produce different types of 3D forms and shapes.
	Production of process	This requirement should continue increasing if the company satisfies the demands from the super-system and more complex 3D forms.
	Size of 3D polymer form	Refrigerator volume should not increase; as a consequence the efforts should be focused on process flexibility and diversification of 3D form.
Sub-System (Process stages)	Extruder production	The extruder production can be influenced by modifications of 3D forms; a more complex 3D form can require more production time.
	Thickness of polymer	This requirement is decreasing, but it can influence other requirements considering two aspects: First, it is expected to continue reducing the material quantity to produce a more complex 3D form. Second, the thickness of the polymer can affect the forming stage and its performance, it is important to relate the complexity of the 3D form with the polymer thickness. The reduction of the thickness of polymers should not affect the energy consumption which is one of the main trends.
	Time to maintenance	It is decreasing, but adding more flexibility to produce 3D forms can influence the time required for maintenances.

4.1.5 Results: Vacuum Forming case study

The results of the application of the method have been useful to bring new knowledge to FORMAT-teamwork and related beneficiaries about vacuum forming technology, which they were not aware before (trend for refrigerator volume and performance). In detail, the average volume of refrigerators is not going to radically change in the next years and it is highly probable that it will stabilize on a constant value. Consequently, it means that the next choices at the organizational level would avoid considering the idea of substituting their forming machines just because the old ones are not capable of producing bigger refrigerators. The competition between forming machines will then occur on a different field, and more specifically in the complexity of the polymer shape (new forms and curve), but taking into consideration their impact in the energy consumption of refrigerators. This specific result about vacuum forming case study has been included in the final deliverable D4.5 of the FORMAT Project. Moreover, this result has been already published in (Cascini et al., 2014).

In terms of the method contribution for FORMAT-methodology, the proposed method has been useful to provide some amendments to the FORMAT-methodology. In detail, the most meaningful contribution has been for the identification of units by reusing the System Operator model during the Stage-A of the FORMAT methodology. The identification of the units has been allowed to extend the boundaries of the data gathering process rather than focusing the attention in a small set of "Performance Characteristic" for the technology under investigation (FORMAT-project, 2013).

4.1.6 Discussions and conclusions: Vacuum Forming case study

The aim of the method proposed in this PhD dissertation is to support design engineers to anticipate information about requirements. According to the objectives stated at the beginning of section 4.1., this case study helps to validate the contribution of the method in a real case study.

For what concerns the method application, the method was applied within the FORMAT-case study, and consequently, the main work developed by the author during STEP 1 and STEP 2 was related to the formalization of the description developed by FORMAT-teamwork. The author characterized the different items of System Operator by using the ENV model and related amendments from section 3.2.2. From the proposed estimation of the past value (STEP-3) was possible to start understanding the main changes among requirements and identify the potential data sources to support the next step (STEP-4). Nevertheless, significant limitations emerged regarding to data gathering process given lacks of internal data sources. The data provided by the FORMAT-partner were related to sporadic years, which did not allow developing an appropriate regression analysis, moreover, the data was mainly related to the economic aspects rather than technical aspects. During the classification of the requirements behaviour (STEP-4), the behaviour's classification helps to stimulate the thinking capability about the future, however, these classifications need to be enriched and confirmed with the expert's knowledge to provide a clear statement about the future of requirements. Finally, STEP-5, STEP-6 and STEP-7 allowed us to harmonize the new knowledge at different System Operator levels. Moreover, these steps allowed us to validate the overall forecasting with the participation of experts and beneficiaries.

From a qualitative viewpoint, the source of knowledge is essential to confirm the qualitative extrapolation more when the analyst is not an expert in the product/process to forecast. The presences of experts allowed to be more precise and accurate to understand the future of requirements. Nevertheless, the qualitative result seems to be less meaningful than quantitative results for experts, because qualitative trend emerges mainly by their own knowledge. In fact, during the case study the experts were more interested about quantitative than qualitative requirements.

From a quantitative viewpoint, the presence of experts can be reduced when the analyst has enough data to exploit requirements. Moreover, the quantitative trend seems to be more interesting than qualitative trends for experts. It was interesting to note that quantitative trends stimulate the discussion and conversation about the future requirements and also allow generating new ideas even beyond the forecasting analysis. However, to gather data from companies is quite difficult in the practice, even more, when is necessary to gather data series about technical aspects. From the case study, the FORMAT-partner mostly focuses its attention to save data for production and sells than technical. This situation confirms that technical data is a limited resource when it is required to understand the future of design requirements. Nevertheless, it is also worth noticing that a surprising outcome has been registered given the previous situation: once the results have been presented, the beneficiaries started to understand the relevance to save company data at different organizational level (not only economic). Since, the internal data availability held back the regression analysis during the method application.

The method has been applied during the FORMAT-project bringing at least two main contributions. First, the method provides new information about vacuum forming technology to the FORMAT-teamwork and related beneficiary, which they were not aware before. Second, the method brings new amendments to the FORMAT-methodology, which was further applied at second case study of FORMAT-methodology. For what concerns to the usefulness, the method also demonstrate to be capable of, at least, to support the anticipation of information for requirements and support the decision making process, thus addressing the "empirical performance validation" and partially "theoretical structural validity". Nevertheless, the usefulness depends largely from the initial knowledge of the beneficiary about the product/process and the new insight that the method can provide them as highlighted by Armstrong (2001).

Given the presence of the author in the FORMAT-teamwork, the method application has been developed mainly on the basis of the iterations within FORMAT-meetings; consequently, the presence of the author as an analyst has been crucial to contextualize the overall method application.

4.2 Case study in the context of cluster mining project: mining mill

A second case study is hereby presented to provide an example of the application of the method and confirms its applicability and viability in an industrial context. Specifically, where the product remains stable as a "commodity" and the process evolves to address the new demands from customers. The case study has been developed within the boundaries of Cluster Mining Project (www.clusterminero.usm.cl) and the Economic Development Agency (CORFO, for its acronym in Spanish). The second application of the method has been carried out with the support of experts of different mining companies from the north of Chile (i.e ATACAMA Region) to understand the evolution of requirements for one of the critical process equipment, in specific, the mining mill. Results among this collaboration between the university and companies have been already published on Nikulin et al. (2013). The method application is a complementary part of the previous obtained results.

This application devotes particular attention to the capabilities of the method to clarify the directions for product and process development for decision makers in an industry as the copper mining one. Moreover, it is interesting also to register the efforts required by analysts in the fulfilment of the different method steps, in particular for an industry where the time for innovation is quite long (Hilson, 2000). In order to understand the context of the motivation behind this case study a short introduction about Chilean mining industry is presented.

During this case study the author applied the method as an external participant with the Cluster Mining-teamwork. The main participation of the author with the Cluster mining-teamwork was for the elicitation of requirements, confirmation of trend analysis and cross-checking the forecasting results. Figure 22 presents the dynamic of the case study within the Cluster Mining project.

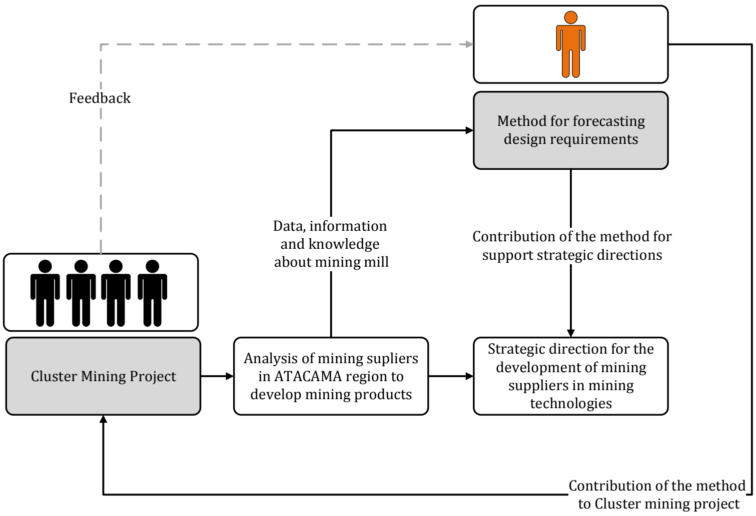


Figure 22: The dynamic of the case study within the Cluster Mining project.

4.2.1 Chilean Mining industry and the need for forecasting

Mining is widely view as an old industry with mature and stable technologies (Tilton and Landsberg, 1999) characterized by long life cycles (Bartos, 2007). As for other industrial fields, such as glass and cement, the major technological innovation discontinuities occur with very low frequencies with regard to high-tech sectors. These industries are intrinsically less technologically dynamic (e.g. in terms of lead times and market entry), but more capital-intensive (Bartos, 2007). Nevertheless, it would be more truthful to investigate the boundary conditions that influence and drive their innovation process, instead of distinguishing them only by the stage of maturity (McGahana and Silverman, 2001).

In the mining industry the lead-time to develop and commercialize new equipment is typically around 7–10 years (Hilson, 2000), while investing in new technologies often implies high capital R&D costs, because of the large scale and complexity of earthmoving equipment and the need to coordinate technology acquisition with mine-development plans (Peterson et al., 2001; Warhurts and Bridge, 1996). Such costs are too high for a single company to take on alone, while strong expertise is required to manage emerging technologies with questionable probability of success. Thus, it is not surprising that in such mature industrial contexts, economic factors usually tend to favour risk-averse technology decisions and short-term refinements that are mainly related to process control and optimization (Peterson et al., 2001). In addition, much of the present productivity advances in the mining industry (e.g. in drilling, transport, permitting and mine closure) have been originated from the outside, by suppliers and/or equipment manufactures rather than from in-house research and development (Azapagic, 2004; Bartos, 2007; Hood, 2004).

Hence, the mining industry can be seen as an integrated value chain involving a number of industry stakeholders (e.g. employees, contractors, suppliers, customers, local communities and authorities) (Bartos, 2007; Azapagic, 2004). Managing such partnerships is highly complex since each stakeholder holds a different perspective and represents a specific driver/factor to take into account (Andrews, 1998). Interestingly, this challenging situation can also act as a driving force to stimulate further technological advances in the following topics: sustainability, safety, and business ethics (Andrews, 1998). Moreover, the need for such advances also comes from the fact that the current productivity expansions have been originated from outside of the industry by means of equipment manufacturers and suppliers (Bartos, 2007). In fact, many innovations that occurred within the mining industry are adopted from other sectors such as construction, automobiles and aerospace (Peterson et al., 2001).

However, not having a full control of the technology evolution is detrimental to the mining industry: market opportunities are missed and difficulties arise in estimating long-term developmental implications, environmental impacts and costs of these technological advances throughout the entire mining process (Hilson, 2000). Moreover, while there is a general demand for placing high priority on improving equipment productivity and reliability (Peterson et al., 2001), more tailored products are needed in order to optimize each phase of operation, especially from the resource consumption point of view, being the mining industry one of the most energy-intensive industries in the world (Rábago et al., 2001).

This overview suggests that more research efforts are necessary in order to support the mining industry by:

- Correctly anticipating new technological innovations and scenarios;
- Properly setting development priorities and design strategies;

Chile is one of the largest exporters of copper worldwide: world production of copper mining in 2011 is estimated at 16.2 million Metric Tons of Fine Mineral (TMF), 32% of which corresponds to the Chilean production. Several studies report about the advancements promoted by the Chilean government to increase the perceived value of this complex industrial field (Tulcanaza and Ferguson, 2001).

Hence, considering these needs and the strong intent of the Chilean mining industry to find new structured strategies to be more and more competitive on the worldwide market, the resulting context has been seen as very attractive and appropriate for developing and testing the proposed method.

4.2.2 Elicitation of requirements at system, sub-system and super-system (STEP-1 and STEP-2)

The mining mill can be considered as one of the critical apparatuses of the mining process: it respectively influences its upstream and downstream activities and the overall productive capacity of the plant (in copper mining). The hardness and abrasiveness of the rock influence the performance and cost of the operations. The internal cavity of a mining mill is covered by plates/lifters that are designed to lift the load (i.e. the ore mixed with water and balls) during the mill rotation. Through the rotation of the mill the load undergoes lifts and falls, with a continuous crushing effect (see also Weir Slurry Group, 2009). Besides, the internal plates have also another function, that is: to protect the internal shell of the mill from the impacts generated by the rotating load. For these reasons, a failure occurring in these plates/lifters can determine the stop of the grinding process and the breakage of the mining shell. In this case study, "plates/lifters" are the elements of the technical system (i.e. the mill) that will be analysed.

The analyst and Cluster Mining teamwork (experts are included as well) agreed that the three main rows characterizing the system operator will be: the world production of copper that corresponds to the super-system, even if it can be considered a broad super system, the Cluster Mining consortium was interested in the results beyond the Chilean boundaries. Moreover, given the relevance of the Chilean mining industry in the world, this super-system definition was in agreement with the objective of the Cluster Mining consortium. The mill process, in specific mining mill equipment, was defined as the main system and its phases as the subsystem level of description (for more details about mining mill process please refer to Nikulin et al. (2013)).

For what concerns the requirement elicitation process, the requirements were collected intensively and considering different contexts and domains, potentially impacting in the milling equipment (e.g. technological, environmental, economic and social).

The requirements were elicited through an interview with the Cluster Mining teamwork related to the mining mill. The complete list of elicited requirements is presented in the Appendix-D. The requirements elicitation process have been carried out by following the above-presented steps (STEP-1 and STEP2), but with the presence of the author as analyst. Moreover, for this case study the author has a certain degree of expertise in the mining industry which simplifies the elicitation of requirements referred to the mining mill. The Cluster Mining teamwork has decided to take into consideration the Miller's (1957) theory to focus the attention in a manageable and meaningful number of requirements rather than a complex and extensive requirements list as presented in the appendix-D.

In Table 11 are presented the chunked requirements list considered by the Cluster Mining teamwork, in detail, a set of three requirements per system operator level were considered. Further, the requirements of the "Present (2014) Requirements" column (Table 11) have been chosen to stress the concept of the mutual relationships between different levels and contexts. For instance, the copper production (super-system level) is strictly related to the capacity of the mining mill (i.e volume of the mill), their efficiency, and availability (sub-system level) which, at the same time, is directly related to the quantity of liners, lifter, and mineral granulometry. Percentage of copper in the ore corresponds to a decrease value of the potential copper to be extracted by tonnes of ore. Finally, Table 11 presents the requirements to forecast given the consortium interest about mining mills.

The column with the heading " Present (2014) Requirements" collects elements and names for requirements while on its right it is possible to notice their units of measurements, following the logic from the ENV model, so as to directly suggest if the requirements are qualitatively or quantitatively measurable (STEP-1, STEP-2 and STEP-3).

Table 11: Requirements list of mining mill organized according to system operator framework after the chunking process.

	Past (1994)	**Present (2014) Requirements**	**Units**	**Qualitative/ Quantitative**	**Requirement behaviour (1994-2014)**
Super-System (Copper production and world context)	Lower	Copper Production	[ton/year]	Quantitative	Increasing
	Lower	Energy consumption of mining industry	[MW]	Quantitative	Decreasing
	Higher	Percentage of the copper available in the ore	[%]	Quantitative	Decreasing
System (mining mill)	Lower	Volume capacity of the mill	[m3]	Quantitative	Increasing
	Lower	Efficiency and availability	[-]	Quantitative	Increasing
	Higher	Maintenance time	[hr/year]	Quantitative	Decreasing
sub-System (mining mills components)	Higher	Quantity of liners	[Number]	Quantitative	Decreasing
	Higher	Quantity of lifter	[Number]	Quantitative	Decreasing
	Stable	Granulometry	[mm]	Quantitative	Stable

4.2.3 Identifying how were the requirements in the past (STEP-3)

All the above mentioned requirements (Table 11) were estimated according to the criteria proposed in STEP-3 by estimating a past value. The System Operator considered a period of time of ±20 years from the present, which is a reasonable elapsed time for this type of industry (Hilson, 2000). Given the knowledge of the analyst in the mining industry it was not necessary the involvement of experts during this step. Furthermore, the identification about how were the requirements in the past was supported on historical data and information retrieved by the author from different external data sources as: www.copperworldwide.com, www.minerals.usgs.gov/minerals, www.metso.com, www.flsmidth.com, www.portalminero.com and General Manual of Mining and Metallurgic (2006) (in Spanish). With this source of data and information, each requirement was evaluated according to the proposed classes (lower, stable, higher).

Moreover, for each requirement different data sources were explored to collect data series. Nevertheless, to collect data series was not possible for all the requirements presented in Table 11. The data series collected for regression analysis were related to the copper production (www.minerals.usgs.gov and www.copperworldwide.com) and capacity of the mining mills in terms of volume (red). With this data and information the next method step was developed.

4.2.4 Quantitative requirements and regression analysis (STEP-4)

During this step all the requirements (Table 11) were classified according to the behaviours proposed in STEP-4 (Section 3.4.3), the classification was supported by analysing the different above-mentioned sources of data and information. Several requirements have presented an "increasing" behaviour during the elapsed time.

Unfortunately, data availability held back the regression analysis during the method application for this case as well. In this scenario, only two requirements have enough data to provide a regression analysis, in detail, the copper production and mining volume. Nevertheless, it is important to understand the meaning of the logistic growth model for each of these requirements.

For what concerns to the copper production, it is important to clarify the meaning of the logistic growth curve. Whit this in mind, the hypothesis is the following: there should be a maximum capacity for copper production around the world; and it is interesting to know if this production capacity has been reached, or it is close to being reached. On this hypothesis, the logistic growth model has been applied to the cooper production to understand the limiting for the production capacity around the world. Figure 23 presents the copper production around world for mining production, independently from the country or where geographically the copper was produced, in detail, the percentage of production of Chile corresponds to the, at least 32% having a strong influence on the World mining production.

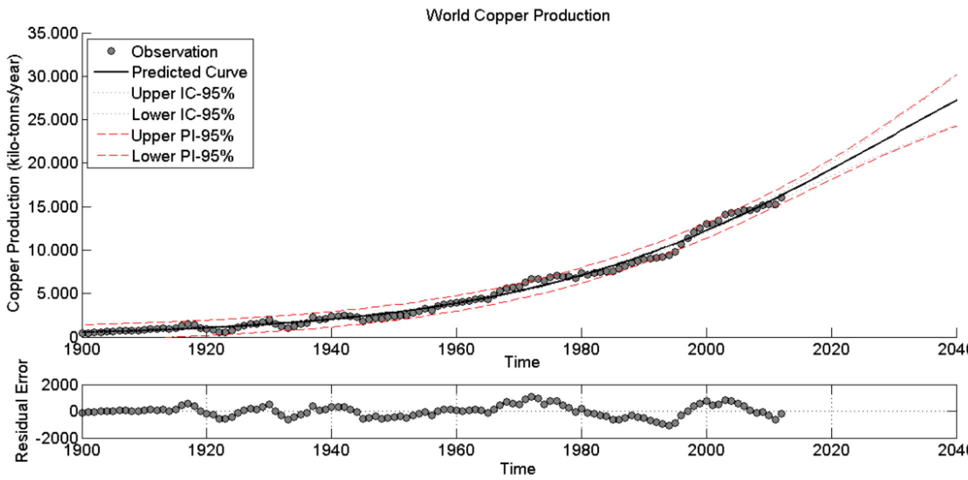


Figure 23: World copper production; Data source: USGS mineral information and cooper worldwide.

Please note that the statistical analysis, through which that regression analysis has been carried out (STEP-4), uses data from the last 115 years. For instance , the regression can provide better results together with the increased availability of data points from which the parameters characterizing the equation of the logistic curve can be regressed (as demonstrated in Appendix-A). Additionally, Table 12 shows the goodness of the fit for the regression analysis, in this case, the regression parameters are significant (p>0,01). Moreover, the r-adjusted is 99% supporting the regression quality as well.

Table 12: Statistical results for regression analysis of world copper production

Parameter	**Value**	**Statistical significance (p)**
Parameter of the regression		
World copper production	46836 [kilo-tons/year]	p<0,01
Period of time for 80% of the cycle [years]	128 years	p<0,01
Middle time when achieving his 50% [year]	2030 year	p<0,01
Results of the fit		
R-Adjusted [%]	99,0%	-

The same logic was followed to develop a regression analysis at the system level for what concerns to the mining mill, and in specific the volume of the mining mill. Considering the mining mill, it is straightforward that it cannot unlimitedly grow in height because of potential problems, mainly, the size of the place where the mining mill is located, putting in risk the overall mining layout (true for the underground mining, false for open mining). Furthermore, an unlimitedly growth of mining mill volume can bring potential problems to the maintenance and transportation given the size of the parts and components. With this in mind, the logistic growth curve has been applied to the mining mill.

It is worth noticing that despite both considerations: i) the volume of mining was increasing and ii) the meaning of the logistic growth model consistently with the evolution of the system, the simple logistic growth model was rejected by checking the statistic results (p-value < 0,1). Nevertheless, to exploit much as possible the logistic growth model a second regression analysis was formulated considering a bi-logistic model (Figure 24).

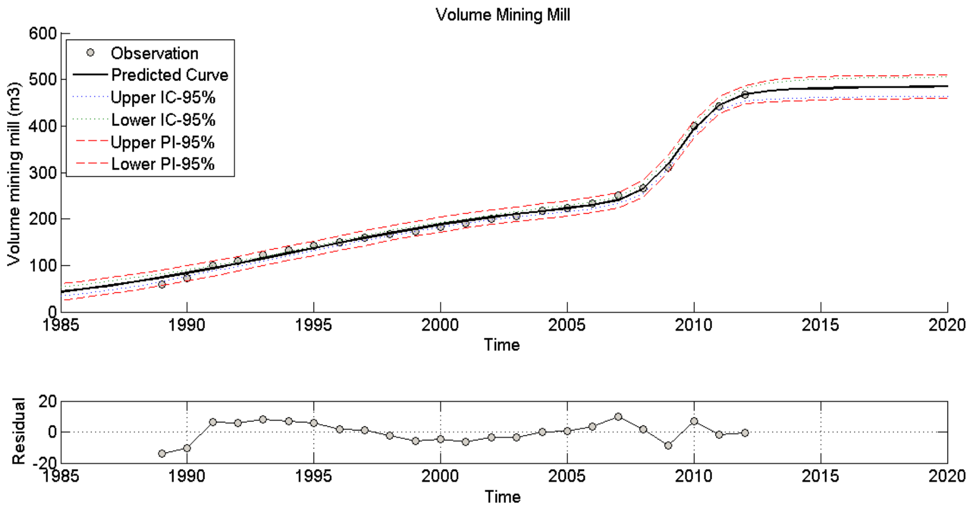


Figure 24: Mining mill volume trend based on bi-logistic growth model. Data source: Mining Magazine (2014)

With the bi-logistic model, the statistic was appropriate to represent the volume trends. In detail, all the regression parameters are significant (p-value < 0,01) and the r-adjusted is 98,5% supporting the regression analysis as well (Table 13). Hence, the application of the bi-logistic model becomes more meaningful under the confirmation with experts about the evolution of mining mill.

Table 13: Statistical results for volume of mining mill under assumption of bi-logistic growth curve.

Parameter	**Value**	**Statistical significance (p)**
Parameter of the regression		
LGC(1):Mining mill maximum volume	232,5[m^3]	p<0,01
Period of time for 80% of the cycle [years]	3,47 years	p<0,01
Middle time when achieving his 50% [year]	2010 year	p<0,01
LGC(2):Mining mill maximum volume	254,9[m^3]	p<0,01
Period of time for 80% of the cycle [years]	25,1 years	p<0,01
Middle time when achieving his 50% [year]	1994 year	p<0,01
Results of the fit		
R-Adjusted [%]	98.9 [%]	

By analysing the logic of bi-logistic growth model, according to the experts, two mill generations characterize the historical evolution of mining mill: the first generation of mining mills is characterized by the biggest mill, known as SAG mills. It was created around the 60's but started to be adopted in the last years of the 70's. The second generation corresponds to the Gearless SAG mill; it was conceived at the beginning of 90's but started to be adopted by companies after the 2000's. Moreover, considering the delay between developers and adopters highlighted by Hilson (2007) a gap between 7 to 10 years in the mining industry seems to be reasonable, at least for experts, the bi-logistic model. The two logistic growth are presented separately in Figure 25.

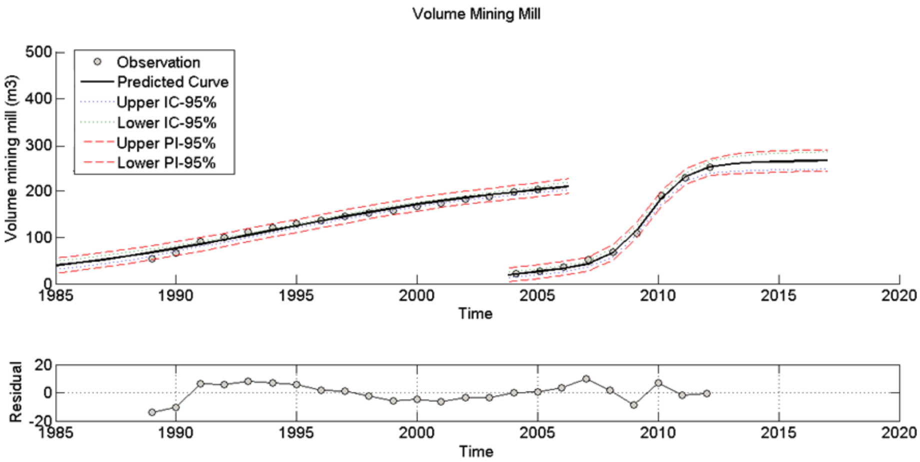


Figure 25: Mining mill volume represented by two simple logistic growth curves.

In the next subsection is presented the knowledge projection for the System Operator future screens.

4.2.5 Envision of the requirements at system level and cross-check value at system and sub and super system levels (STEP-5, STEP-6 and STEP-7)

In the last steps all the requirements were projected according to the criteria proposed in STEP-5, STEP-6 and STEP-7. According the availability of data, each requirement was projected one by one starting from system-level by the author, but then the projections were confirmed by the Cluster Mining-teamwork. At super system level, the projections were developed by one quantitative projection (volume mining mill) and two qualitative projections. Later, the projection of the super-system was developed by one quantitative projection (copper production) and two qualitative projections (Energy consumption and percentage of copper availability). Finally, the projection of the sub-system was developed only with qualitative projections.

The cross-check analysis was developed by comparing each requirement projection with the others at different System Operator levels. This cross-check analysis is to enrich the knowledge projections as recommended in section 4.2.5. Table 14 provides the complete knowledge projection about the future for the design requirements already collected in Table 11. Finally, the knowledge projections were validated with experts. Furthermore, new knowledge that emerged from the method application was used to drive strategic directions for the development of ATACAMA region in Chile.

Table 14: System Operator (future screens) envision according to the different requirements and their relations for mining mill case study.

	Present	**Future knowledge projection (Envision)**
Super System (Copper production and world context)	Copper Production	According to the logistic growth model the copper production is in a growing stage. The copper production is going to continue increasing during the next years. Companies need to be aware on how to satisfy the increased production (demand) for the next years.
	Energy consumption of mining industry	Energy consumption should continue decreasing in the next years.
	Percentage of the copper available in the ore	The percentage of the copper available in the ore is decreasing, and as a consequence, companies' need to increase their production efficiency to satisfy the expected production in the next years.
System (mining mill)	Volume capacity of the mill	The volume of the mining mills is saturated and it is not expected to continue increasing in the next years; the saturation capacity is achieved for both generations of mining mills (i.e SAG mill and Gearless SAG mill)
	Efficiency and availability	Companies need to put their resources into improving the overall efficiency of the mining mill. In terms of availability, the additional efforts are needed in order to reduce the maintenance time.
	Maintenance time	The maintenance time should decrease in the next years to satisfy the requirements from the super-system level. Additional efforts should focus into reducing the time consumption for the installation and maintenance of liners, plates and lifter.
Sub-system (mining mills components)	Quantity of liners and plates	The numbers of liners and plates have been decreasing in the last years; as a consequence, the maintenance time has been reduced as well. New innovations are required for this component to satisfy the requirements at system and super-system level.

	Quantity of lifter	The numbers of lifters have been slightly decreasing in the last years; as a consequence, the maintenance time has been reduced as well. Also in this component, new innovations are required to satisfy the requirements at system and super-system level.
	Granulometry	The granulometry of the ore remain stable.

4.2.6 Results: Mining mill case study

During this case, Figure 23 showed that the copper production is going to continue increasing during the next years, and is very likely that it will require more capacity of production in the mining companies to satisfy the expected production (demand). Moreover, the copper percentage in the ore is also decreasing; as a consequence, the overall production capacity can be decrease making it more difficult to satisfy the market demands. Furthermore, the volume of the mining mill is not expected to increase. In fact, the volume of the mining mill is in a saturated stage, so companies' resources might not be destined in the replacement of new equipment with bigger volume capacity probably because, according to the regression, this type of machines will not be available until a new generation of mining mills appear. According to the Cluster Mining Consortium, the analysis was useful to clarify the requirements for the selection of future mining mills, focusing their attention to look firstly mining mills with higher availability and lower maintenance time rather than the ones with a bigger volume capacity. Moreover, the analysis has been useful for the management of the consortium resources, in specific, focusing into increase the availability of the mining mill by reducing their maintenance time.

In this scenario, the results reported to the Cluster Mining-teamwork have allowed the definition of a more clear direction for the technological development and management of resources for mining mills. A clear strategy was defined to create solutions related to the liners, plate and lifter of mining mills with potential impact in the maintenance time and the mining mill availability. For example, a patent application in this direction has been further developed with given funds provided by Cluster Mining consortium (Chilean Patent nº: 201400660) (Nikulin et al, 2014). The patent application proposes a solution to reduce the failures in mining plates with potential benefits in the mining mill availability. It is important to mention that the research for this consortium is still in development according to proposed directions, in specific to reduce the energy consumption by improving lifter shapes.

4.2.7 Discussions and conclusions: Mining mill case study

The results of the case study point out the relevance of the technical improvement to satisfy the production trends in the mining industry. The presence of the author as an analyst has been, once again, crucial to the application of the proposed method so as to collect data from external data sources.

For what concerns the models used in the case study, the experts were not aware, before this case study, about the System Operator and their usefulness to understand the "system" at different hierarchical levels. Furthermore, the experts perceived that the System Operator is a useful and easy tool capable to provide a more meaningful and holistic representation of the analysed system than a simple list of requirements, because it stimulates in a positive way the analysis of causal relationship which Cluster Mining consortium considered as necessary to drive strategic directions. Nevertheless, the most interesting results for the consortium were about the trend of mining mill volume and the representation of this trend based on the bi-logistic growth model, because they were not conscious before about the specific path of evolution. The representation by the bi-logistic model motivated the discussion about potential new solutions capable to start a new logistic growth curve when one is reaching the maximum. However, further evidence about these ideas related to a new generation of mining mills, substituting the previous one, was not found.

For what concerns to the logistic growth model another limitation emerged, the application of a single logistic growth curve has difficulties to represent all the wide set of possible "increasing" behaviours, for example, when several data fluctuations exist. Nevertheless, the use of several logistic growth (as bi-logistic) seems to be a reasonable solution to overcome this limitation, but also it is important to check the meaning of the different logistic growth curves and statistic results as was presented in this case study for the mining mill.

With reference to the method, the mining mill case study has been used to validate the usefulness of the proposed method in a real case study, in specific to address the validation criteria related to "empirical performance validation" and partially "theoretical structural validity". The proposed method has been showed to be capable, in this case study, to clarify directions for product and process development and strategies towards to the conceptualization of solutions, which was further developed by a panel of experts of the Cluster Mining consortium and the analyst.

Another aspect to be further investigated in this research is about the method repeatability by design engineers without experience in forecasting. From this perspective, the next case study and test attempts to address this scenario.

4.3 Application of the method and test experiment with students

In this section it is presented a third case study prepared by the author to test the method proposal with design engineers without experience in forecasting. The aim of this case study is to validate the ability of the method to guide design engineers to forecast design requirements, and mainly those without experience in forecasting.

In this first subsection a case related to the washing machine is presented. It can be considered as an academic case study to test some of the proposed method's steps and software tool. In the second subsection, the same case study is used to validate the repeatability and usability of the proposed method with students from different countries, in this case from Italy and Chile. The test has been divided into three mutually correlated activities attempting to validate the "theoretical structure" and "capability of the method to guide design engineers without experience in forecasting".

4.3.1 Preparation of a Case study for academic purposes (Washing Machine)

This case study has been prepared to test the proposed method by design engineers without experience in forecasting. The preparation of this case study was based on the learned experience from the previous cases studies (vacuum forming and mining mill) and the literature review analysis about logistic growth papers. As concluded in section 3.3, the forecasting results and related usefulness largely depends on the initial analysts' knowledge about the system and available data source capable to be exploited. Consequently, the preparation of a meaningful case study needs to avoid as much as possible the above-mentioned limitations.

First, as mentioned in the discussions of the previous cases studies, the application of the method for forecasting design requirements requires a certain level of knowledge about the specific system to be analysed. Otherwise, the experts' presence is relevant during the method application to confirm the different steps' outcome (Section 4.1.6 and 4.2.6). With this in mind, the selection of a product/process for academic purposes needs to be a well-known product/process for the test. In this scenario, the washing machine is one of the most widely used home appliances around the world, therefore is familiar to almost everyone. In others words, the washing machine has been chosen to be used as an academic case study in an attempt to avoid as much as possible the presence of experts during the method application. This choice about the selection of washing machine as the system to be analysed avoids the action of giving details about the product to the test's participant.

Second, the author has developed by himself the case study of the washing machine in order to set up the initial data and information for the test. Moreover, the development of this educative case study can be considered as an additional case study as well. Nevertheless, the boundaries of the forecasting results are mainly related to the validation of the capabilities of the method to guide design engineers without experience in forecasting rather than the specific future of the washing machine.

The next subsection describes the process followed by the author in order to prepare the complete academic case study to validate the following criteria:

A. Theoretical structural validity (Pedersen et al., 2000):
   i. Individual constructs constituting the method.
   ii. Internal consistency of the way the constructs are put together in the method.
B. Capability of the method to guide the design engineers without experience in forecasting:
   i. Usability of the time perspective to forecast requirements.
   ii. Capability of the method to provide new insights and conclusions about product/process requirements.
   iii. Effectiveness of the method to be transferable to design engineers independently from the adopted product development process.

4.3.1.1 Preparation of a Requirements list at system, sub-system and super-system level (STEP -1 and STEP-2)

The requirements list was obtained by the author from the example for washing machine proposed by Becattini (2013), in specific from "the set of criteria for elicitation of requirements from tacit knowledge" (Section 3.2.2- Becattini' Phd thesis). Moreover, the requirements list has been enriched with others requirements collected from technical speciation of main suppliers of washing machines (e.g. Whirlpool and Samsung). Additionally, others requirements have been collected from Energy Star (2014) which is an international standard for energy efficient consumer products originated in the United States. The standard was created in 1992 by the Environmental Protection Agency and the Department of Energy (Energy Star, 2014). Since then, several countries around the world and the European Union have adopted the program[1].

The complete requirements list is presented in appendix-E. Furthermore, an additional description has been included as well to support the testing' participants with possible lacks of knowledge about these requirements. Given the long requirements list from appendix-E, a chunked requirement list has been

[1] https://www.energystar.gov/index.cfm?c=partners.intl_implementation

prepared according to Miller's (1956) theory so as to obtain a manageable and simple requirements list for the test. The requirements were organized at the different System Operator levels: super-system (e.g. European home), system (e.g. washing machine), sub-system (e.g. parts and elements). Moreover, the author prepared a simple (well-known) requirement list to avoid as much as possible the lacks of knowledge about requirements (Table 15).

Table 15: Requirements list of washing machine organized according to system operator framework after the chunking process.

	Past (2004)	**Present (2014) Requirements**	**Units**	**Qual. or Quant.**	**Requirement behaviour (2004-2014)**
Super-System (Home in the boundaries of Europe)	Higher	Available time to wash clothes	[hrs],[min]	Quantitative	Decreasing
	Lower	Quantity of clothes per person	[Number of clothes per person]	Quantitative	Increasing
	Slightly larger	Available space to install WM at home	[m^2]	Quantitative	Slightly decreasing
System (washing machine for home)	Lower	Load capacity	[Cubic_feet], [m^3]	Quantitative	Increasing
	Higher	Energy consumption	[KWh per year]	Quantitative	Decreasing
	Higher	Cycle time	[hrs],[min]	Quantitative	Decreasing or fluctuating
Sub-system (Parts and elements)	Lower	Quantity of detergent	[gr], [ml]	Quantitative	Decreasing
	Less	Recyclability of the part[2]	[Level of recyclability]	Qualitative	Decreasing
	Lower	Integrity of the clothes after the washing process	[Quality of the cloths]	Qualitative	Increasing

4.3.1.2 Identifying how were the requirements in the past (STEP-3)

All the above mentioned requirements Table 15 were assessed according to the criteria proposed in STEP-3, by estimating a past value for each of them. Concerning to the definition of time for System Operator, it is worth noticing that a home appliance company as Whirlpool has taken into account a timeframe for the introduction of new technologies of 3 years for manufacturing technology and 4/5 years for products related to that technology (FORMAT- deliverable 2.1). Moreover, the testing' participants had to rely on their personal knowledge about the system; as a consequence, changes have to be recognized by them in the product. In this scenario, the lapse of time proposed by the author corresponds to

[2] This requirement is used to understand if washing machine parts are going to be recycled more or less into the future.

±10 years, which seems to be enough timeframe to recognize products changes from the different test's participants, in specific for young design engineers.

During the gathering data process of requirements, it was possible to obtain data only for two requirements (in specific for load capacity and energy consumption of washing machine). In fact, these lacks of data can limit the validation of method's features and software tool during the test. In an effort to overcome the lacks of data for the test, new quantitative parameters have been added which are not strictly design requirements. Two economic parameters have been added to supply the lacks of data at super-system level. Nevertheless, these parameters have a strong influence in the future of home appliances products as suggested in the Brundtland report (World Commission on Environment and Development, 1987). These parameters are presented in Table 16.

Table 16: Additional economic parameters used to exploit the data available for the washing machine case study.

	Past (2004)	**Present (2014) Parameters**	**Units**	**Qual. or Quant.**	**Parameter behaviour (2004-2014)**
Super-System (European Market)	Lower	Market indicator for WM in Europe	[Percentage]	Quantitative	Increasing
	Lower	Number of WM sold in Europe	[Number of products]	Quantitative	Increasing and fluctuating

Furthermore, two more requirements were added at the level of system to be analysed quantitatively in the next step of the method (Table 17). Even considering that requirements were obtained initially from STEP-1 and STEP-2, these have been reused for further analysis given data availability. In detail, these two requirements were collected from the "Energy Star" website[3] and are related to the requirements for washing machine.

Table 17: Additional requirements used to exploit the available data sources for the washing machine case study.

	Past (2004)	**Requirement Present (2014)**	**Units**	**Qual. or Quant.**	**Requirement behaviour (2004-2014)**
System (Washing Machine)	Higher	Water Factor	[Total weight per cycle/capacity of clothes]	Quantitative	Decreasing
	Lower	Remain Moisture[4]	[Percentage]	Quantitative	Decreasing and fluctuating

At the end of this step, the requirements list has been enriched with new requirements and parameters in an effort to collect enough data to assess the different method features and tools. The requirements and parameters with data

[3] https://www.energystar.gov/index.cfm?c=clotheswash.pr_crit_clothes_washers
[4] This parameter is used by ENERGY STAR in order to understand how much energy is necessary to remove the clothes' moisture.

correspond to: load capacity, energy consumption, water factor, remain moisture and European market indicator. This data will be used to develop the regression analysis in the next method's step.

4.3.1.3 Quantitative requirements and regression analysis (STEP-4)

In this step, all the requirements and parameters from previous steps were classified according to the behaviours proposed in STEP-4 (Section 3.4.3) by using the historical tendencies that the requirements themselves have presented through the elapsed time.

Given the criteria provided for the identification of logistic growth candidates in section 3.4.3, the washing machine load capacity corresponds to the initial candidate to behave logistically (increasing behaviour) if compared to the other elements in the restricted set of presented requirements. Nevertheless, according to STEP-4 (ii-a) a clarification of the meaning is required before providing a logistic growth analysis. In fact, considering the dimensions of the washing machine, it is straightforward that theoretically the washing machine can unlimitedly grow in size, at least, from a technical aspect. However, there might be limitations at homes to have bigger washing machines, for example: space; quantity of clothes to wash, others. Consequently, it is interesting to know how it has been changing the load capacity until reaching a possible maximum constrained by some limiting resource.

The washing machine data was collected from the Energy Star database (2014), which collects data independently of where the washing machine was produced. Moreover, the raw data was treated according to how the Association of Home Appliance Manufactures (AHAM, 2014) monitors the historical home appliances improvement, which is based on the average per year. This data treatment allowed exploiting the logistic growth model to understand how the average load capacity of washing machine has increased in the recent years. In Figure 26 it is presented the logistic growth model for the average load capacity of washing machine.

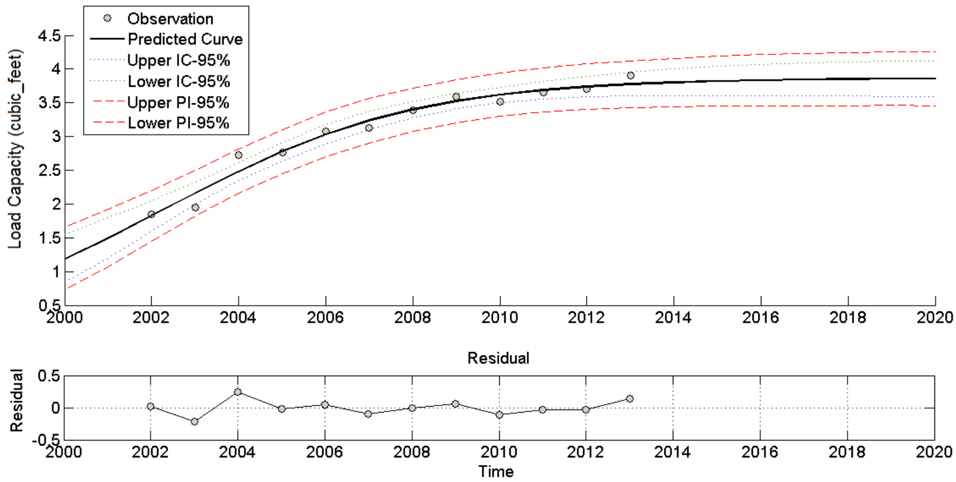


Figure 26: Average load capacity of washing machine per year; Data source: Energy California Commission(2014).

For what concerns the statistics, the results are considered as acceptable according the p-value of the different regression parameters. Nevertheless, the confidence interval in this case is quite large due to the few points available compared with the other case studies. The r-adjusted is 96,1% therefore supporting the regression acceptability as well (Table 18).

Table 18: Statistic results for regression analysis for average load capacity of washing machine.

Parameter	Value	Statistical significance (p)
Parameter of the regression		
Load Capacity of WM	3,87[cu_feet]	p<0,01
Period of time for 80% of the cycle [years]	12,6 [years]	p<0,01
Middle time when achieved his 50% [year]	2002,3[year]	p<0,01
Results of the fit		
R-Adjusted [%]	96,10%	-

As mentioned before, given the lacks of technical data, the use of economic parameters with enough data is important for testing the method features and software tool. In fact, the logistic growth model is widely used to understand the evolution of different economies as presented in appendix-B. Moreover, several authors pointed out that the market evolution can also be represented by logistic growth models by means of a proper treatment of data (Cantono et al., 2009; Christodoulos et al., 2011; Shafiei, et al., 2012). From the gathering data process, raw data was obtained about the European Market for washing machine. This data was treated (normalized) starting from the first year existing in the data series, which correspond to 1990. In others words, the treated data have been used to understand if the European Market for the washing machine is going to reach a maximum or if it is close to do so. On this basis, in Figure 27 the logistic growth model applied to the data of European Market for washing machine is presented. In detail, the Y-axis represents the relative percentage that the European Market has been growing since 1990. The statistic results presented in Table 19 are significant for each parameter (p<0,01). Moreover, the r-adjusted is 97,63%, thus confirming the acceptability of the regression. However, given some fluctuations of data points during the analysed timeframe, the application of the bi-logistic model has been also explored. Even so, the statistics from bi-logistic model are not sufficient to accept the hypothesis that the European Market parameter grows bi-logistically (the p-value for the different regression parameters as K (1); Δt (1), K (2) and Δt (2) are higher than 0.1).

Table 19: Statistic results for regression analysis for European Market.

Parameter	Value	Statistical significance (p)
Parameter of the regression		
Market indicator	47,38 [Percentage]	p<0,01
Period of time for 80% of the cycle [years]	17,40 [years]	p<0,01
Middle time when achieved his 50% [year]	1999,77[year]	p<0,01
Results of the fit		
R-adjusted [%]	97,63%	-

As a result, as shown in Figure 27, it seems that the European Market for washing machines will be saturated in the next years, or in other terms, in the next future it is not expected a large growth. With this in mind, it is important to explore the causes that produced the saturation. As for instance, one of the reasons may be that mostly all European families have a washing machine today, thereby limiting the market growth.

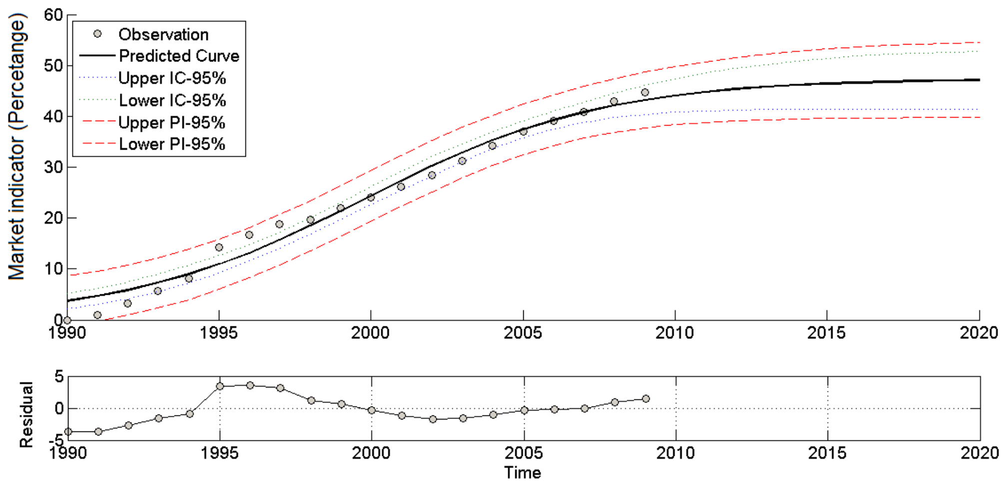


Figure 27: Relative percentage of European Market growth for washing machine since 1990. Data source: Eurostat.

For what concerns the remaining requirements with data, those requirements have been characterized with a “decreasing” behaviour according to the proposed classification (Section 32.), in particular the energy consumption, water factor and remain moisture have been decreasing in the last years.

Given the recommendations to exploit the logistic growth model presented in section 3.3., several performance indexes have been created by combining two requirements. The first performance index was created based on the proposed combination in Figure 14 (Combination A/C). For this performance index, the washing machine load capacity requirement was divided by the energy consumption requirement allowing to obtain an "increasing" behaviour by the combination of them. Nevertheless, a clarification of the meaning is required before providing a logistic growth curve analysis. In fact, the washing machine not going to unlimitedly grow as presented in Figure 26. Moreover, the energy consumption cannot be reduced beyond a minimum level in order to maintain the washing process. Consequently, the performance index should not unlimitedly growth since it is limited by resources. Based on this idea, the logistic growth model seems to be an interesting analysis to explore the potential trend for this performance index. In Figure 28, it is presented the regression analysis for the performance index (Load capacity/energy consumption) based on the logistic growth model.

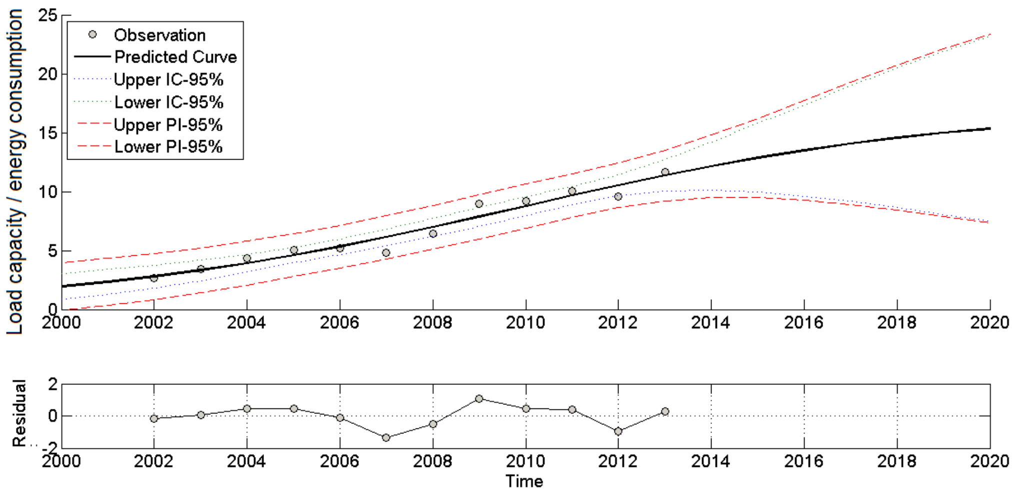


Figure 28: Performance created by the average load capacity of washing machine and average energy consumption per year; Data source: Energy California Commission (2014).

In Table 20, it is presented the goodness of the fit and the regression. In this case, the statistic results are not so appropriate in order to directly accept the suitability of the logistic growth curve as in the previous case studies. On the one hand, the accuracy of this performance index can be considered questionable given the large confidence interval. This situation may be a consequence of the few data points available and the fluctuation of the data points during the elapsed period. On the other hand, the Saturation Parameter (K) is slightly appropriate from a statistic point of view (Table 20). Nevertheless, the author believes that the logistic growth model can represent in a better way the data behaviour, if compared with other regression models. This can be inferred for the following reason: the previous logistic growth model (Figure 26) showed that the load capacity requirement has reached a maximum so this performance index is not going to grow necessarily by increasing the load capacity. On the contrary, the energy consumption is a straightforward requirement for the washing machine improvement. However, the energy consumption cannot be reduced beyond a minimum level in order to maintain the washing process. Consequently, the logistic growth model seems to be a more reasonable regression to represent the evolution of this performance index with respect other regression models.

Table 20: Statistic results for regression analysis for created performance (load capacity of washing machine/energy consumption)

Parameter	**Value**	**Statistical significance (p)**
Parameter of the regression		
Load capacity of washing machine/ energy consumption	17,12 [cu_feet/ KWh per cycle]	0.01<p-value <0.05
Period of time for 80% of the cycle [years]	20,88 [years]	p<0,01
Middle time when achieved his 50% [year]	2009,77[year]	p<0,01
Results of the fit		
R-Adjusted [%]	95,59%	-

The second performance index was created based on the proposed combination showed in Figure 14(Combination A/C). The new performance combined the load capacity and water factor; it is presented in Figure 29. This performance index showed an “increasing” behaviour, but a clarification of the meaning is required before providing a logistic growth curve analysis. In fact, the load capacity of the washing machine not going to unlimitedly grow as presented in Figure 26. In addition, the water factor cannot be reduced beyond a minimum level (true for conventional washing machine, false if new solutions emerge without using water). Consequently, the author believes that the logistic growth model seems to be an interesting analysis to explore the potential trend for this performance index to understand if it is going to reach the saturation or if it is close to do so by using this performance index. In Figure 29 the regression analysis for the performance index (Load capacity/water factor) based on logistic growth model is presented.

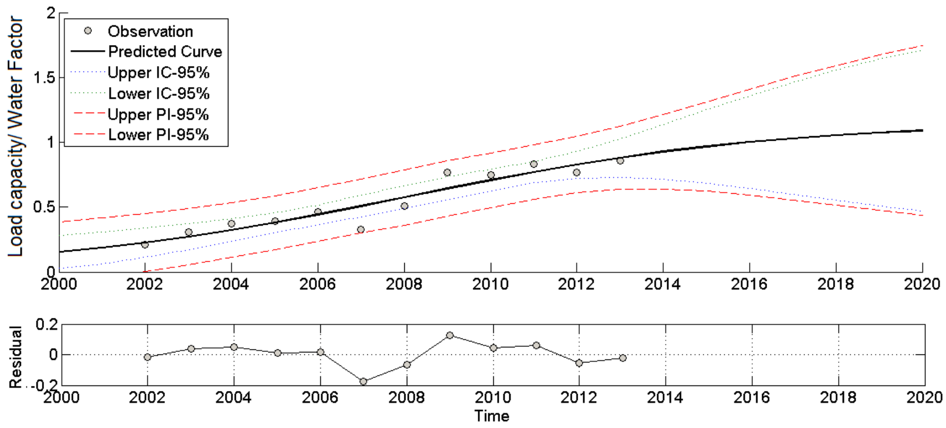


Figure 29: Performance created by the average capacity of washing machine and average of water factor per year; Data source: Energy California Commission.

In Table 21 it is showed the goodness of the fit related to the regression analysis. For this case, again, the statistic results are not so appropriate in order to directly accept the suitability of the logistic growth curve as in the previous case studies. However, as previously discussed, it is not expected that the load capacity continues to grow in the next years and, hence, the water factor cannot be reduced up to a minimum level, at least, for conventional washing machines. In this scenario, the logistic growth model seems to be a more reasonable regression to represent the evolution of this performance index rather than other regression models as linear and exponential. In detail, this performance index is close to reach the saturation level.

Table 21: Statistic results for regression analysis for created performance (load capacity of washing machine/water factor)

Parameter	**Value**	**Statistical significance (p)**
Parameter of the regression		
Load capacity/ Water Factor	1,15 [cu_feet/ gallons per cycle per cubic feet]	0.01<p-value <0.05
Period of time for 80% of the cycle [years]	19,02 [years]	0.01<p-value <0.05
Middle time when achieved his 50% [year]	2008,05 [year]	p<0,01
Results of the fit		
R-Adjusted [%]	89,0%	-

From what concerns to the remain moisture, the data available was with several “fluctuations” during the elapsed time, as a consequences, the applicability of the logistic growth model was limited and rejected(p-value>0,1).The next subsection presents the knowledge projection for the System Operator (future screens) by considering the economic parameter and requirements.

4.3.1.4 Envision of the requirements at system level and cross-check value at system and sub and super system levels (STEP-5, STEP-6 and STEP-7)

During this step all the elements of the System Operator were projected by the author according to the criteria proposed in STEP-5, STEP-6 and STEP-7. The knowledge projection was developed to understand the future of the requirements for the washing machine (Table 22). According to the different results of the regression analysis developed in the previous steps, the load capacity of the washing machine showed to be in the saturated stage. Therefore it is not expected that the washing machine is going to increase more in terms of size in the next years. The efforts of the washing machine producers should not be focused on further increasing the capacity of washing machine. Instead, they should be aware of how to reduce the energy consumption and water factor. For instance, the performance concerning the load capacity and energy consumption is in a final growing stage. Moreover, the energy consumption is forced to be improved mainly by law regulation (Energy California Commission, 2014). Therefore, improvements towards this direction are required. Finally, the performance (capacity/water factor) is also increasing, and it is now close to the saturation stage as well. The knowledge projections and conclusions emerged from these steps are in Table 22.

Table 22: System Operator (future screens) envision according to the different requirements and their relations for washing machine case study.

Level	Requirement	Knowledge projection (Future)
Super-System (Home and Washing machine Market)	Market in Europe	Almost saturated, it is not expected a significant growth in the next years. The market should remain almost stable until a more innovative change in washing machine appears.
	Number of WM sold in Europe	Given that the European market is not expected to increase during the next years, it is not expected a significant growth in the number of sales in this geographical region. Given that almost all European families have a washing machine, the number of sales is mainly driven by the substitution of the old washing machines.
	Available space to install washing machine at home	Strongly related with the capacity of the washing machine. The load capacity is not expected to grow for the next years. Due to nowadays conditions, it is expected to slightly decrease or remain stable.
System (Washing Machine)	Load capacity	Load capacity should not increase in the future; the saturation capacity is achieved. However, it is strongly related to the available space at home; so design engineers need to be aware of how the available space for these appliances at home is changing.
	Energy consumption of WM	Energy consumption has been decreasing in the last years. This is mainly due by governmental regulations and standards and it is strongly related with the capacity of the washing machine and its water consumption (Energy Star, 2014).
	Water Factor	The water factor has been decreasing during the last years. It should further decrease in the next years.
	Performance index: Capacity/Energy consumption.	Load capacity is not expected to be increasing in the future. Future solutions should be focused on decreasing the energy consumption rather than increasing the load capacity. This performance is in a final growing stage, but it should continue increasing by the reduction of the energy consumption.
	Performance index: Capacity/Water factor	Load capacity is not expected to be increasing in the future. Future solutions should be focused on decreasing the water consumption rather than increasing the load capacity. This performance is in a growing but close to saturated stage; it should slightly increase, but caused by decreasing the water consumption. Nevertheless, some alternative washing machine have emerged in the last years by using the concepts of particles and less water quantity, known as "waterless" washing machine (www.xeroscleaning.com)
Sub-System (Parts and elements)	Remain Moisture	This requirement is related to the quantity of water used for the washing cycle; it should continue decreasing in the next years.
	Recyclability	Level of recyclability should continue increasing in order to satisfy environmental policies.
	Integrity of the clothes after the washing process	Integrity of the cloths should continue improving, but using less quantity of water during the washing process.

4.3.1.5 Results: Washing machine case study

Given the absence of a final beneficiary, the results are mainly related to the new insights and conclusions that the method can bring to the analyst. In detail, the application of this educative case study allowed to bring new insights about the future of washing machine, of which the author was not aware before, related to the market and technology.

Furthermore, the proposed criteria for STEP-4 has allowed exploiting better the quantitative data, which has not necessarily an "increasing" behaviour, for example, the energy consumption and water factor. The logistic growth curves related to the two created performances allowed understanding the direction for improvements related to the traditional washing machine.

Given the absence of a beneficiary in the last steps, the author searched for some evidence to support and confirm some of the knowledge projections. As results, several regulatory laws were found to support the need to reduce the energy consumption. As for instance, this year should appear a new regulation from Energy Californian Commission (2014). Secondly, a new alternative solution has been found to reduce the water consumption as "waterless" washing machine (www.xeroscleaning.com). On this basis, this overall information enriched the knowledge of the author about washing machines. Nevertheless, there is no available information about the potential performance of this new type of washing machine, which can end up being limited for its suitability to be adopted in the future.

Finally, this case study has been used to test specific method's step in order to understand the capability of the method to guide design engineers without deep knowledge in statistics.

4.3.1.6 Discussions and conclusions: Washing machine case study

This case study has been useful to explore the method application with the purpose to understand the future of a technology beyond a specific beneficiary. Moreover, the data collected from this case study will be useful to test the different steps of the method and software tool proposed in this research.

For what concerns to the method application without the presence of a beneficiary, the elicitation of requirements was based on Becattini's approach, but enriched with technical specifications from the main suppliers and regulatory associations as Energy Star (2014)(STEP-1 and STEP-2). The author prepared a simple chunked requirements list to avoid the presence of technological experts. Nevertheless, during STEP-3 the lacks of data for those requirements forced to change the requirements list to forecast. The new selection of requirements was based mainly on the availability of data, allowing to prepare, at least, a reasonable test to validate the different method's features and software tools. In this scenario, economic parameters were added to the requirement list as well.

In STEP-4 the different quantitative requirements were forecasted on the basis of the proposed criteria (Section 3.4.3). From this step, four logistic growth curves were developed. On the one hand, two logistic growth curves were strongly supported by statistic results (load capacity and European market indicator). On the other hand, two logistic growth curves were slightly supported by statistic results. Nevertheless, the author pointed out the reasons why these two performance indexes are appropriate to be accepted as logistic growth curves.

In the STEPS 5, 6, 7, the author forecasted the different requirements and economic parameters to understand the future of the washing machine. The knowledge projection was created based on the presented criteria. Moreover, the author explored some alternative solutions according to the direction of improvements which an alternative solution in that direction was found (e.g. "waterless" washing machine).

In general, the presence of experts during the forecasting process is relevant to support and confirm the knowledge projection. Otherwise, the usefulness of the forecasting mainly relies on the new knowledge that the forecast can bring to the analyst. In that case the analyst becomes at the same time the main beneficiary of the forecasting. Even so, these two viewpoints are valid in the practice to assess the forecasting results.(Armstrong, 2001).

The preparation of an educative case study has been useful to confirm that data are an essential part of the forecasting analysis and they are more important when the analyst has lack of knowledge about the product/process to forecast. The next subsection presents a test to validate the specific features of the method and software tool by reusing the collected data from this case study.

4.3.2 Testing of the method and software tool to forecast design requirements

In this section, it is presented the organization of the testing activities to validate some of the proposed method's steps and software tool. This test attempts to validate all the steps except those sub-steps related to the elicitation of requirements and gathering data. The author decision emerged at least for two reasons. First, methods for elicitation of requirements have been fairly studied and tested in (Becattini, 2013). Second, data gathering is a specific sub-step which is beyond the method's capability since it depends mainly in the availability of data sources during the analysis. Consequently, this test attempts to validate the novelties proposed by the author in this PhD research. In this scenario, the test has been divided into three parts: i) Control group test in order to compare a forecasting process and results developed by different groups of students (with and without the method proposal); ii) estimate the suitability of methods and models adopted for the method proposal to forecast design requirements; iii) identify which are the more demanding tasks during the method application by students.

The test has been performed twice in two different places around the world. The first test was carried out in Italy at Politecnico di Milano. The same experiment was repeated in Chile at Universidad Técnica Federico Santa Maria.

4.3.2.1 Participants of the testing activity

Regardless to the testing activity, the test was performed in two different countries, Italy and Chile. The first test was performed by 24 Master Degree students (all male) of the Mechanical Engineering School of Politenico di Milano (Milan, Italy). The test was developed in English language. Then the same test was repeated in Chile, and it consisted in a testing session performed by 14 Product Engineering students (10 female and 4 males) of the Industrial Department at Universidad Técnica Federico Santa María (Valparaiso, Chile); the test was developed in Spanish language.

These groups of students were selected to check the third validation criteria related to the capability of the method to guide design engineers without experience in forecasting. Moreover, they represented a sample of convenience and widespread for the testing activities within the design field (Lemons et al., 2010). A total of 38 healthy participants took part in the overall study. All of these students received some lectures to introduce them partially about TRIZ (i.e System Operator) and forecasting in their respective language, Italian and Spanish. However, those students cannot be considered as TRIZ practitioners or neither forecasters whose experience could have consistently affected and impacted on the method. Furthermore, students did not receive payment for the participation in this test.

4.3.2.2 Test: Control group test

A test was designed in order to determine whether the method for forecasting and software tool to support the process could actually and significantly help the user to develop a forecast for design requirements. Nevertheless, given the highlighted issue about the availability of data, the author has decided to provide a predefined list of requirements and data about requirements attempting to reduce the limitation of data availability highlighted from previous experience on the different cases studies. The version of the method created for this test is presented in the appendix-H (7.8.1.).

The same test was performed twice, the first time in Italy (24 students) and later in Chile (14 students). A total of 38 students (28 male and 10 female) participated in the overall experiment. Each test was organised as follows: one group who performed the forecasting aided by the method discussed in this doctoral dissertation (i.e. Group-B), and another group who was free to use any method that they considered useful to develop the forecasting analysis (i.e. Group A). The students were asked to perform a forecasting analysis for several requirements of the washing machine. The requirements list provided to the student is presented in appendix-F. Figure 30 presents the description of the experiment through an IDEF0 representation. According to Figure 30 the following aspects have to be considered:

- Both groups, A and B, received as input the same requirements (i.e. 8 requirements and 2 economic parameters) for washing machine considering a set of both, quantitative and qualitative items; moreover, they received data for 4 out of the 8 design requirements and 1 out of 2 economic parameters.
- Both groups had the opportunity to choose among the different available software tools and pick which one to use in order to develop the regression analysis, for instance: IIASA, Loglet and FORMAT-prototype.
- Only group B had to compulsory use the method proposal, so that students were compelled to follow the steps proposed by the method, without any support more than a prescriptive guideline (Appendix-H).

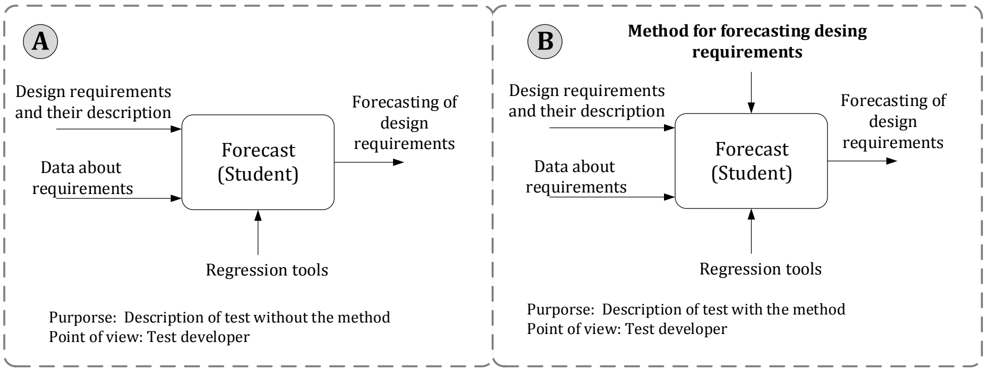


Figure 30: Description of the control group test through an IDEF0 representation

The test was conducted with the same time constrains; 90 minutes for both groups in the two countries. The test was set up to evaluate the proposed outcomes in terms of:

- Perception of usefulness of forecasting in order to drive conclusions about design requirements.
- Effectiveness to develop an appropriate forecasting analysis by assessing the Martino's (1993) elements.
- Suitability of the proposed software tool:
  - Selected software used to develop the regression analysis during the forecasting activity.
  - Perception of the usefulness of logistic growth model to develop the regression analysis.

The entire above-mentioned outcomes were set up by using paper and pencil trough a questionnaire (Appendix -G) and an answers' folder at the end of the 90 minutes. Before starting the description of the results, it is important to mention that results of the different countries (Italy and Chile) were polled together so as to obtain a whole evaluation.

4.3.2.2.1 Test: Results (Control group test)

For what concerns the perception of usefulness of the forecasting analysis, most of the students perceived that forecasting helped them to gain new insights about the product. In detail, 90% of students from group-B (with method) have evaluated positively the use of forecasting to anticipate information about product requirements. At the same time, 84% of the students from group-A (without method) have evaluated positively the use of forecasting (Table 23). Furthermore, students also perceived that their conclusions at the end of the experiment could not have been reached without the aid of the forecast. From group-B (with method), 64% of the participants believed that they cannot develop those conclusions without a forecast activity. From group-A (without method), 69% of the students believed they cannot develop those conclusions without forecasting aqnalysis. In terms of the perception of usefulness, 95% of participants from group-B (with method) perceived that their results are valuable to understand the product evolution. From group-A (without the method), 84% of the students perceived that their results are valuable to understand the product evolution

Table 23: Summary of the students' evaluations about forecasting analysis and their perception of usefulness to bring new insight about the product. (Green box = positive evaluation; red box = negative evaluation)

Perception of usefulness of the forecasting	**Group**	**Definitely no**	**Probably no**	**Probably yes**	**Definitely yes**
Does the forecast help to gain new insights about the product future?	without	5%	5%	**74%**	**16%**
	with	0%	16%	**68%**	**16%**
Do you have arrived to these conclusions without doing the forecast?	without	**11%**	**53%**	37%	0%
	with	**11%**	**58%**	32%	0%
Do you value the results of forecast as useful?	without	0%	16%	**63%**	**21%**
	with	0%	5%	**79%**	**16%**

These results showed that forecasting analysis is perceived as useful to understand the future of requirements, independently from which approach is followed to develop the forecasting analysis. In other words, the anticipation of information about product by itself is perceived as useful, at least for the tested case study. Nevertheless, these above-mentioned students' answers are not strictly related to the quality of the results delivered for them. On this basis, the students' outcomes were analysed according to the essential elements proposed by Martino (1993) to understand how the forecasting analysis was carried out by them. It is important to recall that the quality of the forecasting results largely depends on how the forecasting analysis was developed (Martino, 1993). With this in mind, Table 24 summarizes the number of students in percentage who have developed the activities according to Martino's elements. In detail, the students without the method did not produce any valuable analysis for at least one of the two first Martino's elements (i.e. Technology being forecast and the statement of the characteristic of the technology). The analysis of the product statement was almost neglected by the students without the method.

Table 24: Summary of the number of students in percentage whom have developed the activities according to Martino's elements

	How was the forecasting process set up	**Group-A (without method)**	**Group-B (with method)**
Technology being forecast	Organizing requirements and their hierarchical relationship	5%	**89%**
The statement of the characteristics of the technology	Estimating how were the requirements in the past	5%	**84%**
The period of forecast	Understanding the behaviour of the requirements	0%	**74%**
	Developing a regression analysis for two increasing variables.	100%	**100%**
	Creating performances to exploit data available	5%	**89%**
Statement of probability associated to the forecast	Envisioning quantitative variables (Load capacity and European Market)	100%	**100%**
	Envisioning performance indexes	5%	**84%**
	Envisioning the remaining qualitative requirements	68%	**63%**

In terms of the validation criteria stated at the beginning, and in particular the capability to develop an appropriate forecasting analysis, the students from Group-B were capable to deliver better results than Group-A.

It is important to mention here that the repeatability of the method has to be intended as the capability to follow the different method's steps to achieve the expected objectives without a method facilitator. With this in mind, the students have demonstrated to be capable of, at least, better fulfilling the Martino's steps without any support rather than basing on prescriptive guidelines. The students were capable to follow the different recommendations and steps, except for those activities which were not tested as elicitation of requirements and data gathering.

The criteria of classification of requirements (STEP-3 and STEP-4) have demonstrated to be easily understandable by design engineers without experience in forecasting. Furthermore, 89% of the students were capable to create performances to exploit data availability; moreover, 84% of students were capable to envision at least one performance. According to the results, the most difficult activity to follow corresponds to the knowledge projection of qualitative requirements which requires a more intuitive and individual capability to understand the product future. Moreover, the large majority of students tried to accomplish the quantitative projections rather than qualitative projections.

In terms of the suitability of the proposed software tool, the largest majority of students chose the FORMAT prototype to develop the regression analysis. From

Group-A, the students that decided to use only the FORMAT prototype correspond to the 84%, while, at the same time, 11% of students decided to use the FORMAT-prototype combined with another software tool to develop the regression analysis. Finally, 95%[5] of students from group-A have used the FORMAT-prototype during the test activities as well.

For what concerns Group-B, 74% of students used only the FORMAT-prototype and 21% of the students used the FORMAT-prototype combined with another software tool. At the end, the software tool was used by 95% of students from group-B.

In Figure 31 it is presented the percentage of students that used the FORMAT prototype to perform the test. In detail, some students used more than one software tool at the same time in order to explore and compare the results among the different software tools. It is worth noting that the majority of the students used the FORMAT prototype to check the quality of the regression because it was easy to understand it, if compared with other software tools (IIASA and Loglet).

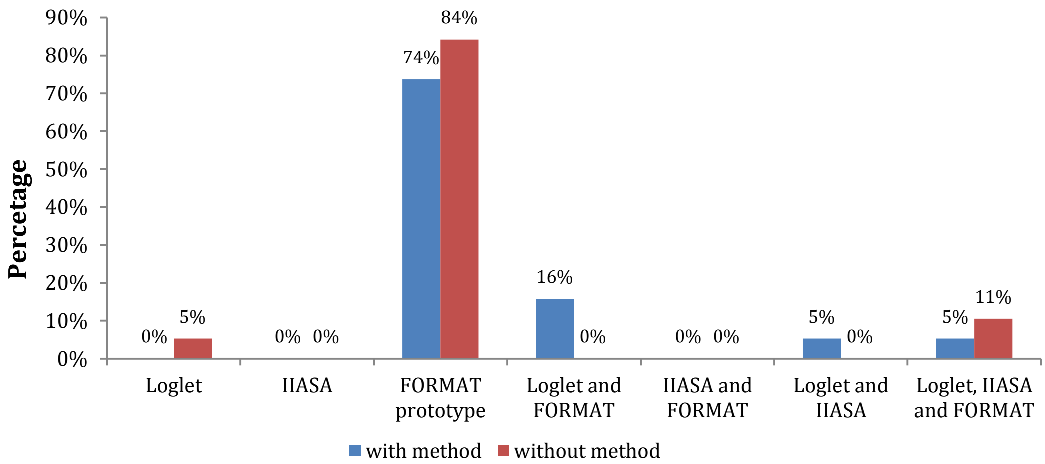


Figure 31: Summary of students' choice of software tools to carry out the regression analysis.

As already mentioned, the FORMAT prototype was used by almost all the students. The FORMAT-prototype showed to be capable of supporting the students, and mainly those without deep statistic knowledge. On this basis, the largest majority of the users evaluated the FORMAT prototype as useful to support them during the regression analysis.

From Group-A, 21% of students evaluated the FORMAT prototype as slightly appropriate, 47% as appropriate and 17% as absolutely appropriate. Finally, the

[5]FORMAT prototype cannot be install computers with Mac OS

software tool was positively evaluated by 79% of students from group-A (without method).

On the contrary, students with the method (Group-B) evaluated the software tool as: slightly appropriate-26%, appropriate-53%, and absolutely appropriate-16%. As a result, the software tool was positively evaluated by 95% of the students from group-B.

In Figure 32 it is presented the complete students' evaluations of the software tool for supporting the interpretation of regression analysis.

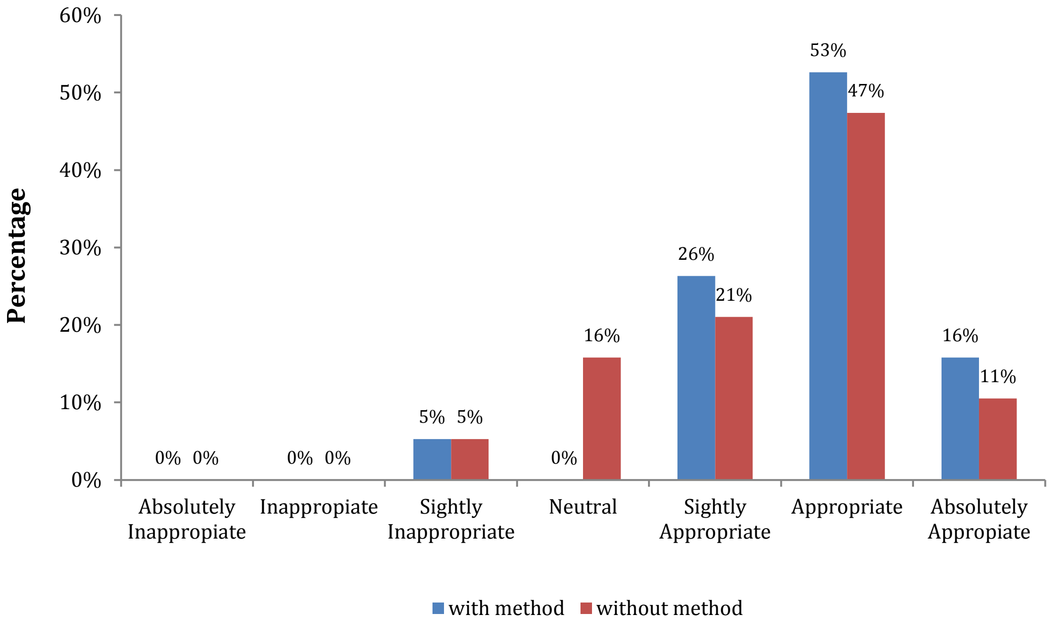


Figure 32: Summary of students' evaluations of software tool to support the interpretation of the regression outcomes.

Furthermore, from a statistic point of view, a 2T-test was used to compare if there are any differences between the evaluation delivered from both group-A and group-B.

$$H_0: \mu_{\text{(results of group B and A are NOT different)}} \neq 0$$
$$H_1: \mu_{\text{(results of group B and A are different)}} = 0$$

The results of the 2T-test are presented in Table 25, which exhibits that null hypothesis is accepted (p-value>0.005). With this in mind, the evidence suggests that there are no differences between the two groups A and B, at least for the delivered evaluation. In other words, the FORMAT-prototype can be considered as useful, independently if used by students with or without method.

Table 25: Statistic by using 2T-test for students' evaluations upon software usability

	N	Mean	St Dev	SE Mean
Group B (with method)	19	5,737	0,933	0,21
Group A (without method)	19	5,42	1,07	0,25
Difference	**mu (Group-B) - mu (Group-A)**			

Estimate of difference: 0,316
95% CI of difference: (-0,346. 0,977)
T-Test of difference = 0 (v/s not =): T-Value = 0,97 **P-Value = 0,339** DF = 35

For what concerns the regression analysis, group-A evaluated the logistic growth model as slightly appropriate-5%, appropriate-47%, absolutely appropriate-5% and it was positively evaluated by 57% of the students without the method. On the contrary, for those with the method (group-B) the logistic growth curve was evaluated ad slightly appropriate-26%, appropriate-63%, absolutely appropriate-11%. As a result, it was positively evaluated by 100% of the students with the proposed method (Figure 33).

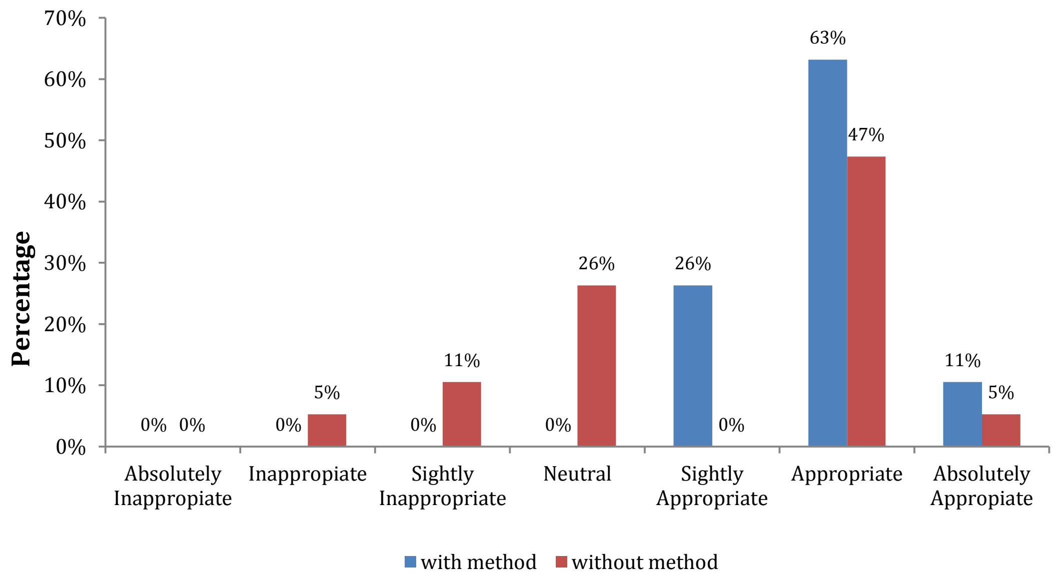


Figure 33: Summary of the students' evaluations upon the usefulness of logistic growth curve to support the regression analysis.

The 2T-test was used to compare differences between the results of the two groups A and B, related to the perception of usefulness about the use of the logistic growth curve as a regression analysis during the forecasting activity. The hypothesis is presented below:

$$H_0: \mu_{\text{(Perception of usefulness of group B and A are NOT different)}} = 0$$
$$H_1: \mu_{\text{(Perception of usefulness of group B is better than group A)}} > 0$$

As output, Table 26 shows that the null hypothesis is rejected (p-value<0.005). In fact, the evidence suggests that there is a difference between the two groups, where group-B has a higher mean than Group-A.

Table 26: Statistic by using 2T-test for students' evaluations upon usefulness of logistic growth curve.

	N	Mean	St Dev	SE Mean
Group-B (with method)	19	5,842	0,602	0,14
Group-A (without method)	19	4,95	1,39	0,32
Difference	**mu (Group-B) - mu (Group-A)**			

Estimate of difference: 0,895
95% lower bound of difference: 0,299
T-Test of difference = 0 (vs >): T-Value = 2,57 **P-Value = 0,008** DF = 24

In general terms, the difference in the evaluations of students about the logistic growth model seems that emerged from the capability of the students to exploit the data available about requirements. In fact, the students from Group-A were capable of developing two regression analyses by using logistic growth model. On the contrary, group-B was capable of developing three or more logistic growth regressions. This result confirms the repeatability of the recommendation for the exploitation of logistic growth model in terms of quantity. In fact, 89% of students were capable of creating performances and exploit better the data available without any support other than prescriptive method step (STEP-4).

4.3.2.2.2 Test: Discussions and Conclusions (Control group test)

Regarding the control group test, it is important to note how the usefulness of the forecasting is perceived by the user according to the new knowledge and insight that it helped them to gain, rather than the quality of their results. Indeed, the forecasting can be considered as a personal learning process as proposed by Kucharavy et al., (2005). Furthermore, the presented results show that somehow forecasting results and their usability strictly depend on the final user (Armstrong, 2001). It is worth noting that giving the students a set of predefined data constitutes by itself a reason to perceive forecasting analysis as useful because they are capable of obtaining results by only doing regressions. Given this condition, many students from group-A (without the method) tend to develop only regressions, skipping most of the relevant phases, therefore omitting a considerable portion of the analysis.

In detail, the students of group-A (without method) did not produce any valuable analysis for at least one of the initial two Martino's elements (i.e. Technology being forecast and the statement of the characteristic of the technology), since they were not aware of the way in which to organize the requirements and understand their statement in order to exploit the information available. It is important to underline that students just tried to develop "regression analysis" rather than a good forecasting analysis. For instance, students avoided understanding "the statement of the requirements" and related relations in order to create more meaningful forecasting analysis. On the contrary, group-B (with the method) provided a structured analysis for the initial Marino's elements. Moreover, they were capable of following each recommendation without the presence of a method facilitator. These results allowed better validating the recommendation in terms of repeatability, at least for the two initial Martino's elements.

According to the third Martino's element (i.e. the period of forecast), only few students without method (Group-A) were capable of exploiting the data available in an appropriate way compared to those from group-B. In detail, students of group-B (with method) organized the requirements and moreover they understood the past of the requirements in order to develop the forecast. Moreover, the students with the method were able to create several performance indexes to exploit as much as possible the available data. The creation of performance indexes allowed them to exploit the data available and to develop more regression analysis. In fact, almost all the students with the method (89%) were capable to create performances. This result allowed to validate the step repeatability, at least, for the recommendation to better exploit the data available based on logistic growth model in terms of quantity. Furthermore, the students' evaluations on the usefulness of the logistic growth support as well this outcome. In detail, the logistic growth model was considered as more useful for group-B than group-A (Table 26).

It is surprising to note that students of group-A did not exploit the data available with other regression models. For instance, IIASA allows to develop simple regression and other analysis which can be considered in some cases as more practical than logistic growth. Nevertheless, the students skip this type of alternative analysis. At the end, the inability of group-A to use the logistic growth model seems to be reflected in their evaluation about usefulness (Table 26).

From the last Martino's step, the students were capable of developing different knowledge projections. From test results, both groups (A and B) were mostly focused on developing quantitative projections rather than qualitative projections. However, group-B was capable of providing more and meaningful regressions by using the performance indexes. This result showed how the quantitative forecast seems to be the more recurrent alternative when it is necessary to understand the future. Finally, the performed test has so far confirmed also that the method is effective to guide users in producing a convergent forecasting analysis without the presence of a method facilitator. Moreover, despite the analysis of the test, the support given by the software tool, and specifically the FORMAT-prototype, clearly revealed that the software tool provides an appropriate recommendation to understand the results of the regression analysis by non-forecasting experts. Moreover, the largest majority chose the proposed software tool to develop their forecasting. In addition, the previous mentioned statement seems to be in accordance if compared with the usefulness of the logistic growth curve to support the forecasting analysis. The students of group-B (with method) considered the logistic growth curve more appropriate to support the forecast analysis compared with the students of group-A. It is likely to infer that this is due to the fact that Group-B was capable of better exploiting the data available about requirements.

In general, group-B was able to follow the different steps without the presence of a method facilitator only by following the prescriptive method steps.

4.3.2.3 Group B: Additional analysis

A complementary analysis was designed to understand in more detail the capability of the method to support design engineers during the forecasting process. This analysis aimed at determining which were the most suitable tools and models adopted during this research proposal. Only the students from group-B (aided by the method) evaluated the method steps in terms of:

- Usability of System Operator to organize the knowledge about requirements.
- Usability of the recommendations for managing the design requirements to exploit the logistic growth model.
- Capability of the method to drive new conclusions about product for design engineers without experience in forecasting.

To obtain the information about these criteria a paper and pencil questionnaire was used. The students were asked to answer a set of questions regarding the test activities, models, and tools used during the forecasting analysis (Appendix-H 7.8.2. and 7.8.3.)

4.3.2.3.1 Test: Results (Students with the proposed method)

With reference to the organization of design requirements, the System Operator was evaluated by the students as slightly appropriate-58%, appropriate-21% and absolutely appropriate-5% (i.e., 84% of the students evaluated positively the use of System Operator). During the test, almost all the students were capable of organizing the requirements at different System Operator levels, thus showing a good repeatability during the test. Nevertheless, the evaluation of the System Operator can be considered as quite lower if it is compared with the evaluation of recommendations to develop the regression analysis (logistic growth model). In detail, students evaluated the recommendations about regression analysis as slightly appropriate-32%, appropriate-58% and absolutely appropriate-5% (i.e., 95% of the students evaluated positively). In Figure 34 it is presented the relative comparison between the System Operator and the recommendations for the regression analysis in terms of the students' evaluations about the model usefulness (Figure 34).

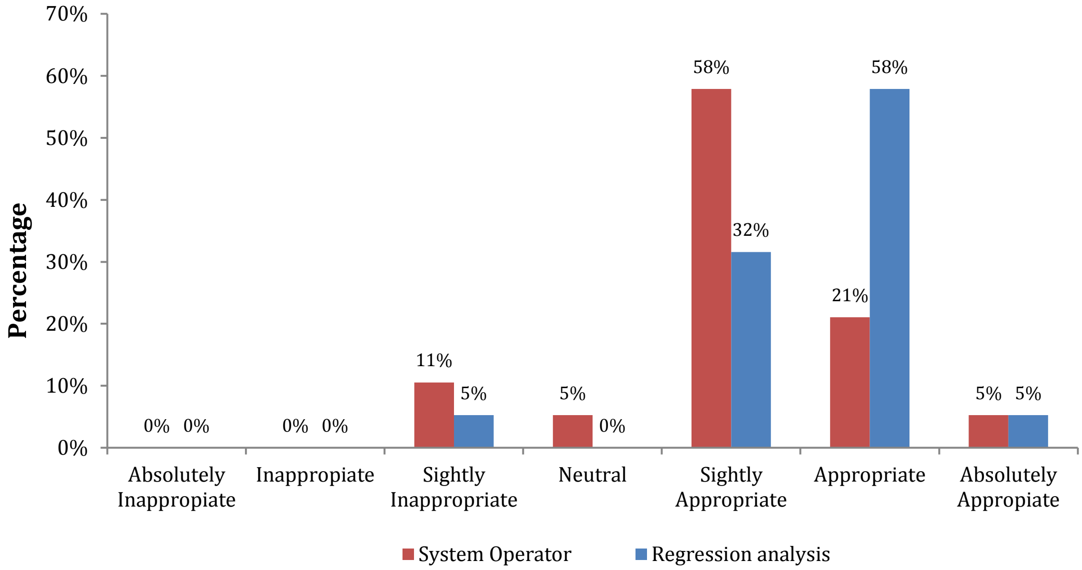


Figure 34: Summary of students' evaluations with the proposed method for the organization of requirements by using System Operator and recommendations for the regression analysis (exploitation of the logistic growth model).

Furthermore, a 2T-test was used to compare the differences between both the System Operator and the regression analysis. This analysis allows understanding if the students' evaluation is significantly different between the adopted models. The hypothesis is presented below:

$$H_0: \mu_{\text{(There are NOT differences between System Operator and Regression analysis)}} = 0$$
$$H_1: \mu_{\text{(There are differences between System Operator and Regression analysis)}} \neq 0$$

The Table 27 exhibits that null hypothesis is rejected (p-value<0,05). In fact, the evidence suggests that there is a difference between the evaluations of the students for the adopted models. Furthermore, these results can be considered as a further confirmation, at least for this test, that quantitative models are considered as more meaningful and useful in practice than qualitative models.

Table 27: Statistic by using 2T-test for students' evaluations about System Operator and Regression analysis (logistic growth curve).

	N	Mean	St Dev	SE Mean
Group B (with method)	19	5,842	0,602	0,14
Group A (without method)	19	4,95	1,39	0,32
Difference	**mu (with method) - mu (without method)**			

Estimate of difference: 0,895
95% lower bound of difference: 0,299
T-Test of difference = 0 (vs >): T-Value = 2,57 **P-Value = 0,008** DF = 24

On the basis of the previous results, the overall proposed method was assessed by the students' as appropriate to support them during the forecasting process (slightly appropriate-26%, appropriate-47% and absolutely appropriate-11%)(Figure 35). The proposed method(test form) was positively evaluated by 89% of the students.

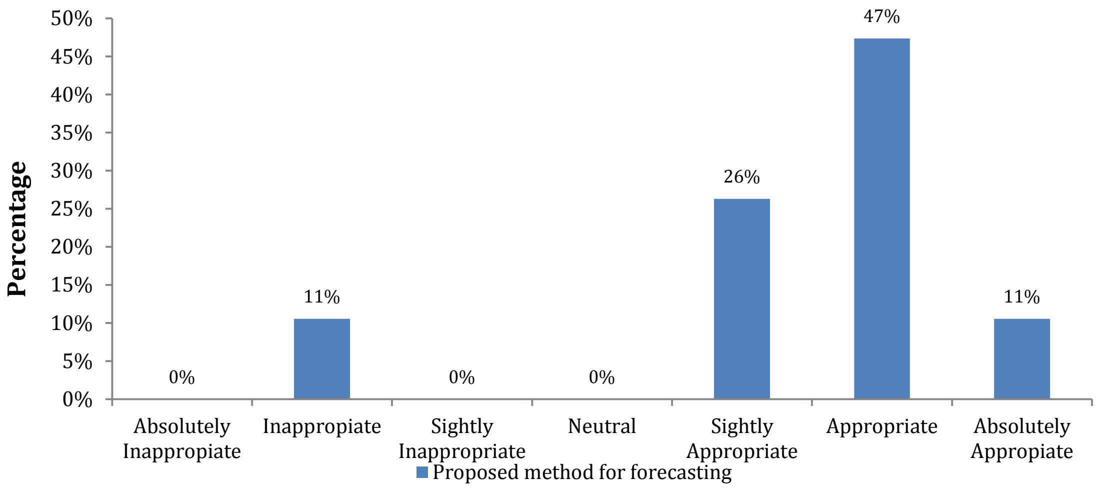


Figure 35: Summary of students' evaluations upon the proposed method(test form).

As discussed in the analysis of the previous case study, the perception of the usefulness of the forecasting results depends on the specific users' knowledge that they have about the product/process. On this basis, the test participants play the role of the main beneficiary of the forecasting analysis as well. Consequently, they can be considered as the most appropriate people to understand if the method application has allowed them to get new insights and conclusions about requirements.

With this in mind, it is important to note to what extent the method seems to play a significant role in helping them to draw conclusions about the product (Table 28). As results, the students believe that they are not able to reach the same conclusions without the method (probably no-68%; definitely no-16%; 84% of the students have positively evaluated this item). Furthermore, the method allowed them to get new insight about the future of the washing machine. The outcomes provided by the students' highlight the usefulness of the method in driving conclusions.

Another relevant aspect is about the efforts needed for the whole method application (test form) when is compared to the outputs. In detail, students considered that the overall effort to follow the method (test form) is acceptable compared to the output it provides (probably yes-63% and definitely yes-26%; 89% of student have positively evaluated this item) (Table 28).

Table 28: Summary of students' evaluations according to the methods' outcome and efforts needed. (Green box = positive evaluation; red box = negative evaluation)

	Definitely no	Probably no	Probably yes	Definitely yes
Could you have reached the same conclusions without using the method?	16%	68%	16%	0%
Are the efforts needed for the whole method acceptable compared to the output it provides?	0%	11%	63%	26%

4.3.2.3.2 Test: Discussions and Conclusions (Students with the proposed method)

With reference to the students' evaluation about the usefulness of the organization of design requirements by the System Operator, they evaluated the proposed model and suggestions as appropriate. Nevertheless, some differences among the students seemed to highlight that the usefulness of a method for forecasting is strongly related with the exploitation of the quantitative tools rather than the qualitative ones (Figure 34). The 2T-test showed that the evaluations of the students present more positive results for the development of regression analyses rather than the use of System Operator. However, the tendency of concentrating on the regression analyses instead of paying attention to the complete frameworks to forecast seems to be a common behaviour of novice forecasters, such as those involved in the testing campaign of the method and has been reflected in the different results of this test activity.

An important result of this activity is related to the reached conclusions and needed efforts. First, the students perceived that they were not able to reach the same conclusions without the method (84%). For instance, the evaluated method's steps have demonstrated to be capable of guiding students without any support other than prescriptive guidelines. Moreover, the students have delivered positive outcomes compared with author's results presented in section 4.3.1. In fact, the evaluated method's steps helped the students managing the available data, information and their knowledge in order to develop an appropriate forecasting analysis as suggested by Martino (1993). Second, a positive result was obtained for what concerns the needed efforts for the method application during the test. This result highlights that the evaluated method steps are suitable to be adopted by design engineers, as demonstrated by this test.

Finally, on the basis of the previous considerations, the overall method(test form) was assessed by students as suitable to be used for forecasting design requirements, and suitable to be adopted by those without experience in forecast.

4.3.2.4 Test: Analysis for the group B by using NASA task load Index

A final analysis was performed by using the NASA task load index to understand in a more detailed way the necessary efforts required by design engineers to adopt the proposed method, in particular the evaluated method's steps. The NASA task load was used to identify the main factors needed for specific activities or tasks while applying the method. The NASA task load is based on six factors: i) mental demand; ii) physical demand; iii) temporal demand; iv) performance; v) efforts and vi) frustration level (Hart et al., 1988). The NASA task load questionnaire was applied by using paper and pencil approach in terms of:

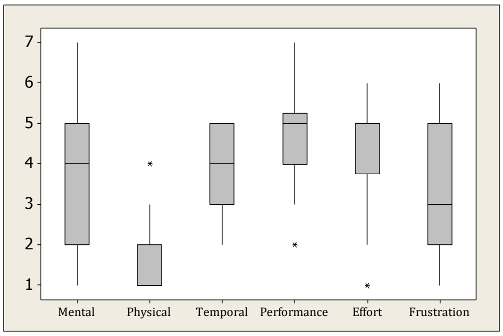
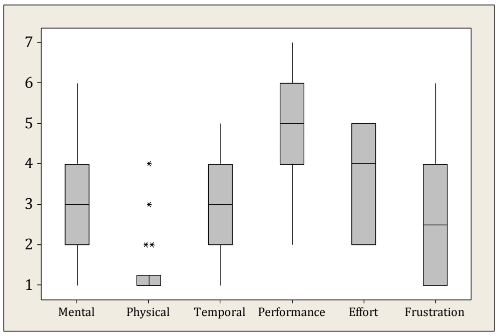
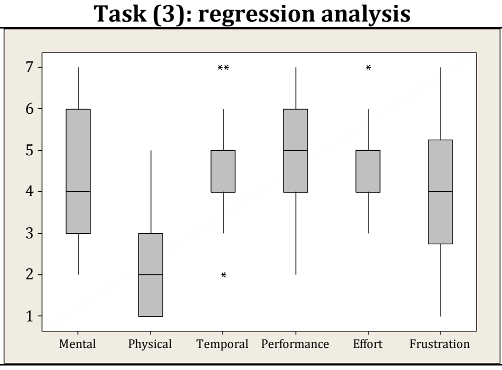
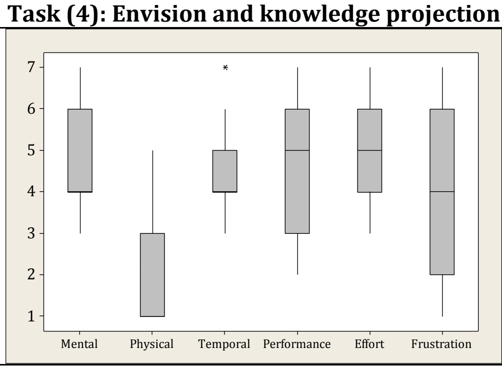
i) Task (1): Organization of requirements and categorization by using System Operator
ii) Task (2): Estimation for understanding the past and present of design requirements
iii) Task (3): Regression analysis by using logistic growth curve model
iv) Task (4): Envisioning and knowledge projections

Outcomes of this questionnaire are expressed on a Likert scale that goes from 1 to 7 (1=Low; 4=Medium; 7= High; these values are related to the different factors as mental, physical, temporal, effort, frustration). The performance factor is measured from 1 to 7, but with a different labelling as recommended by NASA (Hart et al., 1988))(1=Bad; 4=Normal; 7= Excellent).

4.3.2.4.1 Test: Results (Students with the proposed method by using NASA task load index)

Regarding the results obtained by using the NASA task load questionnaire, Table 29 presents a summary of the students' evaluations by using boxplot representation. The evaluation of each task depends on the different factors that affect the students during the method application. The decomposition of the evaluation of each factor is presented in Table 29.

Table 29: Evaluation of different method's tasks based on NASA task load Index; Scale from 1 to 7.

Task (1): Organization of requirements and categorization by using System Operator	**Task (2): Estimation for understanding the past and present**
	
Task (3): regression analysis	**Task (4): Envision and knowledge projection**
	

The four tasks were analysed by calculating the overall workload (Hart et al., 1988). Figure 36 presents the workload demanded for each task. The tasks that required the more demand according to the students' answers correspond to task (3) (regression analysis) and task (4) (envision and knowledge projection). The simplest task corresponds to task (2) (understanding the past and present). Values related to task (3) showed that the regression analysis requires more effort than others for design engineers. Task (3) resulted as relatively demanding; this can possibly be explained by the lack of statistical knowledge of design engineers, as a consequence this task requires more effort by students in order to be accomplished.

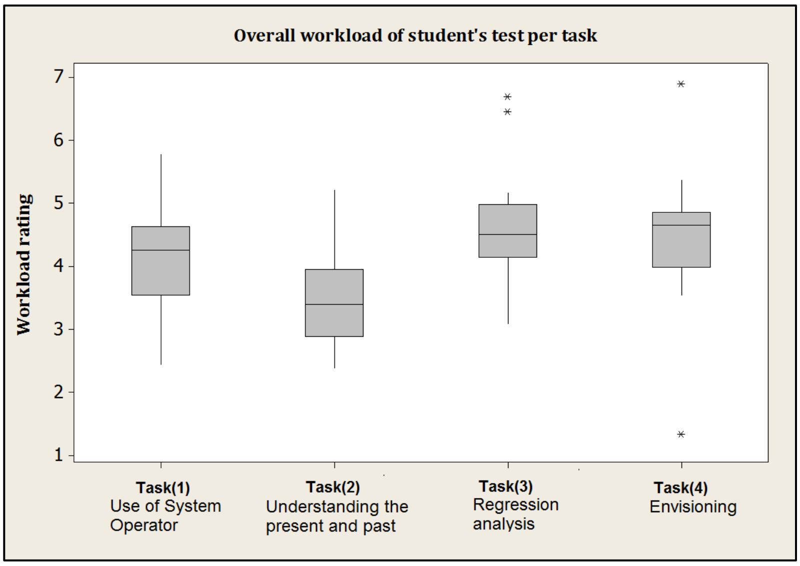


Figure 36: Overall workload index according to the different tasks developed during the students' test.

From a statistical point of view, Anderson-Darling test was developed in order to check the distribution of the students' results. Table 30 presents the statistic of the overall results for the tasks. Moreover, all of the tasks showed a p-value higher than 0.05, so the students' answers can be considered as normally distributed. This test provides a good understanding of the quality of the obtained answers provided by the students by using a statistic viewpoint.

Table 30: Descriptive statistic of the student's evaluation by each task according to NASA task load index.

Number	Mean	Standard Deviation	95% CI-lower	95% CI-Upper	P-value (Anderson-Darling test)
Task (1): Organization of requirements and categorization on System Operator	4,12	0,88	3,68	4,56	0,763
Task(2): Categorization for understanding the past and present	3,49	0,75	3,11	3,86	0,518
Task (3): Regression analysis	4,62	0,90	4,17	5,06	0,126
Task (4): Envision and knowledge projection	4,44	1,19	3,78	5,19	0,068

4.3.2.4.2 Test: Discussions and Conclusions (Students with the proposed method by using NASA task load index)

Regarding the NASA task load questionnaire, the first task concerns the organization of requirements by the System Operator. The students perceived that this task (1) was achieved by reaching a "normal" performance (i.e., the average value of the performance factor was 4, which means that students were capable to reach “normal” results of the activity according to their personal evaluation). In fact, these results can be influenced by the mental and temporal factors, which were not perceived as so demanding to reach the “normal” results (i.e., the average value of mental and temporal demand is 4). Even more, the effort can be considered as “medium” demanding. Moreover, to accomplish the task (1) during the case study does not create so much frustration in the students according to them (i.e., the value of the frustration factor is 3, which means that the task does not generate so much personal frustration to reach the task results). Moreover, the physical demand is almost neglected during this task.

Secondly, task (2) is related to the categorization of requirements for the understanding of the past and present, and it seems to be less demanding than the organization of requirements (task (1)). During the second task, the mental demand decreased from 4 to3 in their average value. In addition, the temporal, effort and frustration factors decreased during the second task too. Moreover, the students believe that their personal performance was slightly higher during this task compared with task (1) (Table 30 -Task (2)).

On the contrary, task (3) is related to the regression analysis and it presents an increasing value among the NASA task factors (Table 30-Task (3 All the factors present a higher value compared with the previous ones. Moreover, the box interval is larger, thus showing a bigger standard deviation in the students’ answers. From Table 30-task (3) is possible to appreciate that the mental demand remains at a similar average value (4 avg.). Nevertheless, the standard deviation increased considerably to higher values, thereby highlighting larger differences in the students’ answers. Furthermore, a physical demand emerged from this task potentially caused by stress conditions during this activity. The temporal, effort and frustration factor increased during this task. This increasing tendency can be a consequence of the students who did not feel confident while developing statistical analysis. However, by observing their results about the performance factor, it seems that the students believed that task (3) was properly accomplished.

Finally, in task (4), which was related to the envisioning and knowledge projection, students showed also an increasing trend compared with the tasks (1) and (2). These results emerged from the synthesis of the results achieved in the previous tasks, which -according to the students’ answers- require more mental, effort and temporal demand. In any case, they perceived that the task (4) was developed positively, according to them (performance average correspond to 5).

General results show that the tasks have slightly different relative values, even considering the fact that task (3) requires a higher workload for students. The average value correspond to 4,62 working-load index that can be considered as “medium”. Consequently, the proposed method can be considered as appropriate for those people who do not have large statistic knowledge. Furthermore, task (4) can be considered as a “medium” demanding task. The students' results showed an average value of 4,44 working-load index. On the contrary, the less demanding task corresponds to task (2) with an average value of 3,49 working-load index. Finally, task (1) can be considered as "medium" as well with an average of 4,12 working-load index.

From this testing phase, it is possible to state that the proposed method of forecasting can be considered as useful. This confirms that the method can be easily adopted by design engineers without experience in forecasting. In detail, the presented results showed that the proposed method seems to be compatible with current knowledge, at least, for young design engineers. Moreover, the proposed method does not require a high workload demand according the NASA task load index (Hart et al., 1988). Therefore, it is possible to conclude that this method can be used, at least, by young design engineers.

Chapter 5

[5] Discussions and Conclusions

This section summarizes the main contributions characterizing this work in order to draw some conclusions based on the hypothesis and the research questions introduced in this doctoral dissertation. Moreover, the strengths and weaknesses of the proposed approach will be discussed.

5.1 Summary of Activities

In the introduction the overall goal of this research was presented. It relates to the anticipation of information about requirements to support the design process. The formulation of such goal comes from the needs of modern industries, which have to face challenges in competition and innovation. In this competitive environment, in fact, the anticipation of products/processes features and characteristics can provide a competitive advantage for companies. On this basis, the technological forecasting method have been proposed as an alternative to anticipate information about design requirements.

With the premise that forecasting methods are capable to anticipate relevant information for design engineering process, and also considering that the early design process stage is a critical stage for the product development process, the main research questions, on which this doctoral research was based, were the following:

- How a design engineer can be guided into use forecasting methods in order to anticipate information about product and process?
- How a method for forecasting can be introduced systematically into the product development process?
- Which is the industrial and academic applicability of a method for forecasting in the design domain?

In fact, in this research different models and methods have been combined and modified in order to answer these research questions. These questions have been answered through the conception of a method for forecasting design requirements that is suitable to be used by design engineers without forecasting experience allowing them to drive conclusions about product and process. The method allows anticipating information about design requirements and it can be easily adopted by design engineers to support the early design process stage.

The second chapter presented the different design phases to properly define the methods features, which should be addressed. Moreover, the role of the knowledge during the early design phases has been analysed so as to understand the way in which it deals with explicit and tacit knowledge. During the early design phases design engineers need to create the requirements list to formalize the knowledge from different stakeholders. Furthermore, in the second chapter, it has been also presented a theoretical framework of different technological forecasting families. From this section emerged that several models are used to forecast, but mainly of them are used with an economic purpose. From the analysis of the state of the art, it clearly emerged that an appropriate forecasting method depends on three elements: i) users (i.e., who is going to use the method); ii) sources of data and information (i.e., where to obtain data and information), iii) forecasting purpose (i.e., what we need to know about the future). On the contrary, Martino (1993) proposed four elements which go beyond the specific forecasting method. According to him,, an appropriate forecasting analysis should follow these elements: i) *the technology being forecast; ii) the statement of the characteristics of the technology; iii) the time of forecast; iv) the statement of the probability associated with the forecast*. On this basis, Martino's elements have been adopted to define the systematic structure of the proposed method.

Section three presents the different models used to develop a method for forecasting design requirements and the related amendments. Firstly, the System Operator created by Altshuller (1984) was adopted as the reference model for conceiving the method. The choice to use the System Operator emerged from the capability it provides to combine different entities at different hierarchical levels. Moreover, the time dimension is already included in the System Operator features. Secondly, the ENV model has been adopted and modified to properly define quantitative and qualitative requirements. Thirdly, the logistic growth model has been chosen in this research to forecast design requirements given its relation with the technical evolution, as pointed out by several authors (Althshuller, 1984; Marchetti, 1985; Samalatov, 2000). Given that design engineers are not necessarily skilled in statistic, a new software tool has been created in order to overcome the limits of software tools conceived to forecast, which are based on logistic growth model as IIASA and Loglet. Finally, a method for forecasting design requirements has been proposed as the main contribution of this research.

The chapter four presents the validation activities conducted in order to evaluate the overall research proposal. Three main criteria were defined to validate the research proposal and answer the research questions: i) Theoretical structural validity; ii) Empirical performance validity; iii) Capability of the method to guide the design engineers without experience in forecasting. Four testing activities have been presented to validate this research. At the end of each testing activity, the results are presented. In addition, the novelties and limitations identified by the author during the validation activities are discussed and analysed. The first two case studies attempted to validate the "empirical performance" of the proposed method. The first case study is developed in the white good industry and characterized by the changes among product and process, while the second one is in the mining industry characterized by changes only for the process and where the product remains stable as a commodity. The other two activities have focused on the validation of "the theoretical structure" and "capability of the method to guide the design engineers without experience in forecasting". An academic case study was developed to test the usability of the method with engineering students.

The test with students allowed validating the repeatability and usability of the method (test form) by inexperienced forecasting users.

Finally, in the next section are presented the achievement of the objectives by taking into account the results presented and discussed during section 4.

5.2 Achievement of the objectives

As briefly mentioned above, the main research goal is the anticipation of information about requirements during the early design process stage to support the design process and strategic directions. A method for forecasting design requirements has been proposed based on the considerations previously mentioned. The achievement of such goal has been subdivided into three different criteria:

A. Theoretical structural validity (Pedersen et al., 2000):
   i. Individual constructs constituting the method.
   ii. Internal consistency of the way the constructs are put together in the method.
B. Empirical performance validity (Pedersen et al., 2000):
   i. Capability to clarify the directions for product and process development and driving related strategic decisions.
C. Capability of the method to guide the design engineers without experience in forecasting:
   i. Usability of the time perspective to forecast requirements.
   ii. Capability of the method to provide new insights and conclusions about product/process requirements.
   iii. Effectiveness of the method to be transferable to design engineers independently from the adopted product development process.

After three years of an exhaustive work, the proposed objectives and goals of this research have been achieved in different detail levels. First of all, “theoretical structural validity” has been achieved by the individuation of a set of techniques from the forecasting research field in order to properly carry out the regression analysis to support the early design phases. In order to reinforce this objective, specifically A-ii, several contributions were developed as a theoretical framework for the organization of design requirements based on ENV logic and theoretical framework about logistic growth curve. This procedure was needed in order to fill the lacks of knowledge about the logistic growth curve into the design domain. Moreover, the test with students allowed validating the suitability of the adopted models in this research.

Regarding the empirical performance validity, case studies were developed in two different industrial contexts as white good and mining industry. Industrial partners recognized the usefulness of the results to clarify the directions of their product and process. For what concerns the FORMAT-project, the method has been useful in order to support the overall method at bringing new information about vacuum forming technologies. Moreover, the proposed method has brought positive amendments to the overall FORMAT-methodology, mainly for what concerns the stage A. For what concerns to the Cluster Mining-project, the method has been useful to clarify directions of R&D about mining mill.

It is important to remark that the method has been tested for almost all the proposed steps except for the elicitation of requirements and data gathering. Regarding the ability of the method to guide design engineers without experience in forecasting, the control group test has been useful to validate the method steps. The method steps allowed gaining new insights and conclusions to students about the product of which students were not aware before. Moreover, the group with the method was capable to bring better results than those without the method. Remarkably, the students with the method exploited in a better way the data available in order to drive conclusions for product (i.e. washing machine). In terms of repeatability, the students with the method have demonstrated to be capable to follow all the steps (test form) without the presence of a method facilitator. The results of the NASA task load index showed that the method does not require so much workload demand, and consequently it can be used and adopted by design engineers without a deep forecasting expertise (as the tested students were).

It is important to mention that author did not have the opportunity to explore the benefits of the method application in the overall design process, starting from elicitation of requirements until the final design proposal. Nevertheless, given the over-mentioned results, the authors considers that the method can be inserted in a standard Product Development Process (Pahl et al., 2007; Ulrich & Eppinger, 2012) or used as a complementary analysis as was demonstrated during the different case studies in this research. Noteworthy, the method is able to support different users with lacks of statically knowledge (i.e. not only design engineers).

Within the engineering design, the introduction of a reliable method for forecasting requirements can provide benefits for the organizations in terms of reducing the waste of resources for the development of product with poor-assessed directions as was presented in this research.

5.3 Limits of the proposed method

The proposed method showed some limitations emerged from the different case studies and mainly concern two specific aspects.

The first one is related to the users. Indeed, the method was conceived to be used by design engineers, who not are necessarily forecasters and statistics. As a consequence, the proposed method, to the eyes of a forecaster or statistical expert might be considered partially appropriate to exploit the data available. However, the method by itself does not exclude the application of other regression analysis as linear regression, ARIMA or others. Nevertheless, the additions of further regression analysis have to always consider the users' knowledge to manage those regression models. For example, vector correlation analysis seems to be an adequate regression model to identify relations among different requirements (appendix-J). Even so, in this research, the vector correlation analysis was quite far from the proposed goal of simplicity to design engineers.

The second weakness is related to the different steps. In fact, the main limitation emerged from data availability about design requirements. Companies do not save so much technical data if it is compared with economic data. Consequently, the method has to be applied by using expert knowledge projections, with potential consequences in the acceptability of its results. On the contrary, when data is available, the logistic growth model presented limitations to fit the overall set of different requirements behaviour that can emerge in practice. A solution might be to use other regression models to predict requirements value. Nevertheless, this approach, as was mentioned before, largely depends on the user's knowledge. Even so, method is capable of supporting the design engineers who not necessarily are forecasting experts. Finally, the method can be intended as an initial step for the introduction of new and more time-perspective methods and models to support the design process, in specific to design engineers.

5.4 Potential applications

Firstly, the author believes that the application of the method can be extended so as to apply it also in the second phases proposed by Pahl et al. (2007). Indeed, the new insight that the method provides can positively stimulate the conceptualization and prioritization of solution for product/process as presented in the mining mill case study. In this direction, further researches have to aim at exploring feasible solutions capable of reaching the forecasting results and consequently increasing the efficiency of the overall product cycle by bridging the development phases. It is important to mention that the proposed method for forecasting does not deal with the way in which the expected knowledge projection is reached. Consequently new methods can be adopted to explore potential solutions combined with the author's proposal, thus supporting not only the initial design process phases. In this manner, it could be possible also to support the later design phases

Secondly, further researches are needed in order to explore and investigate the capabilities of the software tool to fit the different requirements behaviours. The research should aim at better exploiting data available from companies and statistical databases to support the design process. On this basis, the author believes that the FORMAT-prototype can be enriched with other regression models to characterize the different set of requirement's behaviour. Moreover, the software tool can be also enriched by adding new users' features according to the different experience that design engineers can have during application of the method. One example in this direction is Forecasting-Pro (2014), which seems to be an aided-software capable to support economists and managers in developing different regression analysis.

Finally, the author consider this research proposal as a first seed to build a software application capable to guide design engineers at developing forecasting analysis in order to support the design process by following a systematic and structured approach.

[6] References

Agarwal, R. and Audretsch, D. B., (2001). Does Entry Size Matter? The Impact of the Life Cycle and Technology on Firm Survival, Journal of Industrial Economics, Vol. 49 (1), pp. 21-43.

Aguilera, R. F., & Aguilera, R. (2012). World natural gas endowment as a bridge towards zero carbon emissions. Technological Forecasting and Social Change, 79(3), 579–586. doi:10.1016/j.techfore.2011.09.004

AHD on line (1969) Forecasting. American Heritage Dictionary. Retrieved 22, September, 2014, from

https://www.ahdictionary.com/word/search.html?q=forecasting&submit.x=47&submit.y=33

AHD on line (1969) Technology. American Heritage Dictionary. Retrieved 22, September, 2014, from

https://www.ahdictionary.com/word/search.html?q=technology&submit.x=67&submit.y=15

Alencar, M. S. M., Porter, a. L., & Antunes, a. M. S. (2007). Nanopatenting patterns in relation to product life cycle. Technological Forecasting and Social Change, 74(9), 1661–1680. doi:10.1016/j.techfore.2007.04.002

Allen, R. D., Hicks, B. J., & Culley, S. J. (2000). Integrating electronic information for the design of mechanical systems: The designers perspective. 4th World Multi-Conference on Systematics, Cybernetics and Informatics, 2, 266– 271

Alper, J. S., & Gelb, R. I. (1990). Standard errors and confidence intervals in nonlinear regression: comparison of Monte Carlo and parametric statistics.Journal of Physical Chemistry, 94(11), 4747-4751.

Altshuller, G.S.; (1984); "Creativity as an Exact Science: The Theory of the Solution of Inventive Problems". Gordon and Breach Science Publishers, ISBN 0-677-21230-5, (original publication in Russian - 1979).

Andersson K.; (2004); An iterative Question–Answer driven process to support product design. In the proceedings of NordDesign 2004 — product design in changing environment.

Andrews, C. B, (1998), Emerging trends in mining industry partnership, Natural Resources Forum, Vol. 22 (2), pp. 119-126.

Armstrong, J. S. (Ed.). (2001). Principles of forecasting: a handbook for researchers and practitioners (Vol. 30). Springer.

Armstrong, J. S., & Forecasting, L. R. (1985). From crystal ball to computer.New York ua.

Azapagic, A., (2004) Developing a framework for sustainable development indicators for the mining and minerals industry, Journal of Cleaner Production, Vol. 12, pp. 639-662.

Baldussu, A. (2014). A problem solving methodology for the development of bio-inspired products. Systematic use of natural design principles for designers without biological knowledge.

Bartos, P. J., (2007). Is mining a high-tech industry? Investigations into innovation and productivity advance, Resources Policy 32, pp. 149–158

Becattini N, Cascini G; (2014); General-purpose requirements checklist for improving the completeness of a design specification; to be published on the proceedings of the DESIGN conference 2014 - Drubovnik (HR) - May 19th-22nd.

Becattini, N. (2013a) Requirements identification and characterization in innovation processes, PhD Thesis, available at http://hdl.handle.net/10589/74123

Becattini N.(2013b), PRODUCT AND PROCESS MODELLING – STATE OF THE ART UPDATE, available at http://www.format-project.eu/deliverables/public-reports-and-white-papers/deliverable-2.2/view

Becattini, N., Borgianni, Y., Cascini, G., & Rotini, F. (2012). Model and algorithm for computer-aided inventive problem analysis. Computer-Aided Design, 44(10), 961-986.

Becattini, N., Cascini, G., & Rotini, F. (2011a). Correlations between the evolution of contradictions and the law of identity increase. Procedia Engineering, 9, 236-250.

Becattini, N., Cascini, G., Nikulin, C. (2013). "Modelling the dynamics of products and processes requirements". Proceeding of the TRIZ Future Conference, Paris-France, 43-53.

Becattini, N., Cascini, G., Petrali, P., & Pucciarini, A. (2011b). Production processes modeling for identifying technology substitution opportunities. InProceedings of the 11th TRIZ Future Conference (pp. 17-33).

Beck, K., Beedle, M., Van Bennekum, A., Cockburn, A., Cunningham, W., Fowler, M., Thomas, D. (2001). Manifesto for agile software development.

Bers, J. a., Dismukes, J. P., Miller, L. K., & Dubrovensky, A. (2009). Accelerated radical innovation: Theory and application. Technological Forecasting and Social Change, 76(1), 165–177. doi:10.1016/j.techfore.2008.08.013

Bijan, Y., Yu, J., Stracener, J., & Woods, T. (2013). Systems requirements engineering—State of the methodology. Systems Engineering, 16(3), 267-276.

Bonino, D., Ciaramella, A. and Corno, F. (2010) Review of the state-of-the-art in patent information and forthcoming evolutions in intelligent patent informatics, World Patent Information 32, pp. 30–38.

Boretos, G. P. (2009). Technological Forecasting & Social Change The future of the global economy. Technological Forecasting & Social Change, 76(3), 316–326. doi:10.1016/j.techfore.2008.06.003

Cantono, S., & Silverberg, G. (2009). A percolation model of eco-innovation diffusion: The relationship between diffusion, learning economies and subsidies. Technological Forecasting and Social Change, 76(4), 487–496. doi:10.1016/j.techfore.2008.04.010

Cascini G., Fantoni G., and Montagna F., (2013) "Situating needs and requirements in the FBS framework," Design Studies, vol. 34, pp. 636-662

Cascini, G. (2012) TRIZ-based Anticipatory Design of Future Products and Processes. Journal of Integrated Design and Process Science, 16 (3), 29-63.

Cascini, G. (2012). TRIZ-based anticipatory design of future products and processes. Journal of Integrated Design and Process Science, 16(3), 29-63.

Cascini, G., Becattini, N., Kaikov, I., Koziolek, S., Kucharavy, D., Nikulin, C., ... & Vanherck, K. (2014). FORMAT-Building an original methodology for Technology Forecasting through researchers exchanges between industry and academia. Futures, 39(11), 7.

Cascini, G., Rotini, F., & Russo, D. (2009). Functional modeling for TRIZ-based evolutionary analyses. In Proceedings of the 17th International Conference on Engineering Design (ICED'09), Vol. 5 (pp. 371-384).

Cascini, G., Rotini, F., and Russo, D. (2011). Networks of trends: Systematic definition of evolutionary scenarios. TRIZ Future Conference 2008, Procedia Engineering, 9, 355-367.

Cavallucci, D., & Khomenko, N. (2007). From TRIZ to OTSM-TRIZ: addressing complexity challenges in inventive design. International Journal of Product Development, 4(1), 4-21.

Chakrabarti, A. (1994, September). Requirements identification: a central issue in design research. In Proceedings of the East-West Conference on Information Technology in Design (pp. 108-117). International Centre for Scientific and Technical Information.

Chakrabarti, A., Morgenstern, S., & Knaab, H. (2004). Identification and application of requirements and their impact on the design process: a protocol study. Research in engineering design, 15(1), 22-39.

Chang, Y. S., & Baek, S. J. (2010). Limit to improvement: Myth or reality? Technological Forecasting and Social Change, 77(5), 712–729. doi:10.1016/j.techfore.2010.02.010

Change, S. (2004). Technology futures analysis: Toward integration of the field and new methods. Technological Forecasting & Social Change, 71, 287-303.

Chiang, S.-Y., & Wong, G.-G. (2011). Competitive diffusion of personal computer shipments in Taiwan. Technological Forecasting and Social Change, 78(3), 526–535. doi:10.1016/j.techfore.2010.04.014

Christensen, C. (2013). The innovator's dilemma: when new technologies cause great firms to fail. Harvard Business Review Press.

Christodoulos, C., Michalakelis, C., & Varoutas, D. (2011). On the combination of exponential smoothing and diffusion forecasts: An application to broadband diffusion in the OECD area. Technological Forecasting and Social Change, 78(1), 163–170. doi:10.1016/j.techfore.2010.08.007

Chu, C.-P., & Pan, J.-G. (2008). The forecasting of the mobile Internet in Taiwan by diffusion model. Technological Forecasting and Social Change, 75(7), 1054–1067. doi:10.1016/j.techfore.2007.11.012

Chyong Chi, K., Nuttall, W. J., & Reiner, D. M. (2009). Dynamics of the UK natural gas industry: System dynamics modelling and long-term energy policy analysis. Technological Forecasting and Social Change, 76(3), 339–357. doi:10.1016/j.techfore.2008.06.002

Civi, E. (2000), "Knowledge management as a competitive asset: a review", Marketing Intelligence & Planning, Vol. 18 No. 4, pp. 166-74.

Clausing D. (1994). Total Quality Development. A step-by-step guide to world-class concurrent engineering, ASME Press, New York.

Cleary, P. W. and Morrison, R.D. (2012), Prediction of 3D slurry flow within the grinding chamber and discharge from a pilot scale SAG mill, Minerals Engineering, Vol. 39, pp. 184-195.

Coates, V., Farooque, M., Klavans, R., Lapid, K., Linstone, H. A., Pistorius, C., & Porter, A. L. (2001). On the future of technological forecasting. Technological forecasting and social change, 67(1), 1-17.

Coccia, M. (2010). The Asymmetric path of Economic Long Waves. Technological Forecasting and Social Change, 77(5), 730–738. doi:10.1016/j.techfore.2010.02.003

Connelly, M. C., Dismukes, J. P., & Sekhar, J. a. (2011). New relationships between production and patent activity during the high-growth life cycle stage for materials. Technological Forecasting and Social Change, 78(2), 303–318. doi:10.1016/j.techfore.2010.10.004

Cooke, R. M. (1991) Experts in Uncertainty. Oxford: Oxford University Press

CORFO (2010), Mining Cluster in Chile, available on-line at www.unido.org, last accessed July 2013.

Cross, N. (2008) Engineering Design Methods: Strategies for Product Design. Fourth edition. Chichester: John Wiley and Sons Ltd..

Cuhls, K. (2003) From forecasting to foresight processes – New participative foresight activities in Germany, Journal of Forecasting, Vol. 22, pp. 93–111.

Dandotiya, R. (2012). Decision support models for the maintenance and design of mill liners, PhD Thesis

Dandotiya, R. and Lundberg, J. (2012). Economic model for maintenance decision: a case study for mill liners. Journal of Quality in Maintenance Engineering, Vol 18, (1), pp. 79-97.

Devezas, T. (2010). Crises, depressions, and expansions: Global analysis and secular trends. Technological Forecasting and Social Change, 77(5), 739–761. doi:10.1016/j.techfore.2010.04.010

Devezas, T., Cristovão, F., Melo, L. De, Luisa, M., Cristina, M., Salgado, V., Ribeiro, J. R., et al. (2012). Technological Forecasting & Social Change The struggle for space : Past and future of the space race. Technological Forecasting & Social Change, 79(5), 963–985. doi:10.1016/j.techfore.2011.12.006

Diaz-Rainey, I., & Tzavara, D. (2012). Financing the decarbonized energy system through green electricity tariffs: A diffusion model of an induced consumer environmental market. Technological Forecasting and Social Change, 79(9), 1693–1704. doi:10.1016/j.techfore.2012.05.012

Dismukes, J. P., Miller, L. K., & Bers, J. a. (2009). The industrial life cycle of wind energy electrical power generation. Technological Forecasting and Social Change, 76(1), 178–191. doi:10.1016/j.techfore.2008.08.011

Edmundson, R. H. (1990). Decomposition; a strategy for judgemental forecasting. Journal of Forecasting, 9(4), 305-314.

Eppinger, S. D., Whitney, D. E., Smith, R. P., & Gebala, D. A. (1994). A model-based method for organizing tasks in product development. Research in Engineering Design, 6(1), 1-13. S.A. P. M. (2006). Manual General de Minería y Metalurgia. Antofagasta: Portal Minero Ediciones.

Energy Californian Commission(2014).”Home appliances data base”: available from: http://energy.ca.gov/appliances/database/

Eto, H., (2003) The suitability of technology forecasting/foresight methods for decision systems and strategy. A Japanese view, Technological Forecasting and Social Change, Vol. 70, pp. 231-249.

Fantoni, G., Apreda, R., Dell'Orletta, F., and Monge, M. (2013). Automatic extraction of function–behaviour–state information from patents. Advanced Engineering Informatics.

Fekedulegn, D; Mac Siurtain M.P. and Colbert; J.J (1999); "Parameter Estimation of Nonlinear Growth Models in Forestry". SILVA FENNICA. Vol. 33-4. p. 327-336.

Fellers, J., Key factors in knowledge acquisition, in ACM SIGCPR Computer Personnel, 1987, 11(1) pp.10-24

Fildes, R., & Hastings, R. (1994). The organization and improvement of market forecasting. Journal of the Operational Research Society, 1-16.

Firat, A. K., Woon, W. L., Madnick, S. (2008) Technological forecasting – A Review, Working Paper CISL# 2008-15.

Flanagan, John C.; (1954); The critical incident technique. Psychological Bulletin, Vol 51(4), July, 327-358. doi: 10.1037/h0061470

ForecastingPro(2014).”Easy, Accurate, Affordable Forecasting Software” Retrieved 18, December, 2014, from http://www.forecastpro.com/customers/success/index.htm

French, M. J. (1985). Conceptual design for engineers. London: Design Council.

Fye, S. R., Charbonneau, S. M., Hay, J. W., & Mullins, C. A. (2013). An examination of factors affecting accuracy in technology forecasts. Technological Forecasting and Social Change, 80(6), 1222-1231.

Garay, V., Schwarz, S., and Donoso, F. (2012) Informe Tendencias Mercado del Cobre- Balance 2011 y Perspectivas 2012-2013. COLCHICO-Dirección de estudios y politicas públicas.

García-Magariño, I., Gómez-Sanz, J. J., & Pérez-Agüera, J. R. (2009). A complete-computerised delphi process with a multi-agent system. InProgramming Multi-Agent Systems (pp. 120-135). Springer Berlin Heidelberg.

García-Magariño, I; Gómez-Sanz J.J., Pérez-Agüera J.R.; (2009) A Complete-Computerised Delphi Process with a Multi-Agent System; Programming Multi-Agent Systems - Lecture Notes in Computer Science. Springer Berlin Heidelberg

Gerdsri, N., Vatananan, R. S., & Dansamasatid, S. (2009). Dealing with the dynamics of technology roadmapping implementation: A case study. Technological Forecasting and Social Change, 76(1), 50–60. doi:10.1016/j.techfore.2008.03.013

Ghose, A. K., (2009) Technology vision 2050 for sustainable mining, Procedia Earth and Planetary Science, Vol. 1(1), September 2009, Pages 2-6, ISSN 1878-5220, 10.1016/j.proeps.2009.09.003.

Gordon, T.J. and Glenn, J.C. (2003) Futures research methodology, Version 2.0 Millennium Project of the American Council for the United Nations University

Guan, J., & Zhao, Q. (2013). The impact of university–industry collaboration networks on innovation in nanobiopharmaceuticals. Technological Forecasting and Social Change, 80(7), 1271–1286. doi:10.1016/j.techfore.2012.11.013

Guidolin, M., & Mortarino, C. (2010). Cross-country diffusion of photovoltaic systems: Modelling choices and forecasts for national adoption patterns. Technological Forecasting and Social Change, 77(2), 279–296. doi:10.1016/j.techfore.2009.07.003

Gupta, R., & Jain, K. (2012). Diffusion of mobile telephony in India: An empirical study. Technological Forecasting and Social Change, 79(4), 709–715. doi:10.1016/j.techfore.2011.08.003

Guseo, R., & Guidolin, M. (2009). Modelling a dynamic market potential: A class of automata networks for diffusion of innovations. Technological Forecasting and Social Change, 76(6), 806–820. doi:10.1016/j.techfore.2008.10.005

Hales, C., & Gooch, S. (2004). Managing engineering design. Springer.

Harrigan, K. R. (1982) Exit decisions in mature industries, Academy of Management Journal, Vol. 25 (4), pp. 707-732.

Haskins, C., Forsberg, K., Krueger, M., Walden, D., & Hamelin, D. (2006). Systems engineering handbook. In INCOSE,.

Hayes, B.E.; (2008); Measuring Customer Satisfaction and Loyalty: Survey Design, Use, and Statistical Analysis Methods; 3rd Edition, ASQ Quality Press.

Hicks B.J., Culley S.J., Allen R.D., Mullineux G.; (2002); A framework for the requirements of capturing, storing and reusing information and knowledge in engineering design; International Journal of Information Management 22, 263–280.

Hilson, G. (2000) Barriers to implementing cleaner technologies and cleaner production (CP) practices in the mining industry: a case study of the Americas, Minerals Engineering, Vol. 13, No. 7, pp. 699-717.

Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S., & Wood, K. L. (2002). A functional basis for engineering design: reconciling and evolving previous efforts. Research in engineering Design, 13(2), 65-82.

Hood, M., (2004) Advances in hard rock mining technology. In Proceedings of the Mineral Economics and Management Society, 13th Annual Conference, 21–23 April 2004, 22pp.

Huétink, F. J., Der Vooren, A. Van, & Alkemade, F. (2010). Initial infrastructure development strategies for the transition to sustainable mobility. Technological Forecasting and Social Change, 77(8), 1270–1281. doi:10.1016/j.techfore.2010.03.012

IEEE STD 1220–1998 (1998) Standard for Application and Management of the Systems Engineering Process. New York, NY, IEEE.

Ince, E. L. (1962). Ordinary differential equations, 1956.

Jarratt, T. A. W., Eckert, C. M., Caldwell, N. H. M., & Clarkson, P. J. (2011). Engineering change: an overview and perspective on the literature. Research in Engineering Design, 22(2), 103-124.

Johnson, R. A. (2009). Statistics: principles and methods. John Wiley & Sons.

Jones J.C.; (1984); A method of systematic design. In: Development in Design Methodology. Cross N. (ed.); John Wiley & sons; Ltd; Chichester.

Jun, S.-P. (2012). A comparative study of hype cycles among actors within the socio-technical system: With a focus on the case study of hybrid cars. Technological Forecasting and Social Change, 79(8), 1413–1430. doi:10.1016/j.techfore.2012.04.019

Kapurch, S. J. (2010). NASA Systems Engineering Handbook. DIANE Publishing Company. Retrieved from http://books.google.it/books?id=2CDrawe5AvEC

Kaulio, M.A. (1998). Customer, consumer and user involvement in product development: A framework and a review of selected methods. Total Quality Management, 9(1):141-149.

Kendall, M. G. (1946). The advanced theory of statistics. The advanced theory of statistics., (2nd Ed).

King, R. P. (2000) Technical notes 8. Grinding, available at www.mineraltech.com, last accessed July 2013.

Köhler, J., Wietschel, M., Whitmarsh, L., Keles, D., & Schade, W. (2010). Infrastructure investment for a transition to hydrogen automobiles. Technological Forecasting and Social Change, 77(8), 1237–1248. doi:10.1016/j.techfore.2010.03.010

Kucharavy, D.(2013) Combination of Contradictions Based approach and Logistic Curves models for Strategic Technological Forecasting.

Kucharavy, D. and De Guio, R. (2005). Problems of forecast. Proceedings from The 5th ETRIA TRIZ Future Conference. Graz, Austria.

Kucharavy, D., & De Guio, R. (2008, April). Technological forecasting and assessment of barriers for emerging technologies. In IAMOT 2008 conference proceeding.

Kucharavy, D., De Guio, R., Gautier, L., & Marrony, M. (2007, August). Problem mapping for the assessment of technological barriers in the framework of innovative design. In Proceeding of 16th International Conference on Engineering Design, ICED'07.

Kwon, T. (2012). Strategic niche management of alternative fuel vehicles: A system dynamics model of the policy effect. Technological Forecasting and Social Change, 79(9), 1672–1680. doi:10.1016/j.techfore.2012.05.015

Lawrence, K. D., Klimberg, R. K., & Lawrence, S. M. (2009). Fundamentals of forecasting using excel. Industrial Press Inc..

Lee, C.-K. (2009). How does a cluster relocate across the border? The case of information technology cluster in the Taiwan–Suzhou region. Technological Forecasting and Social Change, 76(3), 371–381. doi:10.1016/j.techfore.2008.07.005

Lee, C.-Y., Lee, J.-D., & Kim, Y. (2008). Demand forecasting for new technology with a short history in a competitive environment: the case of the home networking market in South Korea. Technological Forecasting and Social Change, 75(1), 91–106. doi:10.1016/j.techfore.2006.12.001

Lee, J., Lee, C.-Y., & Lee, K. S. (2012). Forecasting demand for a newly introduced product using reservation price data and Bayesian updating. Technological Forecasting and Social Change, 79(7), 1280–1291. doi:10.1016/j.techfore.2012.04.003

Lee, M., Kim, K., & Cho, Y. (2010). A study on the relationship between technology diffusion and new product diffusion. Technological Forecasting and Social Change, 77(5), 796–802. doi:10.1016/j.techfore.2010.01.003

Lemeshow, S., & Hosmer, D. W. (1982). A review of goodness of fit statistics for use in the development of logistic regression models. American Journal of Epidemiology, 115(1), 92-106.

Levary, R. R., & Han, D. (1995). Choosing a technological forecasting method. Industrial Management, 37(1), 14-18.

Liu, W., and Zeng, Y. (2009). Conceptual modeling of design chain management towards product lifecycle management. In Global perspective for competitive enterprise, economy and ecology (pp. 137-148). Springer London

Logistic Analysis: Loglet Lab 2 - http://phe.rockefeller.edu/LogletLab/2.0/

Logistic Substitution Model 2 (LSM2) - http://www.iiasa.ac.at/web/home/research/modelsData/LSM/LSM2.en.html

Longnecker, M., & Ott, R. (2001). An introduction to statistical methods and data analysis. ISBN-13, 854576151.

Lotka, A. J. (1925). Elements of physical biology.

Loveridge, D., & Saritas, O. (2009). Reducing the democratic deficit in institutional foresight programmes: A case for critical systems thinking in nanotechnology. Technological Forecasting and Social Change, 76(9), 1208–1221. doi:10.1016/j.techfore.2009.07.013

Mann, D. L. (2003). Better technology forecasting using systematic innovation methods. Technological

Marchetti, C. (1977). Primary energy substitution models: on the interaction between energy and society. Technological Forecasting and Social Change,10(4), 345-356.

Marchetti, C. (1980). Society as a learning system: discovery, invention, and innovation cycles revisited. Technological forecasting and social change, 18(4), 267-282.

Marchetti, C. (1985). Nuclear plants and nuclear niches: On the generation of nuclear energy during the last twenty years. Nuclear Science and Engineering,90(4), 521-526.

Marchetti, C. (1986). Fifty-year pulsation in human affairs: analysis of some physical indicators. Futures, 18(3), 376-388.

Marchetti, C., & Nakicenovic, N. (1979). The dynamics of energy systems and the logistic substitution model. PRE-24360.

Marinakis, Y. D. (2012). Forecasting technology diffusion with the Richards model. Technological Forecasting and Social Change, 79(1), 172–179. doi:10.1016/j.techfore.2011.02.010

Martin, T. G., Burgman, M. A., Fidler, F., Kuhnert, P. M., Low-Choy, S., Mcbride, M. And Mengersen, K. (2012), Eliciting Expert Knowledge in Conservation Science. Conservation Biology, 26: 29–38. doi: 10.1111/j.1523-1739.2011.01806.x

Martino, J. P. (1993), Technological forecasting for decision making, 2nd ed., North-Holland, New York, 1993.

Martino, J. P. (2003), A review of selected recent advances in technological forecasting, Technological Forecasting and Social Change, Vol. 70., pp. 719-733.

Mayer, R. J., Menzel, C. P., Painter, M. K., Dewitte, P. S., Blinn, T., & Perakath, B. (1995). Information integration for concurrent engineering (IICE) IDEF3 process description capture method report (No. KBSI-IICE-90-STR-01-0592-02). KNOWLEDGE BASED SYSTEMS INC COLLEGE STATION TX.

McClain, K. T., Humphreys, H.B. and Boscan A. (1996), Measuring risk in the mining sector with ARCH models with important observations on sample size, Journal of Empiricial Finance, Vol. 3 (4)

McGahana, A. M. and Silverman, B. S. (2001), How does innovative activity change as industries mature? International Journal of Industrial Organization, 19, pp.1141-1160., pp. 369-391.

Mentzer, J. T., & Kahn, K. B. (1995). Forecasting technique familiarity, satisfaction, usage, and application. Journal of Forecasting, 14(5), 465-476.

Meyer, P. (1994). Bi-logistic growth. Technological Forecasting and Social Change, 47(1), 89-102.

Meyer, P. S., Yung, J. W., & Ausubel, J. H. (1999). A primer on logistic growth and substitution: the mathematics of the Loglet Lab software. Technological Forecasting and Social Change, 61(3), 247-271.

Miller, George A. "The magical number seven, plus or minus two: some limits on our capacity for processing information." Psychological review 63.2 (1956): 81.

Mining Magazine(2014): "Comminution and energy efficiency": available from: http://www.miningmagazine.com/

Miranda, L. C. M., & Lima, C. a. S. (2010). A new methodology for the logistic analysis of evolutionary S-shaped processes: Application to historical time series and forecasting. Technological Forecasting and Social Change, 77(2), 175–192. doi:10.1016/j.techfore.2009.07.007

Miranda, L. C. M., & Lima, C. a. S. (2012). Trends and cycles of the internet evolution and worldwide impacts. Technological Forecasting and Social Change, 79(4), 744–765. doi:10.1016/j.techfore.2011.09.001

Mishra, S., Deshmukh, S. G. and Vrat, P. (2002), Matching of technological forecasting technique to a technology," Technol. Forecast. Soc. Change, vol. 69, pp. 1–27.

Modis, T. (1992). Predictions. Simon and Schuster.

Modis, T. (2011). US Nobel laureates: Logistic growth versus Volterra–Lotka. Technological Forecasting and Social Change, 78(4), 559–564. doi:10.1016/j.techfore.2010.10.002

Modis, T.(2002).Predictions: - 10 Years Later, Growth Dynamics, Geneva, Switzerland.

Nam, C., Kim, S., & Lee, H. (2008). The role of WiBro: Filling the gaps in mobile broadband technologies. Technological Forecasting and Social Change, 75(3), 438–448. doi:10.1016/j.techfore.2007.04.008

Nguyen T.A. and Zeng Y. (2012) "A theoretical model of design creativity: nonlinear design dynamics and mental stress - creativity relation," Journal of Integrated Design and Process Science, vol. 16, pp. 65-88.

Nikulin, C., Graziosi, S., Cascini, G., & Stegmaier, R.(2013a) Integrated Model for Technology Assessment and Expected Evolution: A Case Study in the Chilean Mining Industry. Journal of Integrated Design and Process Science.

Nikulin, C., Graziosi, S., Cascini, G., Araneda, A., & Minutolo, M. (2013b). An algorithm for supply chain integration based on OTSM-TRIZ. Procedia-Social and Behavioral Sciences, 75, 383-396.

Nikulin, C., Retamal, F., & Pastén, P. S. (2014). Método para el análisis de tecnologías basado en curvas logísticas y redes bayesianas. Dyna, 89(5), 569-578.

Nikulin, C., Perazo, F, Stegmaier, R. & Soto, F (2014) Chilean Patent Number: CL 201400660" available from : http://www.inapi.cl/

OED on Line. (1872). Method. Oxford English Dictionary. Retrieved 22, September, 2014, from http://www.oed.com/view/Entry/117561

OED on Line. (1872). Technology. Oxford English Dictionary. Retrieved 22, September, 2014, from http://www.oed.com/view/Entry/198469?redirectedFrom=technology#eid

OED on Line. (1872). Forecasting. Oxford English Dictionary. Retrieved 22, September, 2014, from http://www.oed.com/view/Entry/72980

Pahl, G., and Beitz, W., (1996) Engineering Design. A Systematic Approach". 2nd edition, Springer, ISBN:3540199179, 544 pp.

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2007). Engineering Design: A Systematic Approach (Vol. 157). Springer.

Panda, S., et al. (2013). Bioleaching of copper from pre and post thermally activated low grade chalcopyrite contained ball mill spillage. Frontiers of Environmental Science & Engineering, 1-13.

Pedersen, K., Emblemsvag, J., Bailey, R., Allen, J. K., & Mistree, F. (2000, September). Validating design methods and research: the validation square. InASME Design Theory and Methodology Conference.

Peterson, D. J., LaTourrette, T. and Bartis, J. T. (2001) New Forces at Work in Mining Industry: Views of Critical Technologies, Monograph/Reports, available on-line at www.rand.org.

Phillips, J. G., Heidrick, T. R., & Potter, I. J. (2007). Technology futures analysis methodologies for sustainable energy technologies. International Journal of Innovation and Technology Management, 4(02), 171-190.

Rábago, K. R., Lovins, A. B., and Feiler, T. E. (2001). Energy and sustainable development in the mining and minerals industries. IIED report, available on line at www.iied.org, last accessed July 2013.

Rahman, S. M., Dinar, A., & Larson, D. F. (2010). Diffusion of Kyoto's clean development mechanism. Technological Forecasting and Social Change, 77(8), 1391–1400. doi:10.1016/j.techfore.2010.03.001

Regnell, B., Beremark, P., & Eklundh, O. (1998). A market-driven requirements engineering process: results from an industrial process improvement programme. Requirements Engineering, 3(2), 121-129.

Robinson, M. A., Sparrow, P. R., Clegg, C., & Birdi, K. (2005). Design engineering competencies: future requirements and predicted changes in the forthcoming decade. Design Studies, 26(2), 123-153.

Roozenburg, N.F.M. & Eekels, J.; (1995); Product Design: Fundamentals and Methods; Wiley; Chicester, New York; ISBN:0471943517.

Roper, A. T., Cunningham, S. W., Porter, A. L., Mason, T. W., Rossini, F. A., & Banks, J. (2011). Managing the Forecasting Project. Forecasting and Management of Technology, Second Edition, 40-64.

Routley, M., Phaal, R., & Probert, D. (2013). Exploring industry dynamics and interactions. Technological Forecasting and Social Change, 80(6), 1147–1161. doi:10.1016/j.techfore.2012.04.015

Rowley, J. E. (2007). The wisdom hierarchy: representations of the DIKW hierarchy. Journal of Information Science.

Saaty, T. L. (1988). What is the analytic hierarchy process? (pp. 109-121). Springer Berlin Heidelberg

Salamatov, Y. P. (1991). System of The Laws of Technical Systems Evolution. Chance of adventure (pp. 7–174). Petrozavodsk: Karelia Publishing House (in Russian)

Savransky, S. (2000). Engineering of Creativity: Introduction to TRIZ methodology of inventive problem solving. New York, New York: CRC Press.

Senge, P. M., & Suzuki, J. (1994). The fifth discipline: The art and practice of the learning organization (p. 14). New York: Currency Doubleday.

Shafiei, E., Thorkelsson, H., Ásgeirsson, E. I., Davidsdottir, B., Raberto, M., & Stefansson, H. (2012). An agent-based modeling approach to predict the evolution of market share of electric vehicles: A case study from Iceland. Technological Forecasting and Social Change, 79(9), 1638–1653. doi:10.1016/j.techfore.2012.05.011

Sheiner, L. B., & Beal, S. L. (1981). Some suggestions for measuring predictive performance. Journal of pharmacokinetics and biopharmaceutics, 9(4), 503-512.

Shneiderman B, Fischer G, Czerwinski M, Resnick M, Myers B, Candy L, et al.; (2006); Creativity support tools: report from a US national science foundation sponsored workshop; International Journal of Human - Computer Interaction; Taylor & Francis; 20:61-77.

Shpakovsky N., (2006) Evolution Trees. Analysis of technical information and generation of new ideas" (in Russian), ISBN 5-9348-6048-8, TRIZ Profi.

Simon, H. A. (1965). Administrative behavior (Vol. 4). New York: Free Press.

Simon, H. A.; (1981); The Sciences of the Artificial (2nd ed.); MIT Press; Cambridge, MA.

Slupinski M. (2013), TECHNOLOGY FORECASTING – STATE OF THE ART UPDATE, available at http://www.format-project.eu/deliverables/public-reports-and-white-papers/deliverable-2.3/view

Sneddon, J., Soutar, G., & Mazzarol, T. (2011). Modelling the faddish, fashionable and efficient diffusion of agricultural technologies: A case study of the diffusion of wool testing technology in Australia. Technological Forecasting and Social Change, 78(3), 468–480. doi:10.1016/j.techfore.2010.06.005

Sparkes, J. R., & McHugh, A. K. (1984). Awareness and use of forecasting techniques in British industry. Journal of Forecasting, 3(1), 37-42.

Steenhof, P. a., & McInnis, B. C. (2008). A comparison of alternative technologies to de-carbonize Canada's passenger transportation sector. Technological Forecasting and Social Change, 75(8), 1260–1278. doi:10.1016/j.techfore.2008.02.009

Stuart, M. J. Jr. and Fresko, M., (2010) Autogenous and semiautogenous mills 2010 update, Proocedings of the Fifth International Conference on Autogenous & Semiautogeneous Grinding Technology, September 25-29, Vancouver, Canada

Sustainable Development Strategies Group, (2010) Report: current issues in the Chilean mining sector, available on-line at www.sdsg.org.

Technology futures analysis working group (2004) Technology futures analysis: toward integration of the field and new methods, Technology Forecasting and Social Change, Vol. 71, pp. 287-303.

Tierney, R., Hermina, W., & Walsh, S. (2013). The pharmaceutical technology landscape: A new form of technology roadmapping. Technological Forecasting and Social Change, 80(2), 194–211. doi:10.1016/j.techfore.2012.05.002

Tilton, John E. and Landsberg, Hans H. (1999). Innovation, productivity growth, and the survival of the U.S. copper industry. In: Simpson, R.D. (Ed.), Productivity in Natural Resource Industries, 109–39. Resources for the Future, Washington, D.C.

Tseng, F.-M., Cheng, A.-C., & Peng, Y.-N. (2009). Assessing market penetration combining scenario analysis, Delphi, and the technological substitution model: The case of the OLED TV market. Technological Forecasting and Social Change, 76(7), 897–909. doi:10.1016/j.techfore.2009.02.003

Tulcanaza, E., and Ferguson, G. (2001). The value of information: a guide to the strategic development of projects founded on mineral resource categorization, Transactions of the institution of mining and metallurgy section b-applied earth science , 110, b126-b135

Turk, T., & Trkman, P. (2012). Bass model estimates for broadband diffusion in European countries. Technological Forecasting and Social Change, 79(1), 85–96. doi:10.1016/j.techfore.2011.06.010

Turoff M., Hiltz S.R., Bieber M., Fjermestad J, Rana A,.; (1999); Collaborative Discourse Structures in Computer Mediated Group Communications; Journal of Computer-Mediated Communication; Volume 4, Issue 4 - Wiley.

Turton, H., & Moura, F. (2008). Vehicle-to-grid systems for sustainable development: An integrated energy analysis. Technological Forecasting and Social Change, 75(8), 1091–1108. doi:10.1016/j.techfore.2007.11.013

Ulrich, K. T., Eppinger, S. D., & Goyal, A. (2011). Product design and development (Vol. 2). New York: McGraw-Hill.

Utterback, J. M., & Abernathy, W. J. (1975). A dynamic model of process and product innovation. Omega, 3(6), 639-656.

Vanherck, K & Pucciarini, A (2013) SURVEY OF INDUSTRIAL ORGANIZATIONAL MODELS AND IDENTIFICATION OF RELATED NEEDS AND REQUIREMENTD: available at http://www.format-project.eu/deliverables/public-reports-and-white-papers/deliverable-2.1/view

Verganti, R. (2013). Design driven innovation: changing the rules of competition by radically innovating what things mean. Harvard Business Press.

Verhulst, P. F. (1977). A note on the law of population growth. In Mathematical Demography (pp. 333-339). Springer Berlin Heidelberg.

Vicente, M. R., & Gil-de-Bernabé, F. (2010). Assessing the broadband gap: From the penetration divide to the quality divide. Technological Forecasting and Social Change, 77(5), 816–822. doi:10.1016/j.techfore.2009.12.006

Wang, M.; Zeng, Y.; (2009); Asking the right questions to elicit product requirements, International Journal of Computer Integrated Manufacturing, Vol. 22, No. 4, 2009, 283–298. DOI: 10.1080/09511920802232902

Ward, S., Barr, S., Butler, D., & Memon, F. a. (2012). Rainwater harvesting in the UK: Socio-technical theory and practice. Technological Forecasting and Social Change, 79(7), 1354–1361. doi:10.1016/j.techfore.2012.04.001

Warhurst, A. and Bridge, G. (1996), Improving environmental performance through innovation: recent trends in the mining industry, Minerals Engineering, Vol. 9 (9), pp. 907-921.

Wasserman, G. S. (1993). On how to prioritize design requirements during the QFD planning process. IIE transactions, 25(3), 59-65.

Watanabe, C., Moriyama, K., & Shin, J.-H. (2009). Functionality development dynamism in a diffusion trajectory: A case of Japan's mobile phones development. Technological Forecasting and Social Change, 76(6), 737–753. doi:10.1016/j.techfore.2008.06.001

Watts, R. J., & Porter, A. L. (1997). Innovation forecasting. Technological Forecasting and Social Change, 56(1), 25-47.

Weir Slurry Group, (2009) Mill circuit pum manual, Report, available on-line at www.weirminerals.com, last accessed July 2013.

World Commission on Environment and Development (1987). Our Common Future. Oxford Univ. Press, Oxford.

World Commission on Environment and Development. (1987). Our common future (Vol. 383). Oxford: Oxford University Press.

Worrell, E., Laitner, J.A., Ruth, M., and Finman, H. (2003) Productivity benefits of industrial energy efficiency measures. Energy J 21:1081–1098.

[7] Appendix

7.1 Appendix A - Test comparison between different software tools and logistic growth curve equations

The analysis presented in this appendix aims at understanding the different applied logistic growth curves and mathematics algorithms among different available software tools in literature. The test was divided in two parts. Part A, a test was developed by using experimental data and adding different percentage of noise. Part B, according to the results of the first experiment, two logistic growth curves were compared to select the most suitable for this research.

7.1.1 Part A: Comparison among different software tools

During this analysis four different software tools were tested to identify which one behaves better under different type of data. The selection of the software was based on the practical use and availability of those software tools. The four tested softwares were: i) Loglet lab; ii) Logistic Substitution Model Software; iii) Minintab, in specific the non-linear regression package; and iv) Matlab, a computer code was created to test this software. The selected logistic growth curve used during this test was Meyer's equation which provides a clear understanding of the regression parameters (Equation 1). These parameters have been already discussed in section 3.2.

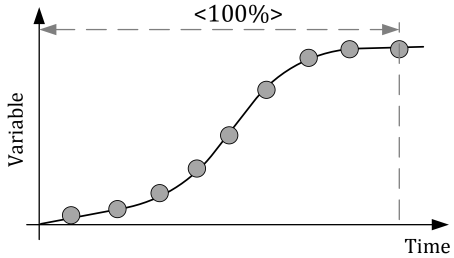
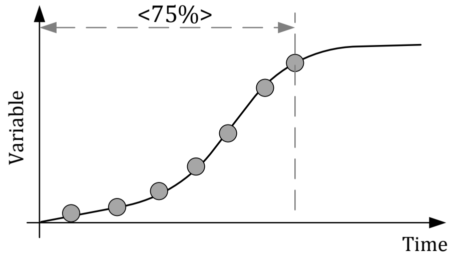
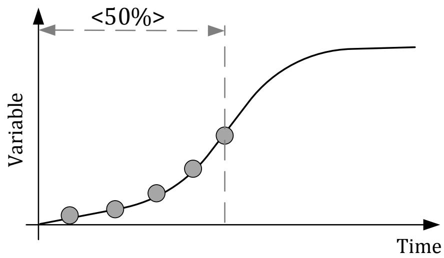
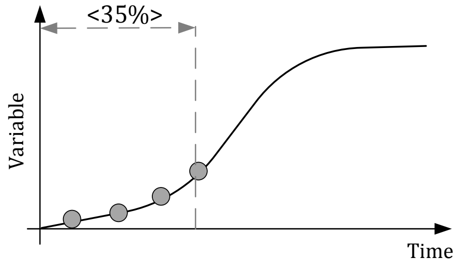
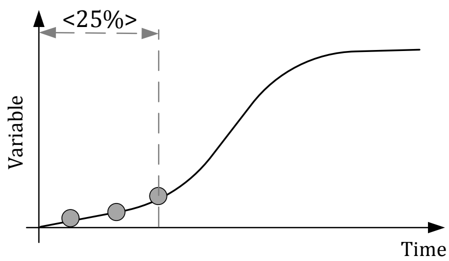
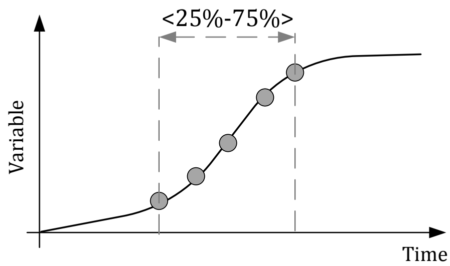
$$N(t) = \frac{K}{1 + e^{-\frac{\ln(81)}{\Delta t}(t - t_m)}}$$

Equation 1: Meyer's equation to test the accuracy and reliability among different software tools to develop logistic growth curve.

The experiment tested the software tools reliability by using different sets of data. Moreover, the tests were useful to identify the main features, advantages and disadvantages between software tools. The software tools have been evaluated considering: i) quality of the results using statistic approach (number of index and indicator to measure the reliability of the results); and ii) flexibility of the software to develop the analysis and interact with the analyst.

Six tests were developed by using different quantity of data points (Table 31). Additionally, the experimental data was modified by using different percentages of noise (i.e. 5%, 10% and 20%). The utilization of both, data quantity and noise's percentages, allows to deal with different real potential situations.

Table 31: Description of experimental test among different software tools which are capable to develop a logistic growth curve analysis.

Test 1: 100% of data points	Test 2: 75% of data points
	
Test 3: 50% of data points	Test 4: 35% of data points
	
Test 5: 25% of data points	Test 6: between 25% and 75% of data points
	

7.1.2 Part A: Results

In the next table is presented the obtained parameter results from different software tools. In black color are presented the accurate results, on the contrary, in red color are presented the non-accurate results according to the initial data. Regardless to the statistic information, the p-value of the regression is represented by the number of stars ((*)=p-value >0.05; (**)=0.01<p-value <0.05; (***)=p-value <0.05) (Table 32).

Table 32: Experimental test to compare different software tools.

Meyer Equation		5% (Noise)				10%(Noise)				20%(Noise)			
Percentage of Data	Parameter	Matlab	Loglet	IIASA	Minitab	Matlab	Loglet	IIASA	Minitab	Matlab	Loglet	IIASA	Minitab
100%	K	49,28***	49,28	49,28	49,27	48,87***	48,87	48,87	48,87	48,64***	48,98	48,98	48,64
	dt	4,95***	4,95	4,95	4,95	5,06***	5,06	5,06	5,06	5,21***	5,25	5,25	5,21
	tm	2,45***	2,45	2,45	2,45	2,46***	2,46	2,46	2,46	2,50***	2,52	2,52	2,50
75%	K	51,12***	50,87	51,12	51,12	48,52***	48,32	48,52	48,52	48,52***	49,07	49,39	49,39
	dt	5,09***	5,1	5,09	5,09	4,97***	4,97	4,97	4,97	4,97***	5,27	5,22	5,22
	tm	2,54***	2,53	2,54	2,54	2,43***	2,42	2,43	2,43	2,43***	2,52	2,53	2,53
50%	K	53,05***	26,03	53,05	53,05	63,48**	26,21	63,49	63,49	85,49**	42,25	85,5	85,50
	dt	5,17***	3,46	5,17	5,17	5,48***	3,5	5,48	5,48	5,79**	5,82	5,79	5,79
	tm	2,62***	1,21	2,62	2,62	3,00**	1,23	3,01	3,00	3,58*	2,22	3,58	3,58
35%	K	43,97**	18,55	43,97	43,97	61,6	18,91	61,6	61,6	248,32	18,22	248,35	248,35
	dt	4,91***	2,98	4,91	4,91	5,32**	3,02	5,32	5,32	6,42*	3,09	6,42	6,42
	tm	2,27**	0,76	2,23	2,26	2,9	0,78	2,9	2,9	5,57	0,74	5,57	5,57
25%	K	5665,6	13,66	618174	3192,97	24,44	13,17	24,44	24,44	23,38	10,4	23,38	23,38
	dt	5,88**	2,52	5,96	5,94	4,19**	2,52	4,19	4,19	4,41	0,55	4,41	4,41
	tm	6,27	0,38	15,89	8,69	1,27	0,35	1,27	1,27	1,23	0,55	1,23	1,23
Between (25%-75%)	K	50,93***	43,85	50,93	59, 93	48,22***	42,89	48,22	48,22	51,42***	42,5	51,42	51,42
	dt	5,06***	4,34	5,07	50,6	4,92***	4,38	4,92	4,92	5,54**	4,51	5,54	5,54
	tm	2,53***	2,24	2,53	2,53	2,41***	2,19	2,41	2,41	2,64**	2,21	2,64	2,64

An additional table was developed for Matlab application; this table presented the confidence interval results for each regression (Table 33). The need of presenting the confidence interval emerged from the understanding of the reliability of the final results by taking into consideration not only the fit, but also the reliable interval of the results. Among the other software tools only Loglet provided a confidence interval but mainly from visual aspects.

Table 33: Results of Matlab application with Confidence Interval.

		5% (Noise)			10% (Noise)			20% (Noise)		
Size of the sample	**Parameter**	**Matlab**	**Confidence Interval 95% [Lower-Upper limits]**		**Matlab**	**Confidence Interval 95% [Lower-Upper limits]**		**Matlab**	**Confidence Interval 95% [Lower-Upper limits]**	
100%	**K**	49,28***	48,59	49,97	48,87***	47,28	50,46	48,64***	45,76	51,52
	dt	4,95***	4,83	5,07	5,06***	4,78	5,33	5,21***	4,72	5,71
	tm	2,45***	2,41	2,49	2,46***	2,36	2,56	2,50***	2,31	2,68
25%	**K**	5665,6	-6670,23	7549,03	24,44	-0,39	49,27	23,38	-33,82	80,58
	dt	5,88**	4,00	7,71	4,19**	2,01	6,37	4,41	-1,47	10,28
	tm	6,27	-17,86	29,68	1,27	-0,55	3,10	1,23	-3,43	5,90
50%	**K**	53,05***	43,77	62,32	63,48**	30,82	96,15	85,49**	30,82	96,15
	dt	5,17***	4,81	5,53	5,48***	4,61	6,36	5,79**	4,61	6,36
	tm	2,62***	2,25	2,99	3,00**	1,91	4,10	3,58*	1,91	4,10
75%	**K**	51,12***	49,62	52,62	48,52***	45,47	51,58	48,52***	45,47	51,58
	dt	5,09***	4,95	5,24	4,97***	4,64	5,30	4,97***	4,64	5,30
	tm	2,54***	2,46	2,62	2,43***	2,26	2,60	2,43***	2,26	2,60
Between (25%-75%)	**K**	50,93***	48,39	53,48	48,22***	43,36	53,07	51,42***	43,36	53,07
	dt	5,06***	4,76	5,37	4,92***	4,28	5,57	5,54**	4,28	5,57
	tm	2,53***	2,41	2,66	2,41***	2,16	2,67	2,64**	2,16	2,67
35%	**K**	43,97**	30,21	57,73	61,6	-44,84	168,03	248,32	-3358,08	3854,71
	dt	4,91***	4,40	5,42	5,32**	3,32	7,33	6,42*	2,18	10,67
	tm	2,27**	1,66	2,87	2,9	-0,37	6,17	5,57	-19,63	30,77

7.1.3 Part A: Discussion and Conclusions

This test aimed at identifying advantages and disadvantages among software tools that allow developing forecasting analysis based on logistic growth curve. To achieve this goal, an experiment was carried out by considering four different software tools that were classified according to the reason for which they were built: i) specific for forecast based on logistic growth curve (i.e., IIASA and Loglet); and ii) statistics analysis (i.e., Matlab and Minitab).

As a result, several differences emerged: Loglet does not provide the user with robust indicators to validate the forecast. Moreover, the results of the regression are focused mainly on analysts' judgment and visual fitness. Differently, the IIASA provides some regression indicator as R-square. However, more robust analyses are missing (e.g., significance of the parameter as p-value). Both software applications have a high flexibility to provide logistic growth curve analysis, but their results are mainly based on analysts' skill. On the other hand, Minitab and Matlab provide similar results with more statistic information about the quality of the fitness. However, Minitab and Matlab were not built with the specific goal of developing logistic curves; the time needed to develop logistic growth curve analysis is higher compared with the other tools as IIASA and Loglet.

7.1.4 Part B: Comparison among different logistic growth curves

This test aims at identifying the most suitable logistic growth curve to be applied by both, beginners and practitioners. The activities were approached in two ways. First, identification of the most suitable and comprehensive results according to the logistic growth curve applied to the forecasting analysis. And secondly, number of parameters used in the logistic equation, that frequently correspond to three parameters: i) first, parameter related to the dimension or saturation value; ii) second, parameter related to the shape of the curve (how fast the curve grows); and iii) third, parameter related to the time position (where is located the curve along the time axis). The activities of this task resulted in the selection of two main logistic curves: simple logistic curve and logistic curve based on Meyer's equation (Table 34).

Table 34: Two of the most common logistic growth curve applied in literature

a) Simple logistic equation	**b) Meyer logistic growth equation**
$N(t) = \dfrac{K}{1 + e^{-\alpha * t + \beta}}$	$N(t) = \dfrac{K}{1 + e^{-\frac{\ln(81)}{\Delta t}(t - t_m)}}$

The new test considers only the best and worst situation based on the previous results (Part A). Minitab analysis was omitted given it provides the same results of Matlab from previous analysis (Part A). The results of the experiment are presented in the next subsection.

7.1.5 Part B: Results

In table 35 are presented the values for the equation parameters. It is important to mention that Loglet does not provide results for the "simple logistic equation", however, it was included for further comparison.

Table 35: Comparison among two logistic growth equations applied in literature and software tools.

			Without noise			5% (Uncertainty)			20% (Uncertainty)		
			Matlab	Loglet	IIASA	R	Loglet	IIASA	Matlab	Loglet	IIASA
100% Data	Both	K	50,00***	50,00	50,00				49,74***	45,31	49,74
	Simple	Alfa	1,70***	-	1,70				1,68***	-	1,69
		Beta	4,25***	-	-				4,18***	-	-
	Meyer	Dt		2,59	2,59				-	2,50	2,61
		Tm	2,50***	2,50	2,50				2,48***	2,50	2,48
25% Data	Both	K	50,06***	4,52	50,06	27,06*	4,44	27,06	6,94	6,22	6,94
	Simple	Alfa	1,70***		1,67	1,72***		1,72	2,22		2,22
		Beta	4,25***			3,60*			2,26		
	Meyer	Dt		1,51	2,59		1,52	2,55		2,00	1,98
		Tm	2,50***	0,64	2,50	2,09**	0,63	2,09	1,02	0,93	1,02
50% Data	Both	K							38,27	23,82	38,27
	Simple	Alfa							1,91**	-	1,91
		Beta							4,17*	-	-
	Meyer	Dt							-	2,11	2,30
		Tm							2,18**	1,78	2,19
75% Data	Both	K							51,92***	51,92	51,92
	Simple	Alfa							1,62***		1,62
		Beta							4,11***		
	Meyer	Dt								2,72	2,72
		Tm							2,54***	2,54	2,54
35% Data	Both	K							717,02	10,94	740,40
	Simple	Alfa							1,59*		1,59
		Beta							6,89		
	Meyer	Dt								0,85	2,76
		Tm							4,33	0,85	4,35

7.1.6 Part B: Discussion and Conclusions

According to the results in table 35, the most suitable equation to use for forecasting based on logistic growth curve corresponds to Meyer's equation, because it is more robust (less sensible according to the number of observation) and it is easy to be used by design engineers (the parameters are easy to understand for beginners).

Finally, a new software tool was developed in Matlab attempting to combine flexibility (as for IIASA and Loglet) and robustness (as for Minitab). This new software tool has been already discussed on section 3.3.

Appendix B - Classification of logistic growth papers from Technological Forecasting and Social Changes Journal.

This appendix collects the classified papers from the main Journal "Technology Forecasting and Social Changes". The papers were split in two groups. Firstly, papers which provide quantitative data about the regression analysis. Secondly, papers which provide a theoretical framework for the application of logistic growth model (Table 36).

Table 36: Classification of papers with application of logistic growth models from Technological Forecasting and Social Changes journal (Papers from 2008 until December 2013).

Paper authors' name	Context		Characteristic of the variable						
	System	Detail of system/ecosystem	Name Parameter	Logistic growth variable (Y-axis)	Rate of Growth variable	Initial observation	last observation	Time period	data points
Bers, J. a., Dismukes, J. P., Miller, L. K., &Dubrovensky, A. (2009).	Theoretical paper								
Boretos, G. P. (2009).	World	economy	GDP	GDP/year	(GDP/year)/year	1948	2008	60	60
	World	geographical	Population	Population/year	(Population/year) /year	1948	2008	60	60
	World	economy	GDP per capita	GDP per capita/year	(GDP per capita/year)/year	1948	2008	60	60
Cantono, S., & Silverberg, G. (2009).	World	theory	Probability	cumulative probability	non defined	0	60	60	(2)
Chang, Y. S., &Baek, S. J. (2010).	World	Technology (Cu/al Wireless)	Performance (Bit per second)	(Bit per Second/year)	non defined	1962	2002	40	(2)
	World	Technology (Fibber optics)	Performance (Bit per second)	(Bit per Second/year)	non defined	1982	2002	20	(2)
	World	Technology(Wireless)	Performance (Bit per second)	(Bit per Second/year)	non defined	1972	2002	30	(2)
	World	Technology (tungsten filament lamp)	Performance (luminous efficacy)	lumens per watt	non defined	1980	2000	20	10
	World	Technology (Compact fluorescent lamp)	Performance (luminous efficacy)	lumens per watt	non defined	1975	2004	29	8
	World	Technology (Low pressure Sodium)	Performance (luminous efficacy)	lumens per watt	non defined	1920	2010	90	12
	World	Technology (Military Fighter Aircraft) (Piston engine-Jet engine)	Performance (Kilometres per hour)	Kilometres per hour	non defined	1930	2010	80	17
	World	Technology (Mass produced Car)	Performance (Kilometres per hour)	Kilometres per hour	non defined	1900	2010	110	20
	World	Technology (Conventional wheeled train) (steam-electric-diesel)	Performance (Kilometres per hour)	Kilometres per hour	non defined	1848	2010	162	12
Chiang, S.-Y., & Wong, G.-G. (2011).	Taiwan	Manufactured computer (Desktop computer)	number of shipment	non provided	number of shipment /year	1988	2007	19	19
	Taiwan	Manufactured computer	number of shipment	non provided	number of shipment /year	1988	2007	19	19

		(notebook computer)							
Christodoulos, C., Michalakelis, C., &Varoutas, D. (2011).	OECD countries	Economy (Market penetration)	Percentages	percentage	not provided	1997	2009	12	24
	US	Economy (Market penetration)	Percentages	percentage	not provided	1997	2009	12	24
Chu, C.-P., & Pan, J.-G. (2008).	Taiwan	Economy (Number of Subscribers)	Number of subscribers (GPRS)	cumulative subscribers/year	not provided	2001	2013	12	14
	Taiwan	Economy (Number of Subscribers)	Number of subscribers (PHS3G)	cumulative subscribers/year	not provided	2001	2013	12	14
Chyong Chi, K., Nuttall, W. J., & Reiner, D. M. (2009).	UK	Economy (gas production)	gas production	cumulative gas production/year	not provided	1987	2004	17	17
Coccia, M. (2010).	World	Economy (Patents)	Number of Patents	Patents/year	not provided	1900	2000	(1)	(2)
Connelly, M. C., Dismukes, J. P., &Sekhar, J. a. (2011).	EPO	Economy (Patents)	Number of Patents	Patents/year	not provided	1900	2010	110	(2)
Devezas, T. (2010).	World	Economic (Population)	Population	Population/year	not provided	1950	2010	60	60
Dismukes, J. P., Miller, L. K., &Bers, J. a. (2009).	Theoretical paper								
Gerdsri, N., Vatananan, R. S., &Dansamasatid, S. (2009).	Theoretical paper								
Guidolin, M., &Mortarino, C. (2010).	Countries	Economic (Population)	MW by country (Japan, German,USA)	not provided	Installed power/year	1992	2006	14	14
Guseo, R., &Guidolin, M. (2009).	Theoretical paper (Mathematic)								
Huétink, F. J., Der Vooren, A. Van, & Alkemade, F. (2010).	World	Economic (H2 vehicle fleet penetration)	Ratio	ratio/year	not provided	2010	2010	(1)	(2)
Köhler, J., Wietschel, M., Whitmarsh, L., Keles, D., &Schade, W. (2010).	Theoretical paper								
Lee, C.-K. (2009).	Theoretical paper								
Lee, C.-Y., Lee, J.-D., & Kim, Y. (2008).	World	Economic (diffusion)	Number of new household	Number of new household/year	not provided	2002	2009	7	3
Lee, M., Kim, K., & Cho, Y. (2010).	World	Economic (Patent)	Patent citations	Cumulative patent citations	Patent citations/year	1991	2005	14	14
Loveridge, D., &Saritas, O. (2009).	Theoretical paper								
Miranda, L. C. M., & Lima, C. a. S. (2010).	World	Economic (Population)	Billions of persons	Billions of persons/year	not provided	1600	2010	410	(2)
Miranda, L. C. M., & Lima, C. a. S. (2010).	USA	Economic (corn production)	Percentage hybrid corn	Ratio/Year	not provided	1930	1970	40	5
	USA	Economic (corn production)	Corn production	Cumulative corn production (Bushels)/Year	not provided	1860	2010	150	(2)
	USA	Economic (corn production)	Corn production	Yield-Bushels per acre	not provided	1860	2010	150	(2)
	USA	Economic (consumption)	Consumption (Million tons)(Steel and cement)	Cumulative consumption (millions tons)	not provided	1900	2009	109	(2)
Modis, T. (2011).	America	Social (Nobel prize winners)	Number of Nobel prize	Cumulative American Nobel prize	American Nobel prize/years	1900	2009	109	109

				winners					
	America	Social (Nobel prize winners per laureates)	Number of Nobel prize per laureates	Cumulative American Nobel prize winners per laureates	Cumulative American Nobel prize winners per laureates/years	1900	2009	109	109
	America	Social (Nobel laureates)	Nobel laureates	Nobel laureates per decade	not provided	1900	2009	109	11
Nam, C., Kim, S., & Lee, H. (2008).	World	Economic (demand)	Demand (thousands units) Wibro Only	thousands units/year	not provided	2006	2012	6	12
	World	Economic (demand)	Demand (thousands units)WLAN	thousands units/year	not provided	2006	2012	6	12
			CO2 production	cumulative mtCO2e/year	not provide	2003	2009	6	(2)
Rahman, S. M., Dinar, A., & Larson, D. F. (2010).	Kyoto	Economic/environmental (mtC02)	production	mtC02	not provide	2003	2012	(1)	(2)
Sneddon, J., Soutar, G., &Mazzarol, T. (2011).	Australia	Economic/environmental (ratio)	Proportion of Australian greasy wool	Percentage	not provide	1988	2006	(1)	(2)
Steenhof, P. a., & McInnis, B. C. (2008).	Canadian	Economic/environmental (ratio)	Proportion	Percentage	not provide	2005	2008	(1)	(2)
Tseng, F.-M., Cheng, A.-C., & Peng, Y.-N. (2009).	World	Economic (TV technologies)	Market share	Ratio	not provide	2000	2007	7	15
Turton, H., &Moura, F. (2008).	World	Economic (Vehicles)	Market share	Ratio	not provide	2000	2007	(1)	(2)
Vicente, M. R., & Gil-de-Bernabé, F. (2010).	Theoretical paper								
Watanabe, C., Moriyama, K., & Shin, J.-H. (2009).	Japan	Economic (diffusion)	Market Ratio	Ratio	Rate of Ratio(velocity)	1996	2006	(1)	(2)
Aguilera, R. F., & Aguilera, R. (2012).	World	Environmental (global fossil carbon emission)	Metric tons of Carbon	Metric tons of Carbon/Year	not provided	1850	2012	162	(2)
Devezas, T., Cristovão, F., Melo, L. De, Luisa, M., Cristina, M., Salgado, V., Ribeiro, J. R., et al. (2012)..	World	Economic (Events)	Intensity of activity accumulated	Number of events/year	not provided	1930	2010	80	80
	World	Economic (Events)	Intensity of activity accumulated	Satellites launching "events"	not provided	1957	2010	53	53
Diaz-Rainey, I., &Tzavara, D. (2012).	Theoretical paper								
Guan, J., & Zhao, Q. (2013). The	World	World patent databases	amount of members of university-industry collaboration patents	member counts/year	not provided	1991	2009	13	13
Gupta, R., & Jain, K. (2012).	World	Economic (Mobile density)	Mobile subscribers per 100	Mobile subscribers per 100/ Year	not provided	1998	2009	11	11
Jun, S.-P. (2012).	Theoretical paper								
Kwon, T. (2012).	World	Economic (Market share)	Market Share for alternative fuel vehicles	Ratio	not provided	0	30	30	(2)
Lee, J., Lee, C.-Y., & Lee, K. S. (2012).	World	Economic (Number of subscribers)	Number of Subscribers	Millions	not provided	0	25	25	(2)
Marinakis, Y. D. (2012).	World	Economic/technology (Cumulative number of research	Number of research publications	Cumulative number of research publications	not provided	0	60	60	14

		publications)							
	World	Economic (Number of farmers adopting hybrid seed corn)	Number of farmers adopting hybrid seed corn	Number of farmers adopting hybrid seed corn	not provided	0	60	60	14
	World	Economic/technology (Cumulative number of research publications)	Number of research publications	Cumulative number of research publications	not provided	0	60	60	14
Miranda, L. C. M., & Lima, C. a. S. (2012).	World	Economic (Number of internet hosts in millions)	number of internet host	cumulative number of internet host in millions	not provided	1990	2010	20	(2)
	World	Economic (penetration index)	penetration index	index	not provided	1996	2012	16	16
	World	Economic (number of events)	number of events building the internet	cumulative number of events	not provided	1955	2010	55	50
Routley, M., Phaal, R., & Probert, D. (2013).	Theoretical paper								
Shafiei, E., Thorkelsson, H., Ásgeirsson, E. I., Davidsdottir, B., Raberto, M., & Stefansson, H. (2012).	World	Economic (Share of Electricity Vehicles)	Share of Electricity Vehicles	Percentage	not provided	2011	2012	(1)	(2)
Tierney, R., Hermina, W., & Walsh, S. (2013).	Theoretical paper								
Turk, T., &Trkman, P. (2012).	Europe	Economic (Number of subscribers)	Number of subscribers broadband per 100 habitants	cumulative Number of subscribers	number of subscribers	2002	2010	8	(2)
Ward, S., Barr, S., Butler, D., &Memon, F. a. (2012).	Theoretical paper								

7.2 Appendix C- Requirements list vacuum forming case study

In table 37 is presented the requirements list of the vacuum forming case study and related classification.

Table 37: requirements list of vacuum forming case study

Level	Process of Cabinet manufacturing (technology) (Requirement at 2013)	Qual. (Ql) or Quant. (Qt)	Units of measure	Context	Behavior based on expert knowledge (Since1993)	Data Available and data source
Super system (Whirlpool Facilities and White Good Industry)	Production of Manufacturing industry	Qt	[Economic-index]	Economic	Fluctuating	YES-External
	Cycle time of Vacuum Forming (VF) phases	Qt	[min]	Technological	Decreasing	YES-Internal
	Vacuum insulation panel (VIP) in top level fridges;	Ql	[YES-NO]	Technological	Stable	NO
	Automation level of the refrigerator	Qt	[Number of electronics and automatic options]	Technological	Increasing	NO
	Refrigerators differentiation level	Ql	[Perception of the customers]	Technological	Fluctuating	NO
	Model of refrigerators	Qt	[Number of refrigerator in the market]	Economic	Increasing	NO
	Material quantity	Qt	[kg]	Technological	Decreasing	YES-Internal
	Effective volume of refrigerator	Qt	[m^3]	Technological	Increasing	YES-Internal and External
	Energy consumption of refrigerators	Qt	[kilowatts]	Technological	Decreasing	YES-Internal and external
	Dimension of the refrigerators	Qt	[length(m), width(m), height(m)]	Technological	Increasing	NO
System (Vacuum Forming)	Time to process polystyrene granules	Qt	[min]	Technological	Decreasing	YES-Internal
	Quantity of scrap produced by refrigerator	Qt	[Kg]	Technological	Fluctuating	YES-Internal
	3D polymer form shape is more complex	Ql	[curves, form]	Technological	Increasing	NO
	Cumulative production process	Qt	[cumulative number of pieces]	Technological	Increasing	YES-Internal
	Energy consumption	Qt	[kilowatts]	Technological	Decreasing	YES-Internal
	Human involvement	Ql	[Number of operators]	Social	Decreasing	YES-Internal

	Environmental Taxes	Qt	[Percentage]	Economic	Increasing	YES-Internal
	Area of production line	Qt	[m²]	Technological and Economic	Unknown	NO
	Initial investments into equipment	Qt	[Cost]	Economic	Increasing	YES-Internal
	Complexity of mold is higher	Ql	[curves, forms]	Technological	Increasing	NO
	Time to maintenance	Qt	[min]	Technological	Decreasing	YES-Internal
Sub-system (Vacuum Process phases)	Thickness of polymer	Qt	[mm]	Technological	Decreasing	YES-Internal
	Capacity of extruder	Qt	[kg/h]	Technological	Increasing	Yes-Internal
	VF cycle time for making 3D shape	Qt	[min]	Technological	Decreasing	YES-Internal
	amount of materials	Qt	[kg]	Technological/Economics	Decreasing	YES-Internal
	VF Length range	Qt	[mm]	Technological	Increasing	Yes-Internal
	VF Width range	Qt	[mm]	Technological	Increasing	Yes-Internal
	Cost for mold	Qt	[Cost]	Economic	Decreasing	YES-Internal
	Complexity of mold	Ql	[curves, forms]	Technological	Increasing	NO

7.3 Appendix D - Requirements list of mining mill case study

In table 38 is presented the requirements list of the mining mill case study and related classification.

Table 38: requirements list of mining mill case study.

	Past (1994)	**Present (2014) Requirements**	**Units of measure**	**Qualitative/ Quantitative**	**Behavior based on expert knowledge (Since 1994)**
Super-system (Copper production and world context)	Lower	Copper Production	[ton/year]	Quantitative	Increasing
	Lower	Energy consumption of mining industry	[MW]	Quantitative	Decreasing
	Higher	Percentage of the copper available in the ore	[%]	Quantitative	Decreasing
System (mining mills)	Lower	Mill production	[ton/hours]	Quantitative	Increasing
	Lower	Size of the mining mill	[m], [ft]	Quantitative	Increasing
	Lower	Mechanical horse power	[MW]	Quantitative	Increasing
	Lower	Efficiency	[-]	Quantitative	Increasing
	Higher	Maintenance time	[hr/year]	Quantitative	Decreasing
	Higher	Number of failure	[Number]	Quantitative	Decreasing
	Lower	Volume of the mill	[m^3]	Quantitative	Increasing
Sub-system (mining mills components)	Higher	Quantity of liners	[Number]	Quantitative	Decreasing
	Higher	Quantity of lifter	[Number]	Quantitative	Decreasing
	Higher	Maintenance time (plate and lifter)	[hr/year]	Quantitative	Decreasing
	stable	Granulometry	[mm], [cm]	Quantitative	Stable
	Higher	Number of failure (plate and lifter)	[number]	Quantitative	Decreasing
	Lower	Percentage of balls	[%]	Quantitative	Increasing
	Higher	Number of accidents	[number]	Quantitative	Decreasing
	Higher	Percentage of water	[%]	Quantitative	Decreasing

7.4 Appendix E - Requirements list of washing machine case study

In table 39 is presented the requirements list of the washing machine case study.

Table 39: requirements list of the washing machine case study

Number	Name of the performance	Unit	Brief Description
1	Compartment capacity of washing machine	[ft^3]	Effective capacity of the washing machine
2	Power Consumption of washing machine	[KWh]	Energy used by a washing machine considering both mechanic and electric energy
3	Water Consumption of washing machine	[gallons]	Quantity of water used by washing machine in every cycle
4	Water Factor of washing machine (WFC)	[total weight per cycle/capacity of clothes]	Performance created by “ENERGY STAR”, a high water factor means a better performance.
5	Energy Factor of washing machine	[ft^3/kWh/cycle]	Performance created by “ENERGY STAR”, helps to compare capacity, consumption by cycle. A higher value for Energy factor means a better performance.
6	Remaining Moisture % at clothes	[Percentages]	Percentage of water evacuation during the spin cycle
7	Modified Energy Factor of washing machine (MEF)	[ft^3/kWh/cycle]	Performance created by “ENERGY STAR”, helps to compare capacity, consumption by cycle and remain moisture, a higher value for Energy factor means a better performance.
8	Number of washing machine sold in Europe	[number]	-
9	Index laundry market in United States	[Index]	This index is used to understand the market condition of the laundry industry in United States.
10	Horizontal door in the washing machine	[YES]	Model of washing machine
11	Wash temperature	[°C]	Temperature used during the washing process.
12	Automatic washer control	[YES]	Type of washing machine
13	Weight of clothes	[lb]	Quantity of weight that the washing machine is capable to wash
14	Vibration of the dampers	[hz]	Vibration during the spinning
15	Wash cycle time	[min]	Time required by the wash cycle
16	Cycles with different kind of textiles	[number]	Number of different cycles available in a washing machine
17	Dimension of the clothes	[ft3]	Size of the clothes to be washed
18	Quality of the clothes after the wash	[clean, not clean]	Quality of the clothes after the washing process.
19	Resistance of the bearing	[MPa]	Mechanical resistance of washing machine parts
20	Resistance of the dampers	[Mpa]	Mechanical resistance of washing machine parts
21	Material quantity to build a washing machine	[lb]	Total amount of material used to build a washing machine
22	Size of the washing machine	[ft^3]	Total dimension of the washing machine
23	Number of rinse cycles	[number]	Number of different rinse cycles available in a washing machine
24	Number of part to build a	[number]	Number of different parts used to build a

	washing machine		washing machine
25	Time to produce a washing machine	[hrs]	Total time to build a washing machine

7.5 Appendix F – Test with students (Data and information)

In this appendix is presented the data and information delivered to the students during the control group test for both Group-A and Group-B.

7.5.1 Application of a method for forecasting: Case study of Washing Machine

The washing machine is one of the most common appliances used at home. A certain company (USM) is interested to know about the future in Europe for this product according to the parameters listed in Table 40. The expected outcomes that the company would like to have are:

a) Forecast for the next 10 years, giving recommendations and descriptions for **each** requirement and parameter.
b) Reliability of the forecast results.

In order to accomplish these outcomes feel free to use all the techniques, methods and tools that you already know.

Table 40: Description of the requirements and parameters for washing machine (test).

N	Name of the requirement and parameter	Units of Measure	Information about the requirement	Data available
1	Market indicator for WM in Europe	Percentage	This indicator is used to understand how much the home appliances market has grown concerning the WM.	From 1990 until 2013
2	Number of WM sold in Europe	Number of Product	-	Not available
3	Available space to install WM at home	[m^2]	-	Not available
4	Load capacity of WM	[ft^3]	Volume of the WM container.	From 2002 until 2013
5	Energy consumption of WM	KWh per cycle	Energy consumption for a WM per cycle, this parameter considers the mechanical and electric energy.	From 2002 until 2013
6	Automatic control panels	YES/NO	Qualitative parameter concerning the level of automatization of WM (In the last years has been increasing).	Not available
7	Water Factor	gallons per cycle per cubic foot	Variable to compare the WM water consumption independent of WM capacity. A lower value means more water efficiency for the WM.	From 2002 until 2013
8	Integrity of the clothes after the washing process	YES/NOT	Qualitative Parameter	Not available

9	Remain Moisture[6]	Percentage	Moisture that remains in the clothes after the washing process.	From 2002 until 2013
10	Recyclability [7]	Less/More	Qualitative parameter concerning the recyclability of the WM parts.	Not available

7.6 Appendix G - Questionnaire for both Groups A and B

In this appendix is presented the questionnaire developed at the end of the experiment for both Groups-A and Group-B.

7.6.1 Section: Evaluation tools and methods

1. According to your feeling, are the LGR appropriate to build the forecasting results?
   - ☐ Absolutely inappropriate
   - ☐ Inappropriate
   - ☐ Slightly inappropriate
   - ☐ Neutral
   - ☐ Slightly appropriate
   - ☐ Appropriate
   - ☐ Absolutely appropriate

2. Is the **software** you used appropriate to provide support and interpretation of the outcomes?
   - ☐ Absolutely inappropriate
   - ☐ Inappropriate
   - ☐ Slightly inappropriate
   - ☐ Neutral
   - ☐ Slightly appropriate
   - ☐ Appropriate
   - ☐ Absolutely appropriate

7.6.2 Section: Evaluation of the test activities

3. What is your feeling about the regression result, are they likely to be correct?
   - ☐ Definitely no
   - ☐ Probably no

[6] This parameter is used by ENERGY STAR in order to understand how much energy is necessary to remove the clothes' moisture.
[7] This parameter is used to understand if the washing machine parts are going to be recycled more or less into the future.

- ☐ Probably yes
- ☐ Definitely yes

4. Are the **results unexpected** or surprising in some way?
   - ☐ Definitely no
   - ☐ Probably no
   - ☐ Probably yes
   - ☐ Definitely yes

5. Do you think that you would have arrived to these conclusions without doing the forecast?
   - ☐ Definitely no
   - ☐ Probably no
   - ☐ Probably yes
   - ☐ Definitely yes

6. Did the forecast helped to gain new insights about the product's future?
   - ☐ Definitely no
   - ☐ Probably no
   - ☐ Probably yes
   - ☐ Definitely yes

7. Do you value the results as useful?
   - ☐ Definitely no
   - ☐ Probably no
   - ☐ Probably yes
   - ☐ Definitely yes

8. According to your projection, how many conclusions about the selected parameters were influenced by a logistic regression analysis?
   - ☐ Number of influence parameter ________________________________

7.7 Part H – Questionnaire about the proposed method and models (Only for group-B with the method)

In this appendix is presented the test version of the method and additional questionnaire developed at the end of the experiment by Group-B. Moreover, this includes also the NASA task questionnaire.

7.7.1 Method for forecasting requirements (test form)

Please execute the forecasting analysis developing each step as it is presented in Figure 37.

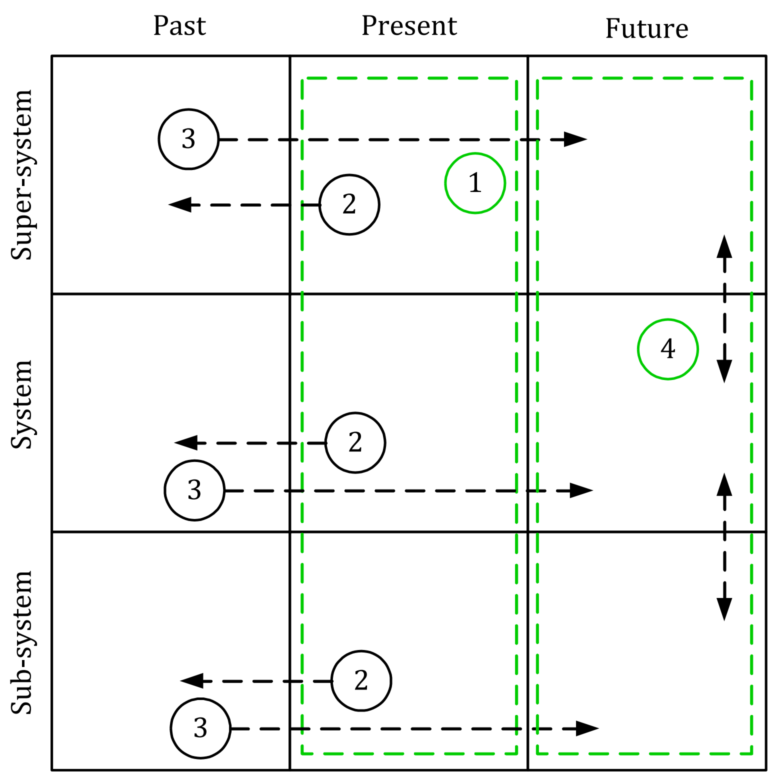


Figure 37: Method's step to understand the dynamics of the design requirements (test form).

Complete the Data Sheet with each of the following steps.

STEP 1: Classification of the parameters of Table 40 at system, sub-system and super-system levels.

i. Definition of system, super-system and sub-system parameters.
ii. Identify which of the parameters are quantitative and which are qualitative.

iii. Identify the context of the parameter as technological[8], environmental[9], social[10] or economic[11].

STEP 2: Looking at the past-time column.

i. Set the starting year for the study.
ii. Estimate how was the parameter in the past (e.g. looking 10-15 years in the past, the parameter was higher, lower, or stable,

STEP 3: Assessment of parameters and regression

i. Provide a description of the parameter how have they been changing if there is any available data for it (e.g. looking 10-15 years in the past, the parameter has been increasing, decreasing, fluctuating or remain stable)
ii. For quantitative parameters, check the data availability.
    a. For an increasing parameter[12]: perform a logistic regression analysis by means of software provided for this test.
        - Check the reliability of the data through the r-squared[13] and p-value[14].
        - Evaluate the regression as appropriate, inappropriate or slightly appropriate.
        - Take notes about the regression.
iii. For technological parameters, create a technological performance combining increasing parameters and decreasing[15] parameters as:

$$\text{Performance} = \frac{\text{Increasing Parameter}}{\text{Decreasing Parameter}}$$

    a. Develop the regression analysis and check the r-squared and p-value.
    b. Evaluate the regression as appropriate, inappropriate, semi-appropriate and semi-inappropriate.
    c. Take notes about the parameters' values (K, tm, Δt)(Figure 37).
iv. Repeat this process for technological and environmental parameters attempting to identify potential new relationships among parameters based on logistic growth model.

[8] Technological: related to the application of scientific knowledge for practical purposes, especially in industry.
[9] Environmental: related to the natural world and the impact of human activity on its condition.
[10] Social: related to the development, structure, and functioning of human society.
[11] Economic: related to the production and consumption of goods and services and the supply of money, but also related to the careful management of available resources.
[12] Increasing parameter: Parameters which show a positive trend in the last years (efficiency) (check the available data).
[13] the r-squared indicator usually supports the result of the fit.
[14] the assumption about the behavior of the Logistic Growth can be accepted or refused by means of the statistical significance (i.e. p-value).
[15] Decreasing parameter: Parameters which show a negative trend in the last years (e.g. energy consumption) (check the available data).

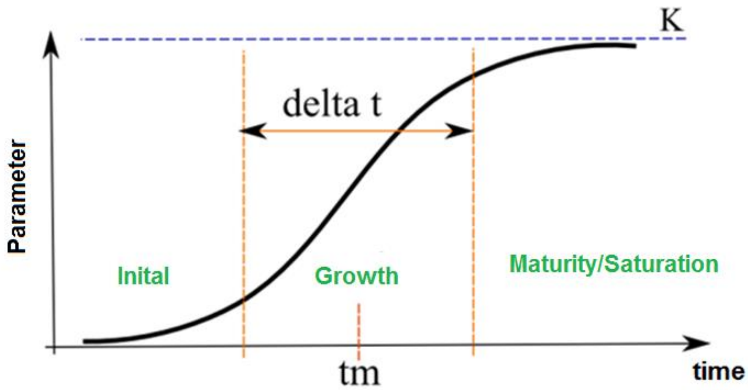


Figure 38: Logistic growth description and stages for test with students.

STEP-4: Envision of future parameters at system level (Future column)

i. According to the regression analysis for parameters and performances:
   - Quantitative: Describe the future scenario for the parameters taking into consideration:
     - Information from the past and present.
     - Parameter values into the future.
     - Identify the stage according to the logistic growth model (Figure 38).
     - Relations between parameters and performances (mutual influence).
   - Qualitative: Describe the future scenario for the parameters taking into consideration:
     - Project the parameters according to their behavior (increasing, stable or decreasing)
     - Information from the past and present.
     - Relations among quantitative parameters and qualitative parameters.

ii. Combining both, qualitative and quantitative parameters, describe the conclusion for the System Operator, taking into account all of the work done (the available data with the LGC results that you wrote in the Analysis Sheet).
   - Add the performance indexes in the System Operator.
   - Suggest directions for R&D activities.

7.7.2 Section: Evaluation of model and tool (Only for Group-B)

1. Was the System Operator technique appropriate to classify the parameters?
   - ☐ Absolutely inappropriate
   - ☐ Inappropriate
   - ☐ Slightly inappropriate
   - ☐ Neutral
   - ☐ Slightly appropriate
   - ☐ Appropriate
   - ☐ Absolutely appropriate

2. Was the **STEP-3 (assessment of parameters and regressions)** appropriate to guide you for the regression analysis process?
   - ☐ Absolutely inappropriate
   - ☐ Inappropriate
   - ☐ Slightly inappropriate
   - ☐ Neutral
   - ☐ Slightly appropriate
   - ☐ Appropriate
   - ☐ Absolutely appropriate

2.1. Did you create a new performance using the method?
   - ☐ No
   - ☐ Yes
   - ☐ Partially

   If the answer is *Partially* or *Yes*, could you describe which parameters did you combine?

   ____

   ____

3. Was the **FORMAT software** appropriate to provide you recommendations about the regressions?
   - ☐ Absolutely inappropriate
   - ☐ Inappropriate
   - ☐ Slightly inappropriate
   - ☐ Neutral
   - ☐ Slightly appropriate
   - ☐ Appropriate
   - ☐ Absolutely appropriate

4. Is the **method** appropriate to achieve the expected results?
   - ☐ Absolutely inappropriate
   - ☐ Inappropriate
   - ☐ Slightly inappropriate
   - ☐ Neutral
   - ☐ Slightly appropriate
   - ☐ Appropriate
   - ☐ Absolutely appropriate

7.7.3 Section: Quality of results with Method (extra questions)

1. Could you have reached your conclusions without using the method?
   - ☐ Definitely not
   - ☐ Probably not
   - ☐ Probably yes
   - ☐ Definitely yes

2. Are the efforts needed for the whole method acceptable compared to the outputs it provides?
   - ☐ Definitely no
   - ☐ Probably no
   - ☐ Probably yes
   - ☐ Definitely yes

7.7.4 Section: NASA task load questionnaire (Only for group-B with the method)

You have to evaluate each step according to the parameters in table 41.

Scores: 1=Low; 4= Medium; 7=High

Table 41: NASA task load (answer table)

Steps	Mental Demand[16]	Physical Demand[17]	Temporal Demand[18]	Performance[19]	Effort[20]	Frustration level[21]
Classification of the parameters						
Looking the past-time column						
Assessment of parameters and regression						
Envision of future parameters at system levels						

[16] How much mental activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)?
[17] How much physical activity was required (e.g. pushing, pulling, controlling, activating, etc.)?
[18] How much time pressure did you feel to carry out the task? Was the pace slow and leisurely or rapid and frantic?
[19] How successful do you think you were in accomplishing the goal of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
[20] How hard did you have to work (mentally and physically) to accomplish your level of performance?
[21] How insecure, discouraged, irritated, stressed and annoyed did you feel during the task?

Circle the parameter of each pair that contributed more to the workload of the **method.**

Effort Or Performance	Temporal Demand or Frustration	Temporal Demand or Effort	Physical Demand Or Effort
Physical Demand Or Temporal Demand	Performance or Frustration	Physical Demand or Performance	Temporal Demand Or Mental Demand
Frustration Or Effort	Performance or Mental Demand	Mental Demand or Effort	Performance Or Temporal Demand
Metal demand Or Physical Demand	Effort or Physical Demand	Frustration or Mental Demand	

7.7.5 Data Sheet: Student test (Group-A)

Table 42: Data sheet, student test (Group-A)

Description	**Requirement**	**Future (Knowledge Projection)**

7.7.6 Data Sheet: Student test (Group-B)

Table 43: Data sheet, student test (Group-B)

	Past (Time)	**Present**				**Future (Knowledge Projection)**
Level	Description of the Parameter	Requirement or parameter	Context	Qual. or Quant.	Variable behavior	Description
Super-System						
System						
Sub-system						

7.8 Part I - FORMAT prototype (Description and user manual)

In this section is presented the FORMAT prototype and related features created during this PhD research.

The FORTMAT-prototype allows to perform regressions with simple logistic growth, rate of growth and bi-logistic (comparison or decomposition of two logistic growth curves), also to develop regressions in the form of a Fisher-Pry transform. Figure 39 shows the main window of the application including: data table, control panel, popup menu to select different analysis and error graphs.

Statistic information about the regression includes standard deviation, p-value and confidence interval for each parameter of the regressions. Moreover, information about the quality of the regression is provided also through Bayesian Information Criterion, Akaike Information Criterion and Root Mean Square Error (RMSE). Of course, all these indexes are explained to the user with implications in the context of technology forecasting to facilitate the interpretation of the results. The features are described in more detail in the next subsections.

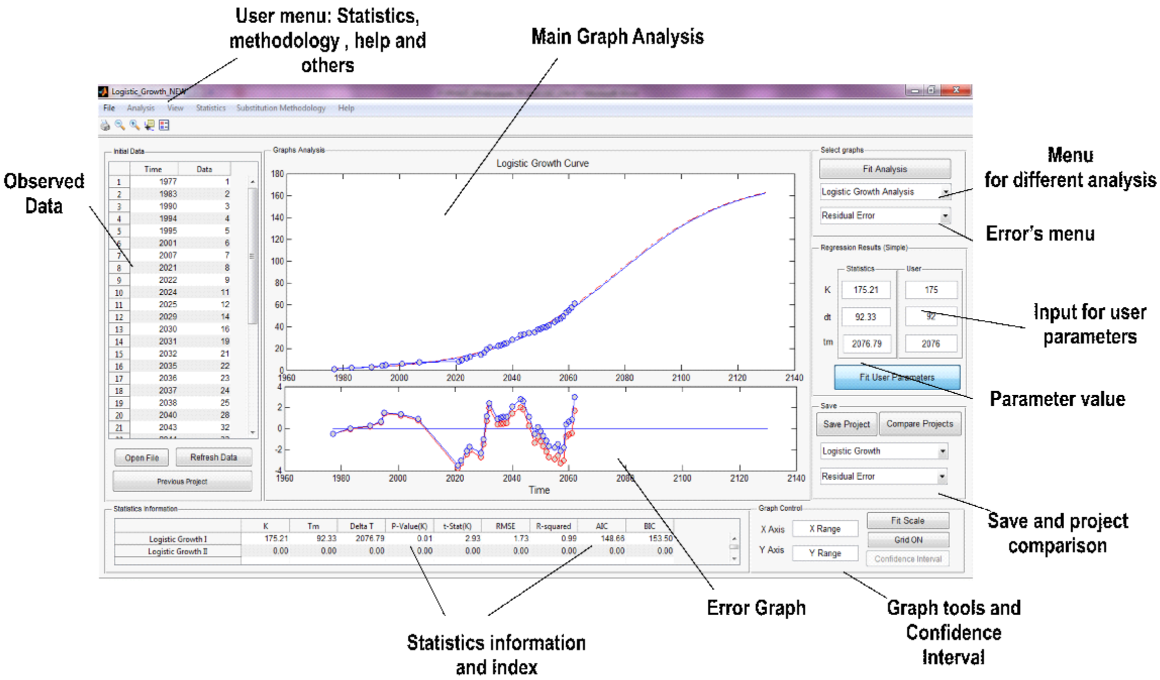


Figure 39: FORMAT-prototype and related features.

7.8.1 Description of features of the FORMAT-prototype

A software tool was created to support the user into developing a forecasting analysis based on logistic growth. The software tool was created by using MATLAB, however it can be installed without it by using the packaging installer (MRCInstaller) and executable (FORMAT_prototype).

7.8.1.1 Commands to call and view data

The actual version of the software application can only read excel files (.xlsx). Data has to be organized in two columns X and Y. Copy and paste is not available for this software version (**Open File**)(Figure 40).

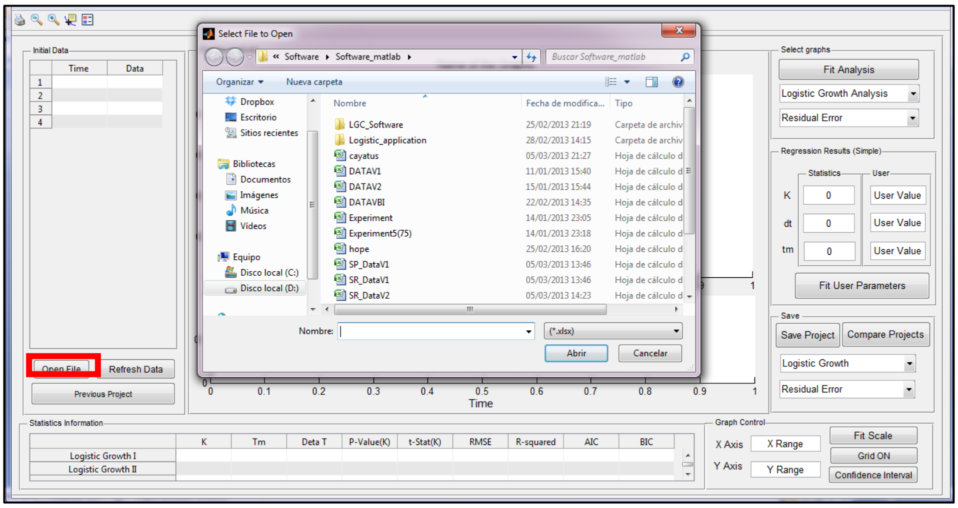


Figure 40: Commands to open excel files with data.

The user can modify the data file directly from the table; the button "refresh data" updates the modifications provided by the analyst (i.e. The modified or deleted data will be cleaned from the table)(Figure 41).

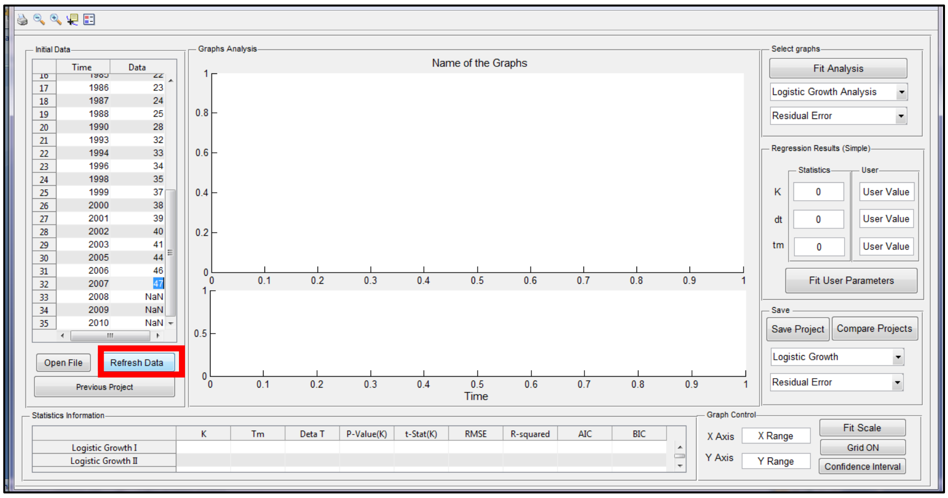


Figure 41: Commands to modify data form user' panel.

7.8.1.2 Regression analysis and graphic results

FORMAT prototype allows developing different types of regression analysis and shows different types of outcomes. The red boxes present the buttons related to the different regressions and graphic results (Figure 42), such as:

- **Fit Analysis:** this command reads the data and provides the Logistic Growth regression, Rate of Growth, Fisher-Pry Transformation and Bi-Logistic.
- **Popup-menu Logistic Growth:** With this menu the analyst can select different types of graphics in order to see the forecasting results (Logistic Growth Curve, Rate of Growth, Fisher-Pry Transformation, Bi-Logistic.).
- **Popup-menu Error:** With this menu the analyst can select different types of graphics in order to see the residual error of the regression.

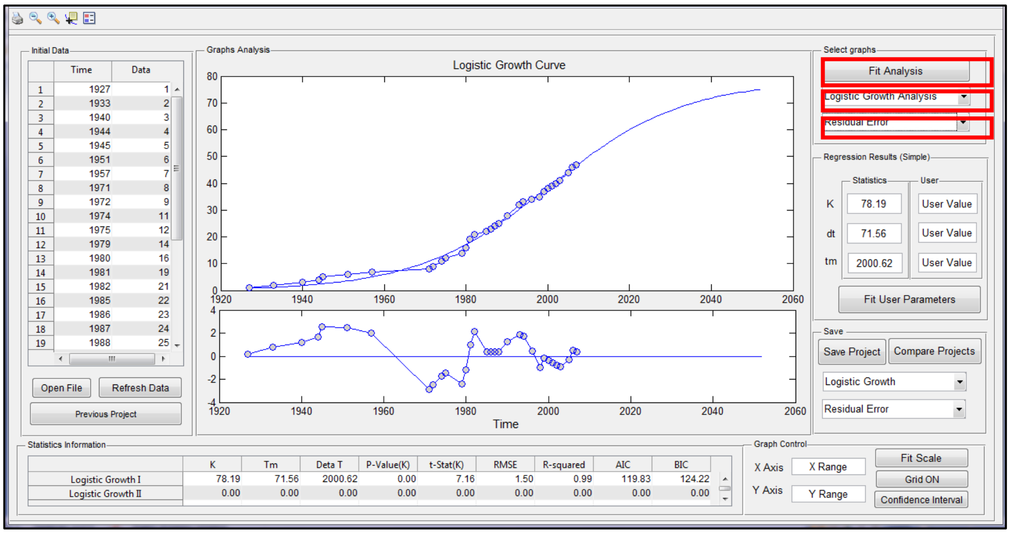


Figure 42: Commands for fit data, select analysis and graphs.

7.8.1.3 Statistics indicators and messages

When the users select “Fit Analysis command” immediately the software returns the values for the different parameters using the statistical approach: “*K*” (saturation capacity); t_m (middle point of or location of the parameter); Δt (elapsed time to grow between 10% and 90%). This results have to be checked according to the statistic information, which are described below.

The table of statistical indexes provides data information about the regression quality to the analyst. The statistical information that the FORMAT-prototype provides is the following (Figure 43):

- **P-Value (K):** p-value is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true. P-value is less than the predetermined significance level, which is often 0.05 or 0.01, indicating that the observed result would be highly unlikely under the null hypothesis.
- **t-stat (K):** t-statistic is a ratio of the departure of an estimated parameter from its notional value and its standard error (these *t*-statistics are used to test the significance of the corresponding regression) (i.e., two regressions with the same K value and p-value, the highest value for t-stat is considered as the best fit).
- **RMSE:** Root Mean Square Error is a frequently used to measure the differences between values predicted by an estimator and the values actually observed.
- **R-squared:** is a statistical measure of how well a regression approximates real data points.

- **AIC**: The Akaike information criterion is a measure of the relative goodness of the fit of a statistical model. The AIC is grounded in the concept of information entropy, in effect offering a relative measure of the information lost when a given model is used to describe reality. Helps in the selection of the best fit regression between two models with similar statistical information (i.e two models with same statistics (p-value and t-stat), the best regression can be selected according to the AIC).
- **BIC:** Bayesian Information Criterion is a criterion for model selection among a finite set of models (note: When fitting models, it is possible to increase the likelihood by adding parameters, but doing so may result in overfitting. The BIC resolves this problem by introducing a penalty term for the number of parameters in the model. The penalty term is larger in BIC than in AIC.). The BIC has the same meaning of AIC, however according to the number of parameters and data this can penalized. (i.e. Two models with the same statistical information and AIC, but with different number of data, the best model can be selected according to the BIC).

i. Logistic Growth I (row): Provides the results of the analysis for simple logistic growth curve.

ii. Logistic Growth II (row): Provides the results of the analysis for bi-logistic growth curve.

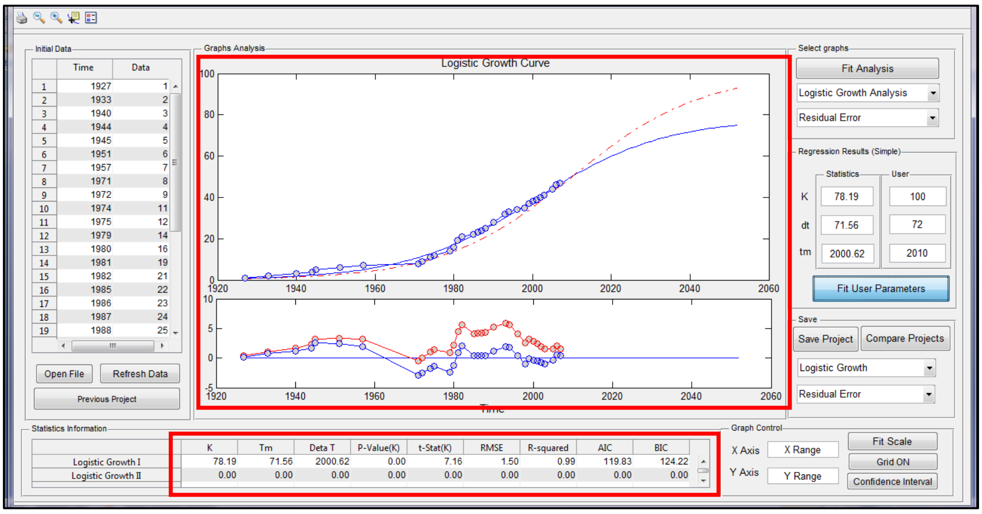


Figure 43: Table with statistical information about the regression.

If the users require support to understand statistic results several messages boxes are provided in order to support the understanding of the regression results. Example of messages boxes is presented in Figure 44, the colour of the boxes are related to the p-value of the regression parameters, for instance:

- If p-value is lower than 0.05, the regression is appropriate, so the colour box is green.
- If p-value is between 0.05 and 0.1, the regression is slightly appropriate, so the color box is yellow.
- If p-value is higher than 0.1, the regression is not appropriate, so the color box is red.

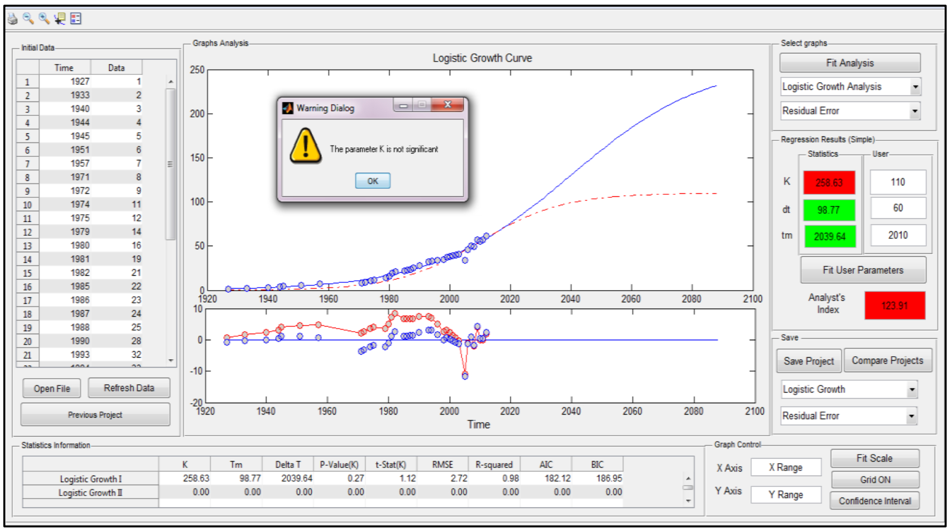


Figure 44: Messages and colour boxes to support users about statistics information.

7.8.1.4 Basic control graphics

In order to see the data and graphic results several graphics were developed (Figure 45); the descriptions of the commands are presented below:

- **Grid on command:** This command provides the grid over the two graphics.
- **X - Range values input:** Provides the maximum and minimum value for the scale graph in X axis. The range has to be with the following structure: [minimum maximum].
- **Y - Range values input**: Provides the maximum and minimum value for the scale graph in Y axis.
- **Confidence Interval command**: Provides the Confidence Interval only for the Logistic Growth regression.

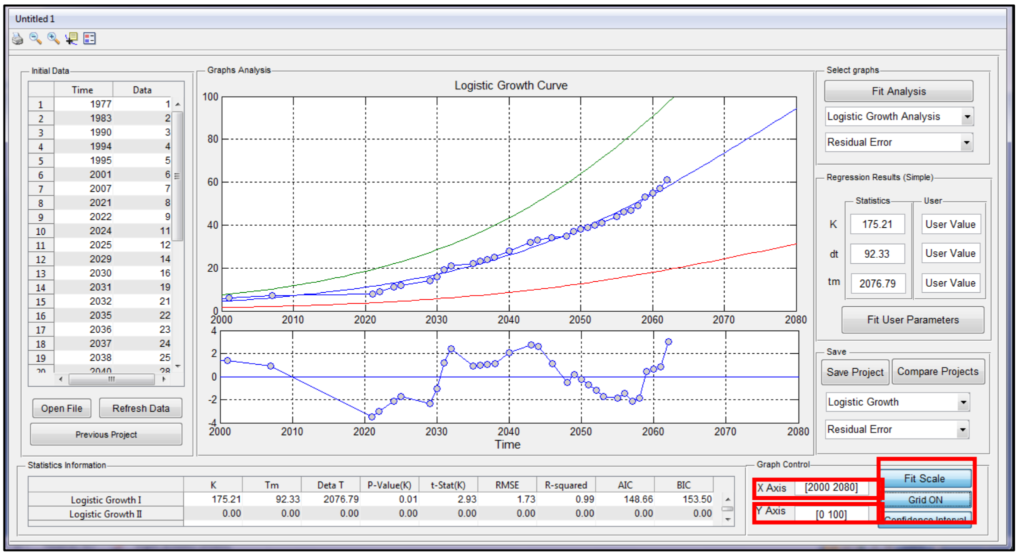


Figure 45: Additional commands for graph and curves visualization.

7.8.1.5 Save project and comparison with different projects

Finally, the FORMAT-prototype has several commands to save and compare projects (Figure 46). These commands are useful to compare several logistic growth curves.

- **Save project command:** Allows to save the actual results in a excel file, the file can be used to compare with others analysis.
- **Compare Project command:** Allows to call the saved project and made a comparison between current statistics and previously saved results.
- **Popup-menu Logistic Growth (Save box):** Allows to compare the current analysis with another analysis previously saved using different models as: Logistic Growth, Rate of Growth and Fisher-Pry.
- **Popup-menu Error (Save box):** Allows to compare the current analysis with another analysis previously saved using different errors as: residual and percentages errors.

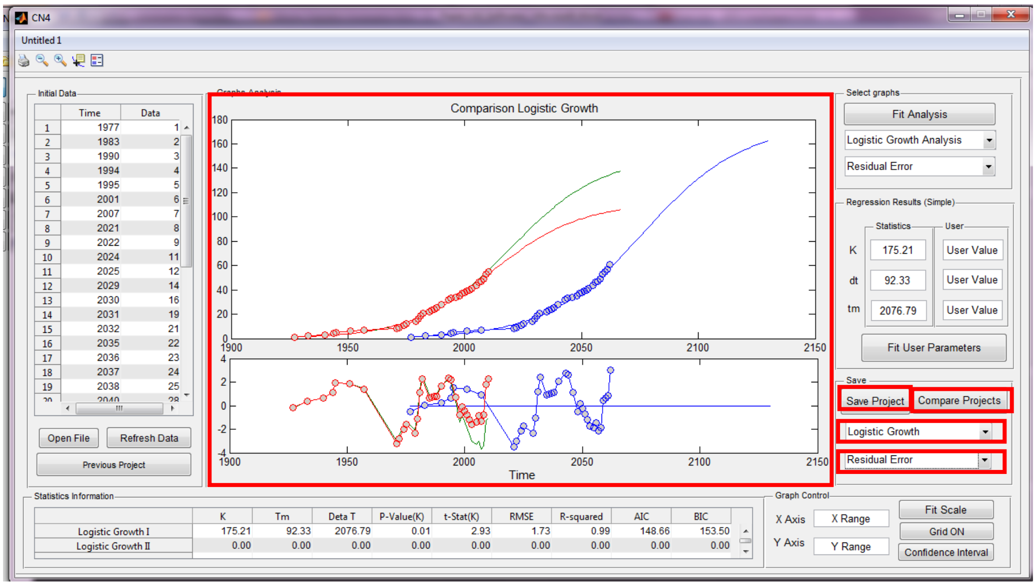


Figure 46: Commands to save and compare projects.

7.9 Part J – Vector Error-Correction model

In this appendix is presented an alternative regression analysis developed by the author. The analysis was developed by using STATA 12.0. In figure 47 are presented the results of vector error-correction model for washing machine case study. The vector error-correction model allows to develop a correlative forecast among the different analysed variables. It is important to mention that the vector correlative analysis has been developed by looking only the best fit representation according to the available data.

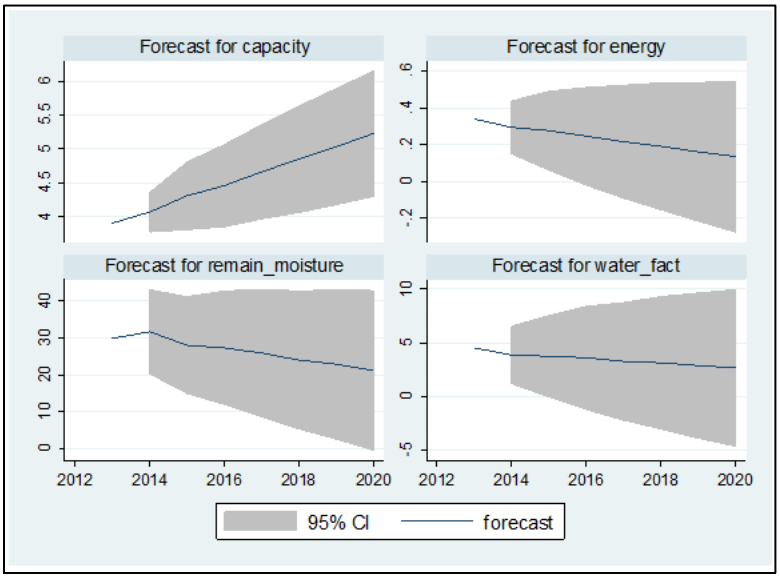


Figure 47: Graphical representation of the forecast based on vector error-correction model.

```
. tsset years
        time variable:  years, 2002 to 2013
                delta:  1 unit

. vec capacity energy remain_moisture water_fact, trend(constant) rank(2) lags(1)

Vector error-correction model

Sample:  2003 - 2013                               No. of obs      =        11
                                                   AIC             =  2.836378
Log likelihood =  .3999214                         HQIC            =  2.471553
Det(Sigma_ml)  =  .0000109                         SBIC            =  3.415135

Equation           Parms      RMSE     R-sq      chi2     P>chi2
----------------------------------------------------------------
D_capacity            3     .139611   0.8276   33.60006   0.0000
D_energy              3     .068158   0.4502   5.732822   0.1254
D_remain_moist~e      3     5.42713   0.7445   20.39835   0.0001
D_water_fact          3     1.27596   0.5023   7.063905   0.0699
----------------------------------------------------------------
```

Figure 48: Indicator provide by STATA for the vector error-correction model.

7.9.1 Discussion

The presented analysis allowed to explore a more complex analysis to exploit data available. The vector error-correction model was used to identify relations among variables. Nevertheless, several limitations emerged when adopted by design engineers. First, this type of data requires a large quantity of data to provide appropriate relations among variables. Second, the forecast does not necessary represent the real phenomena of the variables. For example, according to figure 48 the energy consumption can obtain a negative value in the future which in reality is not feasible. As solution, the users can set a value which limits the energy consumption in the future. Nevertheless, this approach is not totally practicable with the purpose of the forecasting (predict future). Third, the usability of this approach largely depends on the user's knowledge about the statistic and how the user is capable to exploit data from a statistic viewpoint which is beyond of this PhD thesis.