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Requirements Identification and Characterization in Innovation Processes

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1 Introduction

"*It is necessary to innovate to be competitive, it is necessary to enhance problem solving skills to develop valuable innovations*", is the common mantra both in the industrial world and in the product development research domain. Indeed, the dynamics of change is accelerating: on the one hand, existing markets can limit opportunities for industrial development, while new ones may open great chance of increasing the corporate business capabilities. On the other hand, the capability to rapidly address the needs emerging from the market according to the new discoveries and inventions in technology has a paramount role in the innovation dynamics. Therefore, a corporate strong innovation culture must accept changes: **it is necessary to face the challenges of new demands emerging from the market by catching the latest progresses of science and technology and translating them into new solution concepts, being them products, processes or services.** To this purpose, also from the marketing side of innovation, it is quite clear that it is necessary to pursue such a goal with a double perspective:

> *"In order to achieve and maintain competitive success in today's turbulent marketplace, top management must spend at least as much time thinking about customers' needs and how these might be met innovatively as thinking about internal operations. (Johne, 1999).*

If carried out systematically and not just as a sporadic reaction to market threatening conditions, such an industrial approach has a double effect: First, it allows to safeguard the corporate future by reducing the risk of shrinking the conquered market share in favour of competitors. Second, it allows to anticipate new demands by shifting the current technical limitations to new levels, so that it is possible to obtain a further competitive advantage.

Besides, it is quite clear that this kind of competitive strategy is a complex phenomenon, being it affected by two factors, technology and market, that are complex by themselves. This is one of the reasons why innovation requires adequate efforts and resources to be carried out with success and the contribution of very diverse industrial figures. Since this work is focused on engineering design, management issues, such as the subdivision of industrial roles, are not addressed. However, it is very important to consider which are the skills that the people involved in innovation projects must have (e.g.: Lin, 2009) as a means to understand which objectives should be addressed by an innovation process. Two different competences are crucial to obtain successful outcomes in innovation: the first one concerns all the decisions about "what to do", the second one is mainly focused on "how to do". In other words there is a double issue to be addressed in innovation context and related projects: effectiveness and efficiency (Gardner, 2006). None of the two dimensions can be neglected, and from a different perspective, other authors stress this concept, clarifying that in a collaborative engineering environment both rationality and optimality are relevant drivers and, more important, it is necessary that decisions about "doing the right thing" drive the subsequent decisions so as to "do the things right" (Lu, 2009 and Labib, 2004).

To increase effectiveness and efficiency in designing products, processes and services, design methods and tools play a relevant role in enhancing the capability of both individuals and groups to generate outcomes of high-value for both market (products, services) and industry (processes). To this purpose, it is worth noticing that design methods and tools supporting design

activities for innovation in industry are progressively entering in corporate culture as the key to innovate. However, their adoption is still far from being a standard, because of two main reasons. On the one hand, some of these methods rely on the assumption that the probability of finding good ideas increases with the number of concepts produced in creative sessions. This assumption has been proved during years, but experimental activities, as well as industrial practices, have shown that brainstorming-like methods lead sometimes to successful outcomes, but are no cost effective. Indeed, they are so less structured that the huge number of generated ideas requires a great amount of time and resources, which are necessary to perform an accurate selection of the most promising ones. On the other hand, some companies choose to rely on structured methods to enhance their capability to generate new products and gain or, at least, keep a competitive advantage against their competitors. The higher is the level of formalization of methods and the higher becomes the chance of producing high-value outcomes, but also the resources (time and money) needed to train designers and enable them to proficiently apply those methods. One of the main limitations -emerged by the use of structured methods for design in industry- pertains the time consuming and costly investments before obtaining significant results.

On this regard, Gero has analysed the role of unstructured/intuitive and structured methods (respectively Brainstorming and TRIZ) for generating solutions concepts, concluding that these methods proceeds according to very different design paths (Gero, 2012): while the former proceeds through an unconstrained search for solutions, the latter points out which are the problems to be addressed according to the list of objectives to be achieved.

The above evidences show that structured or, in other words, systematic methods are the best candidate to effectively and efficiently support innovation projects, because of their intrinsic logic aimed at identifying goals and objectives before to start generating solutions, thus avoiding costly trials and errors. Two main issues appear as paramount in this context. The first one concerns the identification and of the available sources capable to define and characterize the objectives to be achieved for innovation. The second one, but not less important, is about making the methods for systematically driving the design process proficiently exploit these competences for defining such objectives.

The identification of objectives directly concerns the sphere of knowledge. Needs emerge as a consequence of undesired changes in the individuals or in the environment they are immersed in. They have to be interpreted according to the situation into which they occur and previous experiences play a great role in the internal formalization of perceptions into organized concepts (Gero, 2004); formalized as the objective should be in order to properly drive decisions. It follows that knowledge is something pertaining to the internal world (tacit knowledge) and that has to be manifested outside the individual so as to be discussed, shared and most of all, used and reused (explicit knowledge) in a continuous process of improvement and enrichment. Experts and customers, from this perspective, represent the best sources of knowledge to be exploited for eliciting information about the objectives. Moreover, such sources allow keeping the double viewpoint oriented to both market and technology. Nevertheless, the externalization of knowledge represents a challenge because what has been tacitly owned is not necessarily also representable in a codified form. The introduction of instruments capable of eliciting knowledge from the available sources is, therefore, of critical importance to feed systematic design methods. Objectives, in design methods, play a crucial role in all the stages for the development of solutions. The design process can be driven with effectiveness by setting the goal of the activity, once the specific objectives are all known. Moreover, they also drive the design process efficiently since they also constrain the wide space for searching solutions into a smaller one that collects just suitable solutions (which implicitly means that unconstrained searches are often ineffective and inefficient).

To this purpose, in engineering design, some instruments currently support the definition of requirements to be met by the design proposal, and in several cases they are also very effective. However, these instruments suffer from two different and contradictory aspects. The ones that can have multiple applications (such as Design for X) allow just addressing one main objective at a time by means of guidelinesfor designing. On the contrary, the ones that address a wide range of requirements often have just specific applications (such as standards or checklists, which are most effective and complete if adopted with appropriate contextualization in the field of interests). With reference to the abovementioned consideration, the idea underlying this research work is that a new set of criteria abstracting the definition of requirements can overcome the above-mentioned limitations.

From a different perspective the elicitation of knowledge is a process in charge of humans and a facilitator that carries out the analysis is required, thus introducing a further limitation to the adoption of systematic design methods within industrial contexts.

In order to overcome the highlighted limitations concerning the adoption of systematic methods in industries, the possibility of using computers for supporting the design processes for innovation has been examined in literature. Engineering industries, indeed, can rely on very advanced computer system to manage the development stages of their innovation processes. However, the role of computers in the early phases of development processes (such as the definition of requirements, as well as during the identification of problems and during the generation of new ideas) is actually poorly exploited (Cascini, 2004; Leon Rovira, 2009; Cavallucci, 2011). In a context where computers are seen as a shortcut to reduce the need to train employees by methodological experts in industrial contexts, both the structured and unstructured human-driven approaches to support design have been embedded into commercial products to support individuals or groups in solving design problems (e.g.: the demand for innovative consumer products, which need to be sustainably designed, manufactured, advertised, used and disposed). Yet, the efforts to embed this kind of approaches into computer applications has generally failed so far, because of their poor usability and negligible capabilities to light the spark of human creativity, which is necessary to produce high-value and surprising outcomes.

According to the above-introduced issues, this work aims at supporting innovation processes by introducing new criteria at a high level of abstraction for the definition of requirements, so as to go beyond the current limitations of current methods and tools having such aim. Thus, criteria for requirements elicitation can be contextualized in a variety of different situations without missing the aim of mapping a wide range of objectives with the same instrument.

In the context of engineering design, this can support both the identification of the requirements for achieving a desired set of goals and the execution of the early stages of the design processes, so as to ease the definition objectives for industrial development with higher effectiveness. Moreover, according to the -still poorly explored- wide range of opportunities provided by computers, the criteria for requirement identification and characterization will be organized according to a framework capable to be fully or partially expressed in an algorithmic way, in order to facilitate its implementation in computer applications.

Section 2 presents an analysis of the state of the art in the field of innovation from the perspective of engineering design. Different, alternative or complementary definitions and classification of innovations will be presented. On this basis, the role of requirements in the innovation scenarios will be discussed together with the main sources to elicit requirements. Specific attention will be given to the different stages of systematic development processes with reference to the contribution of requirements in driving design choices. At last, computer applications will be reviewed in order to highlight persisting limits to be overcome.

Section 3 collects the original contribution of this work. After a preliminary description of the specific objectives of this research, it is divided into two parts: the first one is oriented to the definition of a set of criteria for describing requirements at an abstract level, in order to support the identification of both market and technology requirements during different stages of the innovation project development. The second one stems from the main characteristics of the criteria and describes the architecture of an algorithm for addressing the early phases of the design process, so as to prioritize objectives to be achieved and barriers to be overcome, so as to support the identification of priorities among several technical requirements in conceptual and embodiment design phases.

Section 4 presents the results of the six different applications carried out both in industries (mainly) and in academic contexts. In details it describes the experimental activities carried out both on products, on processes and on market requirements. The double purpose is, first, to demonstrate the versatility of the criteria to map different facets of innovation and, second, the fulfilment of specific objectives according to the industrial need from which this research originated. Some of the proposed applications have already been published in journals

At last, section 5 discusses the outcomes of this research activity, highlighting to what extent the objectives have been satisfied, which limits have emerged during the development and the testing of both the criteria for requirements elicitation and the algorithm for prioritizing directions for development in problematic design situations as well as which further opportunities originated from this activity.

Some parts of the research activities presented in this volume has been already published or accepted for publications in Conference Proceedings (Becattini, 2010; 2011-a,-b,-c) or in Scientific Journals (Becattini, 2012-a; 2013-a,-b). All these researches have been carried out by the author in first person, by taking advantages of discussions and reflections emerged with co-authors.

2 Analysis of the state of the art

This Section aims at defining the context on which the whole research focuses. Moreover, it also presents some considerations about the limitations emerged from the analysis of the various contributions in the diverse related domains of science. It is subdivided into five parts.

The first one considers the different meanings the word "innovation" has assumed according to different authors, together with different and not mutually exclusive characterizations.

The second one starts focusing, with a broad scope, on the role of requirements in innovation in reference to its largely recognized drivers: market and technology.

Then, in the third part, the differences among data, information, knowledge and wisdom are clarified so as to introduce knowledge as the source to draw from in order to define requirements. A specific attention is paid to the difference between tacit and explicit knowledge and to the diverse chances of catching them where available.

The role of requirements within the design processes that aim at the development of innovations is examined with great details in section four. The purpose is to clarify the usefulness of requirements and the characteristics that a design specification (a structured set of requirements) should have in order to drive with effectiveness and efficiency the whole development process.

The section is closed by a brief analysis about the role of computers into the design processes so as to identify potential opportunities for developing new systems for supporting the design processes also through the management of requirements.

2.1 Innovation - Definitions and related scenarios

2.1.1 Definition(s) of innovation

> *Innovation is not a single action but a total process of interrelated sub processes. It is not just the conception of a new idea, nor the invention of a new device, nor the development of a new market. The process is all these things acting in an integrated fashion (Myers and Marquis, 1969)*
>
> *It matters little, as far as human behaviour is concerned, whether or not an idea is 'objectively' new as measured by the lapse of time since its first use or discovery . . . If the idea seems new and different to the individual, it is an innovation (Rogers & Shoemaker, 1972).*

All the above two definitions are presented together also in (Trott, 2005) and are reported here because they highlight different facets of the same concept. The former clarifies that innovation is not a simple phenomena, but it is rather a complex process. As stated in (McAdam, 2007), innovation involves people, processes as well as science and technology. Technological innovation is per-se a complex and dynamic phenomenon, but the introduction of further variables affecting individuals, relationships and habits increases the number of dependences and mutual influences.

According to these definitions it seems that, to come up with an innovation, it is first necessary to generate ideas. Once they would be translated into inventive solutions and implemented in a tangible entity, their capability to turn into innovations depends on the size of the audience choosing that solution on the market. The second one, on the contrary, points out

that novelty, even if from a relative and not absolute point of view, is the critical feature of what should be considered an innovation. Moreover, from the perspective of the management of technical innovation, also Schilling points out that the development processes should be aimed at achieving both a technical and a commercial success (Schilling, 2010).

On a very similar wavelength, Burki and Cavallucci propose three different definitions for idea, invention and innovation. They describe ideas as the "*intangible fruit of imagination*", inventions as the practical and concrete result of the ideation activity and, finally, innovation as an idea turned into an artefact (being it a product or a process) that successfully addresses the market needs and is therefore accepted by customers (Burki, 2011). Moreover, they pointed out that these three different dimensions are obviously entangled, but innovations are not just simply contained in a subdomain of successful inventions generated from the wide world of ideas. Figure 1 shows the relationships among these three different world according to Burki and Cavallucci. However, innovations can result as the market success of both inventive and not-inventive ideas, but inventions, in the author's opinion, necessarily must come out from ideas. The set of definitions by Burki and Cavallucci, indeed, should be further clarified by specifying what distinguishes an inventive idea from a non-inventive one.

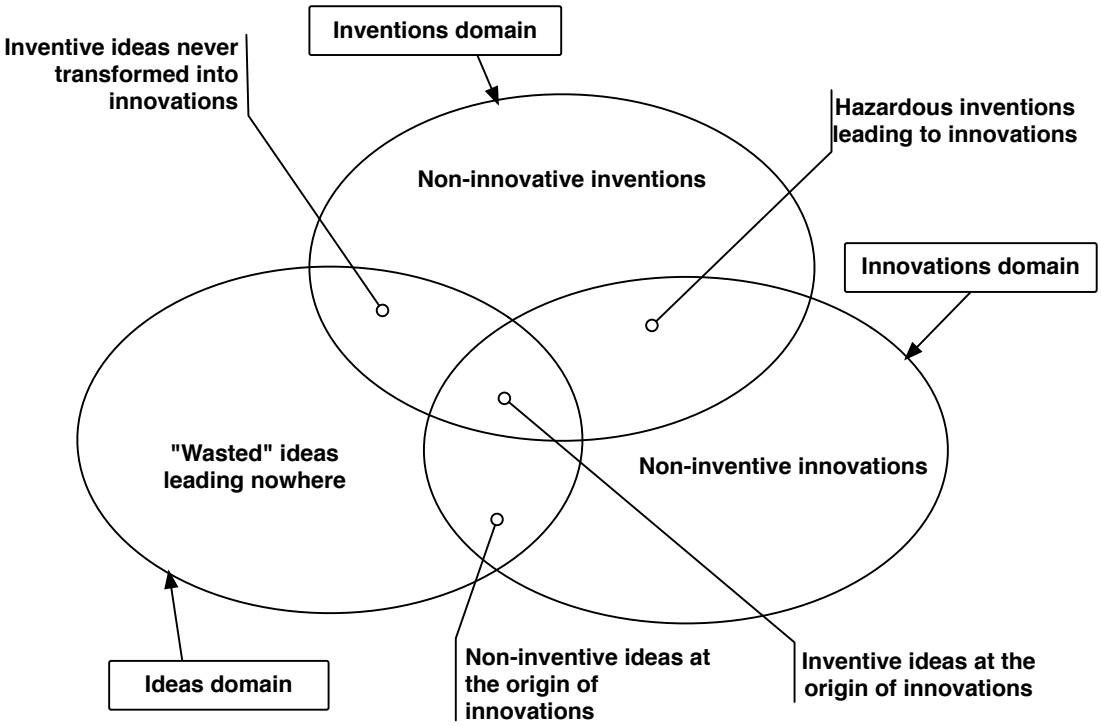


Figure 1: relationships among ideas, inventions and innovations according to Burki and Cavallucci, after (Burki, 2011)

From this perspective probably patent law represents the most widely accepted reference source to define inventions. Patent Law recognizes as inventive a technical solution that is useful, novel (no single prior art reference shows the identical development), and not obvious to a person ''skilled in the art''. On this basis it is evident that non-inventive design ideas are those in which at least one of the previous feature is missing, constituting a residual of the classes of inventive ideas. Besides, novelty, here and in opposition with the Rogers and Shoemaker's definition of innovation, is presented as a characterising feature of inventions. This apparent paradox require to distinguish what has been intuitively stated in the definition of Rogers and Shoemaker: the concept of "new " (or "novel") can be considered both from the point of view of an individual that generates something new to his own knowledge and with reference to the whole history of

human kind. These two different concepts of "Novelty" distinguish what in cognitive sciences, psychology and artificial intelligence is commonly referred as P-Creativity (Psychological Creativity) and H-Creativity (Historical Creativity) (e.g.: Boden, 1994).

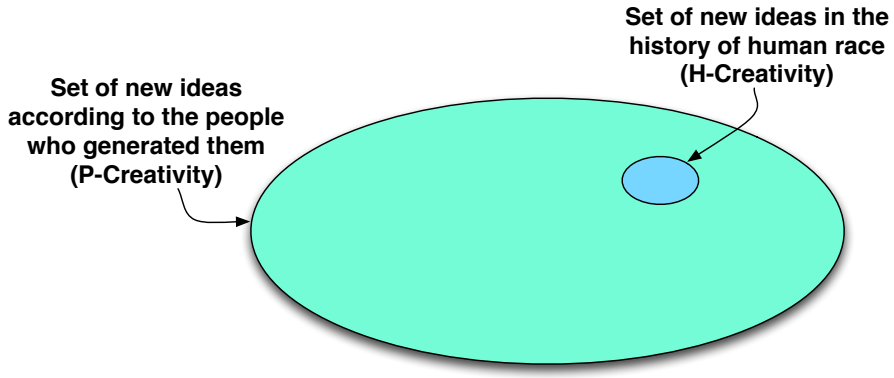


Figure 2: Classification of creative ideas according to the novelty of the ideas. H-Creativity ideas are a subset of P-creative ideas.

Despite the not complete agreement among the diverse definitions presented, it has been clarified that innovations and inventions are two different but tangled concepts that stem from human mind. The broader meaning of innovation generally characterize the commercial success of products, processes or services, even if not innovative. However, according to the scope of this work, in the following the terms innovation should be intended as the complex process that produces outcomes capable to satisfy demands from both general and specific markets, through the concretization of a novel and useful solution concept in a product, a process or even a service.

2.1.2 Innovation Scenarios

Many different types and scenarios of innovations are presented in literature. Trott classifies different types of innovations and points out that certain innovations may trigger or even force new changes in different contexts, leading, as a consequence, to different types of innovations.
The innovation types presented in (Trott, 2005) are listed below:

- Product innovation as the development of an existing product with new or improved features, as well as the development of a new product from scratch;
- Process innovation as the development of a manufacturing process capable to assign new characteristics or features to a product;
- Organisational innovation as the changes in the corporate structure, being them related to Human resources, means for working, etc.;
- Management innovation as the changes occurring the way the corporate business is conceived and delivered according to, for instance, quality;
- Production innovation as the changes occurring in terms of better efficiency in producing, the different corporate products;
- Commercial/marketing innovation as the changes occurring in the way the corporate products are advertised, sold and delivered to the reference audience;
- Service innovation as the changes occurring on the way certain functions are carried out, being them related to the introduction of a new way to satisfy a mutually related set of needs, e.g. by completely substituting the users or the way they communicate.

This very wide set of innovation types represents one further evidence supporting the assumption

that innovation is a complex phenomena. In the following it will be clarified which is the dynamics that binds product and process innovation. Before going into those details it is necessary to introduce also the classification proposed by Schilling. In her book "*Strategic management of Technological Innovation*" she changes the scope of the analysis: she switches from the type of innovation to the opposite features that characterizes innovation and, moreover, she focus her description on the distinctive traits of technological innovation (Schilling, 2010). Four different criteria (Figure 3), with an internally binary classification, characterize technological innovation. First, the extent and the magnitude of changes; second, the target of innovation outcomes according to the industrial business and, third, from the perspective of the design process, as well as, fourth, the knowledge required and used to produce an innovative outcome. Before the detailed examination of each criterion, it is interesting to notice that this categorization is not mutually exclusive, since the same innovation can, for instance, both present small differences from existing practices and, at the same time, may require a completely new knowledge to be introduced in the company for its development. By her own admission,

> *[…] where an innovation […] depends on the time frame and industry context from which it is considered. Thus, while the dimensions […] are valuable for understanding innovation, they should be considered relative dimensions whose meaning is dependent on the context in which they are used. (Schilling, 2010)*

Several correlations among the different classification have been grasped from the analysis of industrial test cases and examples of innovations, however a quantitative study to verify their consistency is still missing.

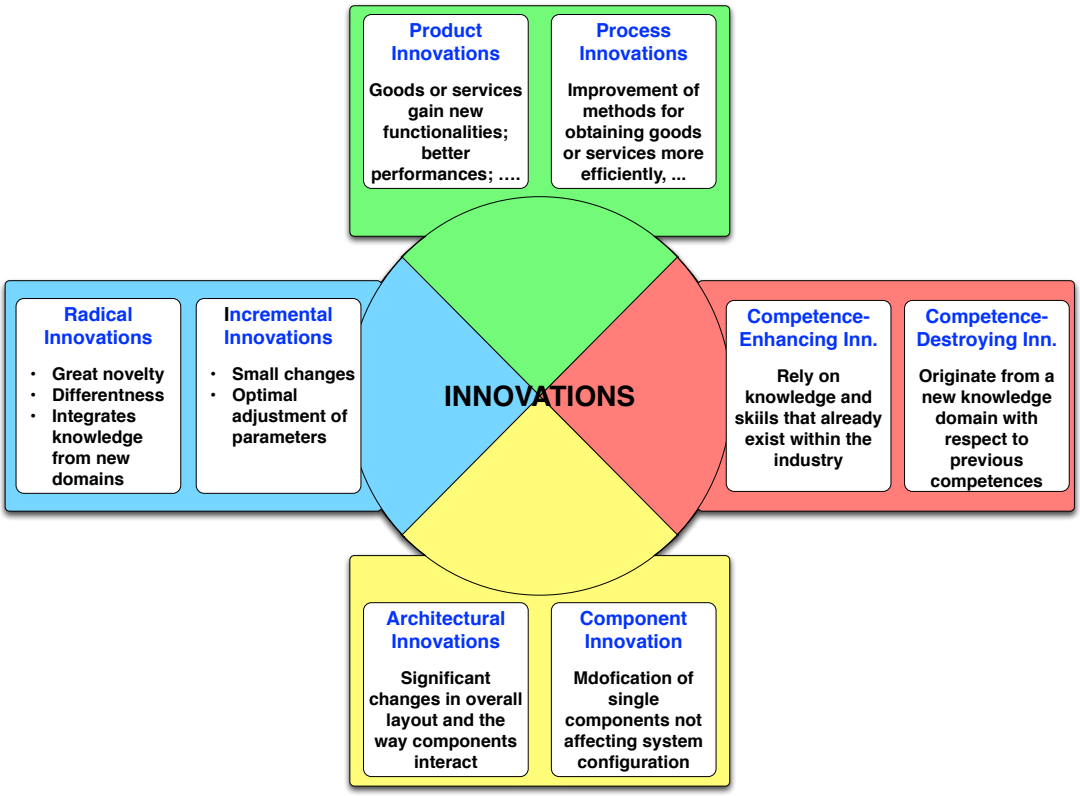


Figure 3: The four different classifications of innovations according to Shilling (2010). Top: innovations targeting towards different facets of the corporate business. Right: knowledge required to develop innovations. Bottom: Innovations targeting towards different hierarchical levels within the design process. Left: magnitude of changes in innovation.

2.1.2.1 Architectural – Component Innovation

Herbert A. Simon, in "The Sciences of Artificial" describes a complex system as

> *[…] one made up of a large number of parts that have many interactions. […] in such systems the whole is more than the sum of the parts in the weak but important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole (Simon, 1981).*

Moreover, he emphasizes that one of the distinctive features into which complexity manifests itself is hierarchy. A hierarchically organized system can be partitioned into different subsystem according to a homogeneous criterion distinguishing the levels of organization, thus repeating with a fractal organization into increasingly detailed subsystems. This is also the case of technical systems, where a single component carries out one or more function by interacting with other components, within the broader scope of carrying out the main useful function for which the whole system has been designed.

In this framework, Architectural and Component innovation clarifies where the innovation occurs in reference to the objective of the design activity and to the hierarchy of the technical system. Indeed, the design activity may focus on the redesign from scratch of a single component or of the whole technical system. Given the hierarchical nature of technical systems it is important to establish in advance a shared view about the level of partitioning under which the objective of innovation will be taken into account. In other words, a technical system can be part of a greater one where it plays an auxiliary role in carrying out the main useful function. On the one hand, the action of redesigning this technical system can be considered as an architectural innovation if the extent of innovation is considered by taking into account the technical system as a whole. On the other hand, if the technical system gets considered as a part composing a greater artefact this kind of innovation goes under the notion of component or modular innovation (Figure 4).

Figure 4: Examples clarifying the concept of component and architectural innovations. The introduction of a more comfortable seat represents a component innovation for the bicycle. The transition from the velocipede in the middle of the figure to the bicycle with crankset and chain is an example of architectural innovation.

Since the reference system from where to look at artefacts is crucial in determining this kind of innovation, it is worth taking into account the criteria that have been implicitly described above: changes in the design of components that do not alter the standard configuration of the whole technical system (in which the component is embedded) should be considered as component innovations. On the contrary, whenever the overall architecture of a technical system gets redesigned and/or there is a significant change in the functions and the relationships among

components it is worth considering it as an architectural innovation. According to this last statement, please note that since architectural innovation "*involves remapping functions to components*" it can also become a trigger for component innovation as claimed in (Pil, 2006).

2.1.2.2 Product – Process Innovation

Product innovation is probably the most widely recognized form of technological change for both experts and non-experts, probably because it represents the most diffused corporate strategy to keep competitiveness in reference markets as witnessed by (Johne, 1999). This is a quite obvious consideration if one takes into account that the main reason behind the existence of a certain firm is to sell their products or services.

On the contrary process innovations pertains to the way a certain company produces, manufactures, advertises and sells a products. From a strictly engineering point of view, relevant process innovation can entail one or more action aimed at reducing the consumptions of costly resources to manufacture products and the related potential harm to the environment. Moreover, under this classification, it is possible to collect all the changes oriented towards the increase of effectiveness and efficiency, such as the improvements in throughput capability, the reduction of working times as well as the volume of non-standard products. In other words, process innovations aim at producing, immediately or in the long term, costs savings so as to improve the profitability of existing products or, on the other hand, to reduce the market cost of product for sale, in order to increase the market share.

In this context, the work of Utterback and Abernathy has clarified that this two different facets occur according to a specific dynamic cycle within a specific industrial context (Utterback, 1975). Figure 5 shows a single cycle of development of a product and the process for manufacturing it. The purpose is to qualitatively estimate the extent of each innovation (y-axis) of each other according to the time dimension (x-axis), so as to infer a general description of mutual relationships and innovation dynamics.

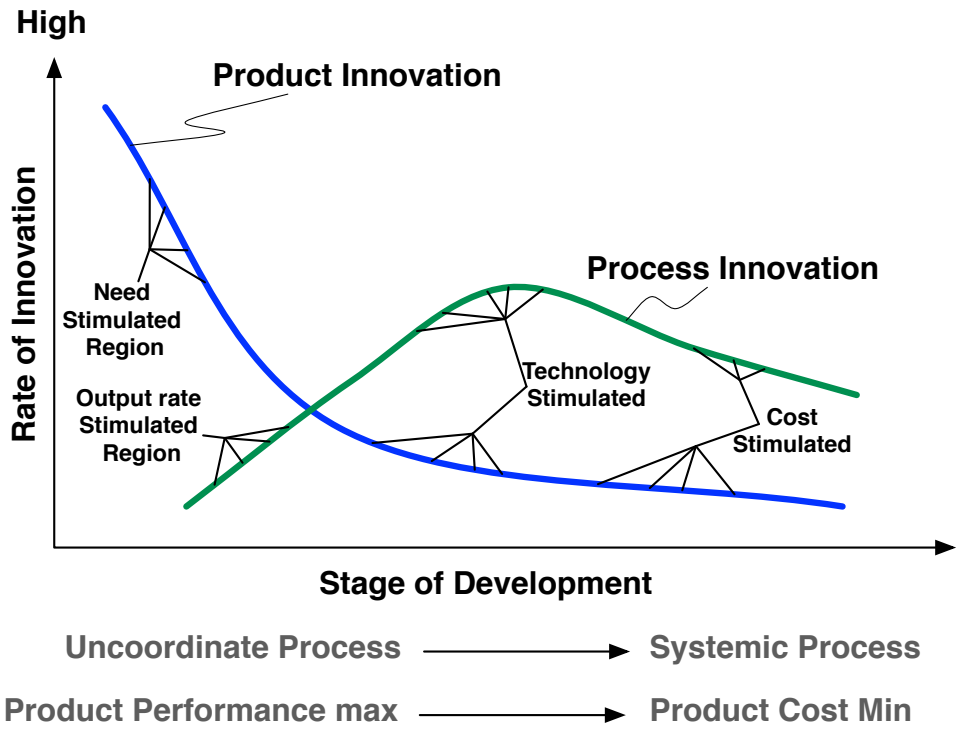


Figure 5: Innovation and Stage of development, from (Utterback, 1975)

Emerging demands and related needs represent the motivation to develop a new product, therefore, at the early stage of the development process, once the innovation is still at the immature state of idea, there is no need to understand and study which manufacturing process is capable to produce it. However, once the concept of solution and its characteristics have been mostly defined, it is also necessary to plan an adequate sequence of manufacturing phases to obtain exactly the expected product. At this moment the focus is mainly concerned on the improvement of productivity, since an adequate throughput is the key to start manufacturing products and obtain adequate revenues, capable to fill the gap of initial investments. Once commercialized and sold, a product undergoes minimum changes. Better product performances or features can be achieved more easily through an improved manufacturing process, rather than redesigning system parts that, at this level of development, have been already accepted by customers. Therefore after an initial stage of development mostly driven by product requirements, the subsequent phases of the development phases are dominated by a process-oriented innovation. At last, it is represented that the reduction of cost is the main driver, impacting, as well as technology in the previous stage of development, on both product and processes, with poor impacts on the former and more significant ones on the latter.

As for Component and Architectural innovation, even this classification can be considered a little ambiguous, depending on the level of detail considered as reference. Indeed, in this case it is not the technical systems that determine the borders of observation and recognition of the innovation scenario, but firms. A company, producing apparatuses to be employed in manufacturing industries, carries out a product innovation whenever it brings significant changes with respect to the existing machines so that it is possible to obtain new or improved characteristics on the object it has to knead. On the other hand, once their customers introduce the new and innovative machine within their manufacturing lines, they consider this action as a process innovation.

2.1.2.3 Competence-enhancing – Competence-destroying Innovation

This classification of innovation, more than the previous two, is subjected to ambiguousness according to the slant from where it is analysed. Indeed, this innovation scenario entails the domain of knowledge and its validity and obsolescence. To this purpose, the only required disambiguation concerns the knowledge available and used within a company to develop a new product or process. Indeed, competence-enhancing innovations are those who are grounded on knowledge that has been already integrated within the corporate boundaries and it is related to the knowledge concerning one of its core businesses. Yet, competence-enhancing innovation are not necessarily built by just exploiting available knowledge. New knowledge can be developed along such processes, but the point is that it stems from already existing knowledge.

On the contrary, competence-destroying innovations origin from a completely different source of knowledge and they often turns the existing corporate knowledge into an obsolete set of notions that could be still poorly exploited in that industrial field of application.

For what concerns the dynamics of innovation, some studies tried to recognize patterns occurring in correspondence of competence-destroying and competence-enhancing discontinuities (Tushman, 1986). In that paper several examples of both discontinuities are presented and according to them the authors have pointed out the following regularities. Competence-destroying innovations occurs during periods of high uncertainty in the industrial environment, such as the emergence of new competitors and or the modification of relevant laws and regulations. Conversely, competence-enhancing technological breakthroughs are achieved by

already affirmed industries in contexts where the industrial environment is undergoing a period of relative calm, when new players are not appearing and the overall constraints for the development of new solutions are at most slightly redefined.

Therefore it is now evident that the corporate core competences and business represent the only reference point from where determining if an innovation is competence-enhancing or -destroying. The same innovation, neglecting the extents of its change for now, can open completely new markets to the company that introduces it, but it may also limit the potential of other competitors that historically relied their business on a standard, but now obsolete, habits grounded on a, probably, static knowledge.

Detailed aspects concerning knowledge, within industries and sparse throughout the market, will be considered with greater attention along subsection 2.3.4.

2.1.2.4 Incremental – Radical Innovation

The extent of changes and the magnitude of the advances between the new and the old generation of a product or a process, as well as the changes occurring between two competing technologies (an innovative and a well-established one) represent the discriminant factor between incremental and radical innovation. Trott and Schilling have convergent opinions about what distinguishes a radical from an incremental innovation. The former describes industrial innovation as the combined presence of major innovations, which are radical, and minor innovations, which are incremental (Trott, 2005) and doesn't make any distinction on where the extent of such changes should be measured (e.g.: structural characteristics, system performances, …). The latter, indeed, focuses on two different characteristics to make this assessment, such as *newness* and the degree of *differentness* (Schilling, 2010). Both this characteristics can be determined in reference to existing practices by discriminating radical innovation as something significantly new and different and incremental innovation as the one occurring whenever just minor changes occur, such as simple adjustments in the parameters characterizing the design of a product or process.

Several contributions in literature address the same concept, e.g. Veryzer refers to discontinuous innovation such as the ones that triggers radical changes in customer use (Veryzer, 1998), bridging to the concept of "*disruptive innovation*" as proposed by Christensen in his "*the Innovator's Dilemma*" (Christensen, 1995). Indeed, disruptive innovations can be considered innovations having worse product performance but being cheaper, simpler, smaller, and, frequently, more convenient to use. Thus, such innovations allow to completely discover new market of customers that are not interested in top-level performance. Disruptive innovations are not so common, but they can lead to market restructuring so that industrial followers or even newcomers in the industrial competition gain, in a short term, an unexpected market share by simply introducing a new way to address unexpressed needs from the market. This may cause, in turn, a business contraction, or even the failure, of companies aiming at improving their products without looking also at different demands, thus "*doing everything right*" but neglecting of doing the right thing. On this subject a Markides proposes a clarification in the meaning between the concepts of disruptive innovation and radical innovation: from his point of view disruptive innovation includes both the concepts of product radical innovation and business model innovation (Markides, 2006). In this framework, a further contribution comes from Veryzer, since his work also allows pointing out that the main discontinuities appear whenever a significant technological change is appreciated by a wider range of customers in the market (Veryzer, 1998). Figure 6 adapts such concepts into a scenario matrix diagram. In this context, it appears evident that considering incremental and radical innovations as the only alternative in a technology-market driven situation lacks of completeness. To this regard, a confirmation that these two axes

really represent the appropriate drivers to describe innovation is presented in (Allen, 1986).

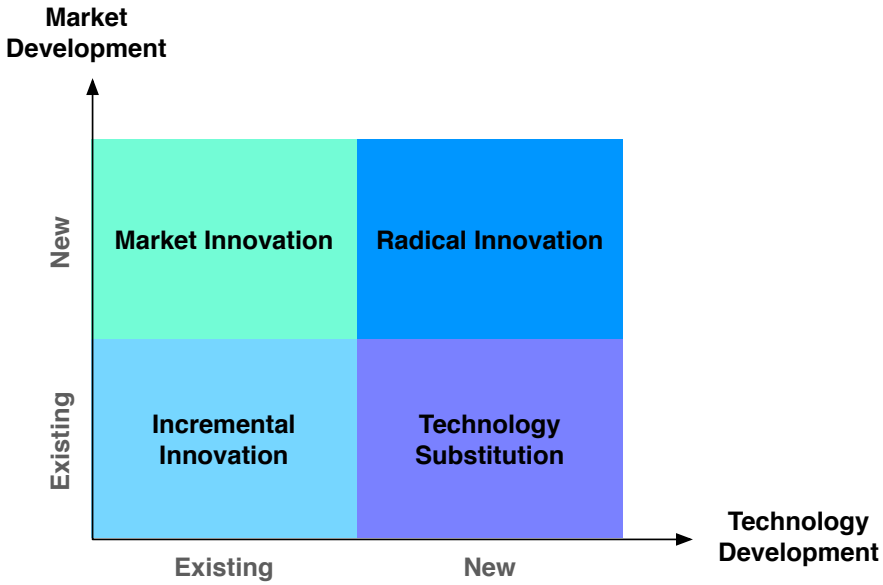


Figure 6: Scenario Matrix for innovation according to Market and Technology Development, adapted from (Cross, 2008).

Indeed, Allen, in a different working, paper clearly states:

> *Innovation can be depicted very simply as a process that mediates between two streams of activity […]. One of these is the development of technological knowledge or, as we more commonly call it, 'technology'. The other is a developing set of market needs. The basic process of innovation is then the matching of information drawn from the two streams. One stream provides market needs; the other provides technological capabilities or potential solutions to meet the market needs. Both knowledge of the technology and knowledge of the market are required (Allen, 1997).*

These two axes will be briefly presented here with the purpose of describing the two scenarios not yet appeared in Schilling's classification; both the dimensions will be then further examined in Section 2.2 in order to further clarify the contribution that requirements may play in driving innovation processes.

As for what is in Figure 6, technology substitution and market innovation represent two specific innovations that occur according to the existing condition, respectively, of market and technology. The former represents innovation driven by technological knowledge: technologies capable to obtain a significant increase in performances, when embedded into products, processes or services that address an existing need, imply that the innovation allows to gain further market shares, but in the known borders where competition is already occurring.

On the contrary, the latter aims at determining which are the alternative segments of market, if any, where new products, processes or services using known and established technologies can be launched in order to, at least partially, skip the need to compete by developing specific targeted offers that are cost-effective and attractive.

For what concerns ambiguity in determining incremental or radical innovation, the comparison between novel outcomes and existing ones allows to produce assessments having just a relative value and it is necessary to determine which is the context into which such an

estimation is carried out. The time span in which the assessment is carried out can lead to very different conclusions, since what could be considered a radical innovation in the past could now represent an incremental innovation in a wider context where new innovative entities has appeared. On the other hand, the radicalism of an innovation also depends on the knowledge of the assessor, since what appears in significant discontinuity with past practices for someone may be usual and common to other people.

For sake of completeness, and with reference to the contribution of knowledge to radical innovation, it is worth mentioning that risk is probably one of the most effective indicators to describe radical innovation. Indeed, what is significantly new may break off customer beliefs. Such potential scenario concerning a loss of acquaintance, in turn, may determine an uncertain situation in the corporate strategy that has some potentially revolutionary concept to develop and several costly and risky barriers to overcome in order to realize it.

2.2 Role of requirements in the innovation scenarios

Regardless of the context or the conditions in which it may appear, a "*situation*" can be represented as a state in which someone presents some discontent (Roozenburg, 1995). The recognition of such a situation is the key to understand and capture the underlying demands that should be fulfilled to introduce solutions capable to mitigate or, even better, completely remove the cause of discontentment. However, such strategy runs on a double track since, as explained in Section 2.1.2.4, also technology offers opportunities to prevent the emergence of potential situations of discontentment in the market by improving the performance level of existing technical systems to be redesigned.

According to these considerations, the following paragraphs aim at describing why requirements are so important for driving choices in the innovation scenarios. A distinction will be made between market-driven requirements and technology-driven requirements, in order to be consistent with the abovementioned classification of innovation drivers.

2.2.1 Market driven requirements – needs and demands

As remarked by Johne (1999), to pursue innovation in existing market it is both necessary to understand if any new strategy can be put into practice to better serve the existing market or, on the other hand, if it is possible to catch the existence of new potential markets.

To this purpose, the uttermost importance is addressed to the characterization of different markets, because of two different reasons. First, a poor characterization of the market can limit the industrial vision and therefore the intrinsic capability of researching and developing appropriate products. Second, potentially each of the individuals acting as a customer could be seen as a potential market that companies can try to tackle, with a very focused product differentiation; thus creating a strong link between the business corporate and the customer. A so detailed characterization of market is mostly due to the underpinning belief that marketing activity should structure the corporate business by reflecting the customer's perspective.

Kumar (2012) calls into question the efficacy of market segmentation, the most diffused strategy to carry out customer-focused innovations by identifying customer demands and related needs. Indeed, customers are individual consumers of products and the partitioning of the whole market in smaller groups sharing a certain degree of homogeneity (Howaldt, 2007) can represent a strong limitation for catching all the opportunities coming from this wide audience. In this regard, several specific industries can try to address specific individual market needs by introducing flexible means to deliver their core business (such as industries operating on virtual markets,

where interfaces can be built by the users themselves or determined by the choice they made).

However, the practical impossibility of a wide range of business to reach all the single customers and manage their data for planning appropriate industrial strategies, suggest that market segmentation still represent an effective method to address the research of new markets. Wedel and Kamakura (2000) have reviewed different techniques for market segmentation and the recognition of customer profiles. Since such methods go beyond the purpose of this work it is sufficient mentioning that customers get clustered according to different criteria, such as geographic variables (country, city, …), demographic variables (age, gender, …), behavioural variables (time to purchase, attitude toward products, …) as well as the psychographic variables (social status, interests, …). Thus, the definition of customer profiles and the identification of potential markets can be inferred through the appreciation and the disregard about product, process or service features, both existing and to be potentially integrated. Customer requirements can be prioritized and new ones can be generated with reference to the different market segments whose needs are satisfied by a specific range of products.

While the identification of new market segments represents a key issue for every firm to increase profits, industries willing to survive the competition on the market and operating in condition of disadvantage must rely on affordable targets. In this sense market niches represent a great opportunity. To this regard, there are several contribution evidencing that smaller firms (e.g. SMEs) better compete in the market if their products differ from what bigger firms manufacture (Porter, 1979). This happens because such market niches allow to substantially skip the competition by supporting the definition of the features of products, processes or services so as to satisfy the needs of market segments that bigger firms consider as non-profitable according to their model of business (e.g.: Caves, 1977).

Therefore, it is straightforward that criteria supporting the definition of customer requirements in different situations represent a key to standardize and replicate with greater efficiency the identification of new market opportunities. With a wide list of customer requirements, it is possible to:

- prioritize the objectives for the development processes concerning products, processes and services, thus improving the effectiveness of the innovation processes;
- catch the surprise and the appreciation of customers for features that they have not been conceived yet;
- determine better strategies to differentiate products according to different customer target to address as a means to support competitiveness of both big companies and small and medium enterprises.

2.2.2 Technology driven requirements - Constraints in the design space

From the point of view of innovation management, Trott remarks:

> *When it comes to operationalizing the process of innovation, this invariably involves considering the technology position of the firm. Hence, the implementation of an innovation strategy is usually achieved through the management of technology (Trott, 2005).*

This sentence clearly explains that technology plays a paramount role in the concretization of innovation. As customer demands evolve, also technology undergoes its specific paths of evolution (Althsuller, 1988). In this perspective, technology development represents the capability to put into practice the most advanced progresses of sciences; in a word it represents the result of

applied science. Differently from science, technology is not characterized by discoveries, despite it may trigger them; it rather concerns to the concretization of human demands for overcoming conditions set by the environment. In this sense, the vision of Simon is paradigmatic:

> *The natural sciences are concerned with how things are. […] Design, on the other hand, is concerned with how things ought to be, with devising artefacts to attain goals (Simon, 1981).*

Technology, in this sense, represents something that is not determined through the analysis of what exists, but rather by the synthesis of an artificial entity having a specific purpose (function). Therefore, designing represent the process according to which different demands can be satisfied as a result of the identification of solutions. This is the reason why technologies and the related innovations require a search in a space of alternatives that, in turn, has to be constrained by both the goals to be achieved and the rules to be respected (Simon, 1973).

In this perspective, both studies in Cognitive Sciences and in Artificial Intelligence have recognized that designing can be described as the search for solutions in a cognitive space. In other words, the ideation process -or the synthesis of technical solutions- has been computationally recognized as a search within a design state space where individual knowledge can be represented with the purpose of moving from a problem state to a goal state (Simon, 1973). From this perspective, AI researches have highlighted that multiple actions can characterize different steps forward in the search for good technical solution. Such process must be at least P-creative, since existing solutions are, by definition, not suitable to address new demands. Indeed, as presented in Figure 7, three different models of creativity, from a computational point of view, have been highlighted: Combination, Exploration, Transformation (Boden, 2009).

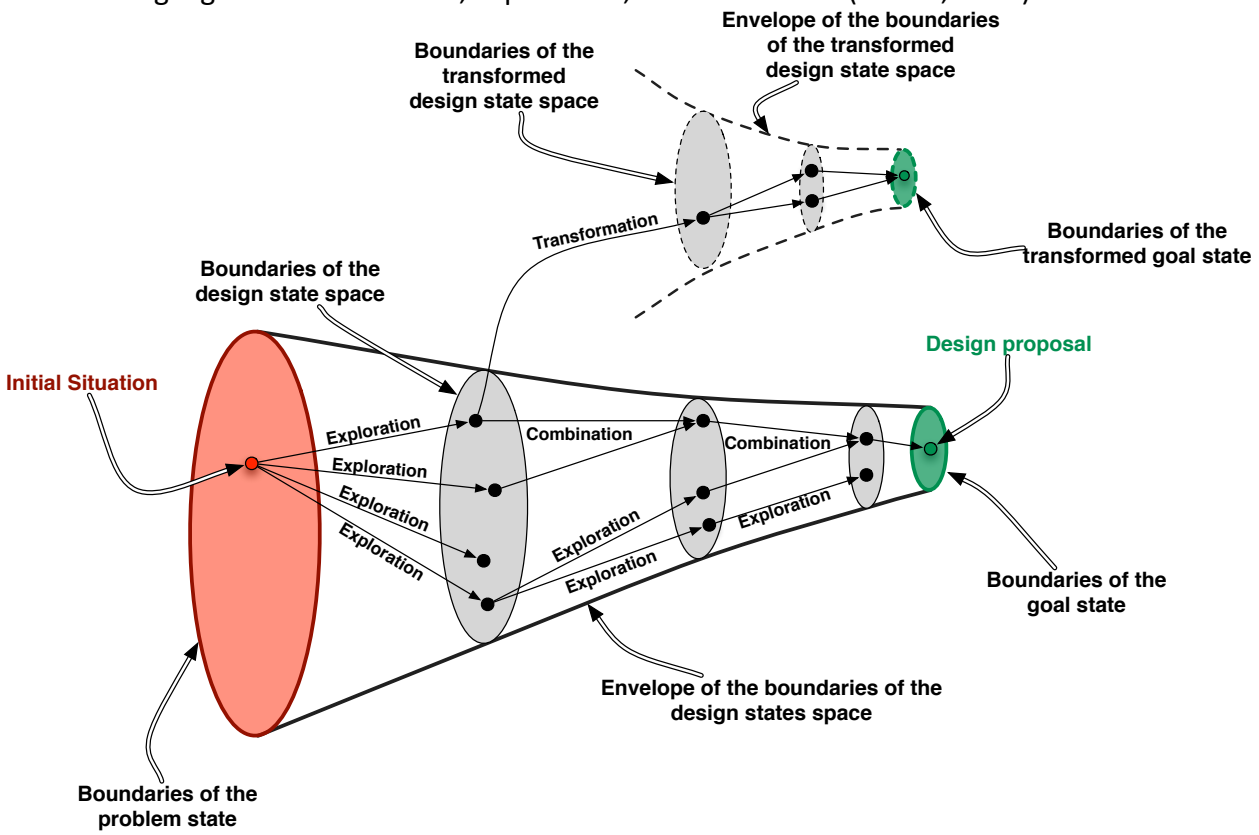


Figure 7: Representation of a design process from the problem to the goal state (single-line arrows are creative processes, double-line arrows are labels)

First, the goal state can be reached by means of the *Combination* of already known (or emerged) solution concepts. Second, it is possible to *explore* the design space so as to operate generative rules that produce a new concept. Both this cognitive processes produce outcomes that can be even represented within the initial design space. The third cognitive process, on the contrary, produces a *Transformation* of the design space, so that the identified solution concept can be just represented in a design space that differs from the initial one because some of its dimensions has radically changed or even disappeared. Each of these three different processes can be used for characterizing the steps forward in the search for a solution capable to attain the goal state. Again Boden (2009) remarks that these three different models of creativity are valid beyond the technological perspective with which they have been presented and are therefore applicable to the different contexts where creativity is present. In summary, three different relevant factors should be highlighted, according to this description.

1. Both the problem state and the goal state can be characterized by means of requirements. The problem state is characterized by values that are not currently achieved, thus generating a situation of discontent. The goal state, in turn, sets the target values to be achieved to remove discontentment.
2. The synthesis of technical systems requires boundaries for limiting the size of the space where to efficiently perform searches for solutions capable of concretely synthesizing a product of human mind. Such boundaries represent requirements to be satisfied as well.
3. These requirements also represent a driver for the cognitive processes that must effectively lead from the problem state to the goal state.

In order to clarify the meaning of this last sentence, *combination*, *exploration* and *transformation* will be hereby analysed with reference to the requirements determining the design space. The *combination* of already existing technical solutions satisfying, each one, specific requirements imply that the search through the design space have followed, at least, a double track holding individually different priorities that, together, allow to reach the goal state. *Exploration*, as well, follows the same path according to the identification of suitable partial solutions progressively addressing a greater set of requirements, so as to narrow the space for search to thos requirements not yet fulfilled. *Transformation*, in turn, can be driven by the selective modification of the design space through a selective removal of requirements that can over-constrain the search, thus limiting the potential identification of radically novel kind of technical solutions or, more in general, way to address a situations where customer demands and needs ought to be satisfied.

According to this analysis, it is possible to state that general criteria for the identification and the characterization of requirements for a technical system can support the efficiency ("*do the things right*") of the whole design process by limiting the range of available alternatives for synthesizing a solution concept. Foremost, according to the objective of supporting innovation processes with effectiveness ("*do the right thing*"), such criteria can play a paramount role in supporting the effectiveness of the design process:

- by recognizing which are the objectives to be achieved;
- by constituting a metrics that allow to define the suitability of a solution according to the situation to be addressed;
- by driving the searches for solutions within the design space.

2.3 Sources for requirements identification and elicitation

In order to better understand where to find adequate sources to identify requirements, a preliminary distinction between data, information and knowledge is presented. It also has the purpose of clarifying to which dimension the competences mentioned in Section 2.1.2.3 should be addressed and which are the relevant issues to tackle for building a general set of criteria for requirements elicitation.

2.3.1 Definitions of data, information and knowledge

The identification of relevant sources from which it is possible to enrich the individual or the corporate competences is paramount; however, it is also necessary to make an appropriate distinction among the various levels under which such sources of competences can be organized.
The acknowledged framework to organize such set of sources is represented by the so-called Wisdom Hierarchy (but also known as the Information Hierarchy or the Knowledge Hierarchy) that includes and specifies the relationship among Data, Information, Knowledge and Wisdom - DIKW (Rowley, 2007). The definitions by Ackoff, from which she stems her work, represent a meaningful starting point, since they also highlight the mutual relationship between categories.

All the symbols representing a property of entities, as well as events, should be considered as ***Data***. It turns into ***Information*** once such data gets selected according to the relevance of its content. Therefore, the terms hierarchy is not properly used in this context, since the relationship that binds Data and Information is not merely "structural". In other word such a transformation concerns a process of inference. ***Knowledge***, indeed, is represented as the result of the transformation of Information into know-how, which means that the relevant content is also interpreted and organized in a way that is reusable according to the meaning that has been conferred to Information. As well, also the relationship between Information and Knowledge is not strictly hierarchical, rather relational. According to this definition of Knowledge, it is evident that this is the level that allows to transfer elsewhere some content organized according to the meaning of a previous interpretation. At last, ***Wisdom*** pertains to the sphere of judgement and it is in relationship to Knowledge because it assigns values to the know-how (Ackoff, 1989).

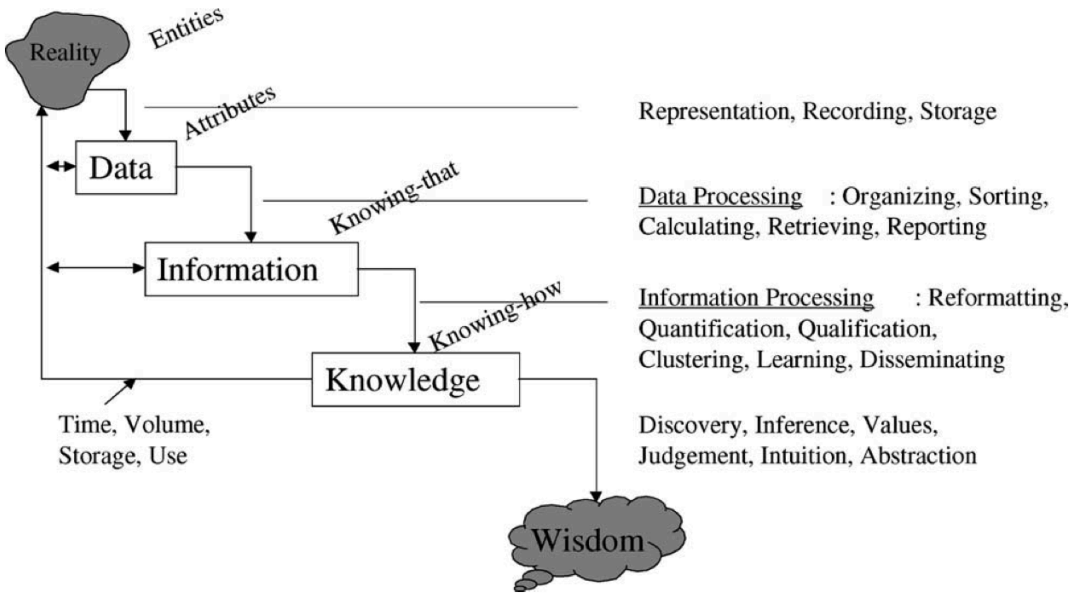


Figure 8: Representation of relationships among Data, Information, Knowledge, Wisdom from (Spiegler ,2003)

The great contribution of these definitions is made evident by a direct link to effectiveness and efficiency. First, since Knowledge represents "know-how" it collects all the necessary procedure to do things efficiently, "*in the right way*". Wisdom, in turn, makes distinctions and priorities among knowledge elements according to their importance, in other words it determines the "know-why" which is critical to pursue effectiveness and "*doing the right thing*".

However, the characteristics highlighted by Rowley according to her review, in the author's opinion, allow to better distinguish Data, Information and Knowledge also from a perspective of their management. ***Data*** is an unorganized and unprocessed set of discrete units that collect objective facts or observations whose meaning is null until it is not considered within an appropriate the context. ***Information***, in turn, collects processed and organized data that is meaningful and relevant, in a word useful, within the context in which it has been considered and examined. On the contrary, there is a wide consensus about the difficulty of Knowledge definition. However, the most relevant commonality that pools different views concerns the fact that ***Knowledge*** pertains the personal sphere and several processes can breed it, such as the synthesis of multiple sources of information over time as well as study, learning and experience (Rowley, 2007).

Both Knowledge and Wisdom pertains to the individuals, but it is just the former that can be transferred outside the personal sphere. Indeed, judgements can be communicated to others, but the weight of personal opinions on judgement is something intimate that takes also into account all the knowledge already stored by the individual and that varies according to the context.

2.3.2 The role of knowledge in innovation processes

In Section 2.1.2.3 it has been highlighted that innovation processes requires the use of corporate competences. Moreover, Section 2.3.1 has shown how knowledge and wisdom are relevant for carrying out, in general, tasks with effectiveness and efficiency. Several contributions in literature specify that the world of corporate competences entail the domain of knowledge and to what extent it is relevant for innovation processes.

Perez-Arao et al. have pointed out that ability concerning the nurturing and the acquisition of meaningful and relevant knowledge represents one of the most important keys to build corporate competences and drive successful processes of innovation. Therefor, it appears clear that an approach that strictly focuses on creating and then defending the acquired share on a market also narrows the opportunities of strategic success, since they also depends on organizational competences (Perez-Arao, 2007). In this perspective, Smith (2011) has considered which is the impact of knowledge in, say, "social" workplaces, pointing out that its role affect most of the activity that everyday people carries out and that it also has a double dimension in humans: it expresses itself both on a personal sphere (as previously defined) and on a social sphere since it "*represents the pooled expertise and efforts of networks and alliances*". Such statement demonstrates over again that knowledge deserves to be considered as part of corporate assets just as other intangible ones like management systems, brand identity, customer information and corporate reputation (Smith, 2011). Given the increasing role of knowledge in corporate culture and the manageable structure of information and data, the need of providing firms with appropriate means that are capable to manage such data through computers has emerged (Roth, 2010). In Section 2.5 these facets will be considered from the perspective of the support of such systems in design activities; nonetheless, it is now important to determine which are the potential sources of innovation processes in engineering design.

To this purpose and among the others, Hicks et al. (2002) have already remarked that design is a knowledge-intensive activity and that, hence, along the different phases of the design process, many sources of information support engineers in their tasks. Figure 9 (Allen, 2000) presents a classification of the different sources of information and organizes them in clusters. At a glance it is clear that these clusters range in a very wide span of different information, potentially introducing multiple perspectives on the same concept. Knowledge from inside of the company, therefore, has to be integrated with information from customers as well as standards, policies and so forth. On the contrary, with a deeper examination, it appears that such information and knowledge can be also categorized according to the viewpoint of their owners. Indeed, it is possible to notice that such sources can be divided into human-carried and formalized. This aspect introduces the classification of knowledge into tacit and explicit; it would be briefly addressed in the following section and later examined into further details according to the relevant sources of knowledge for the characterization of requirements. Notwithstanding, it appears clear that all the human-driven information is characterized by certain skills, by certain “know-how”. This bond between skills and knowledge goes under the concept of expertise and Hicks et al. (2002) remark that it has a crucial role in transforming information into knowledge through meaningful interpretation. Such a process, to Smith (2001), is so natural for those owning expertise that it possibly occur in a context of complete unawareness. Polanyi (1967), to this regard, states that in a process of knowledge acquisition it is possible to learn without being consciously aware of doing so, there must also be a process of "*discovery without awareness*".

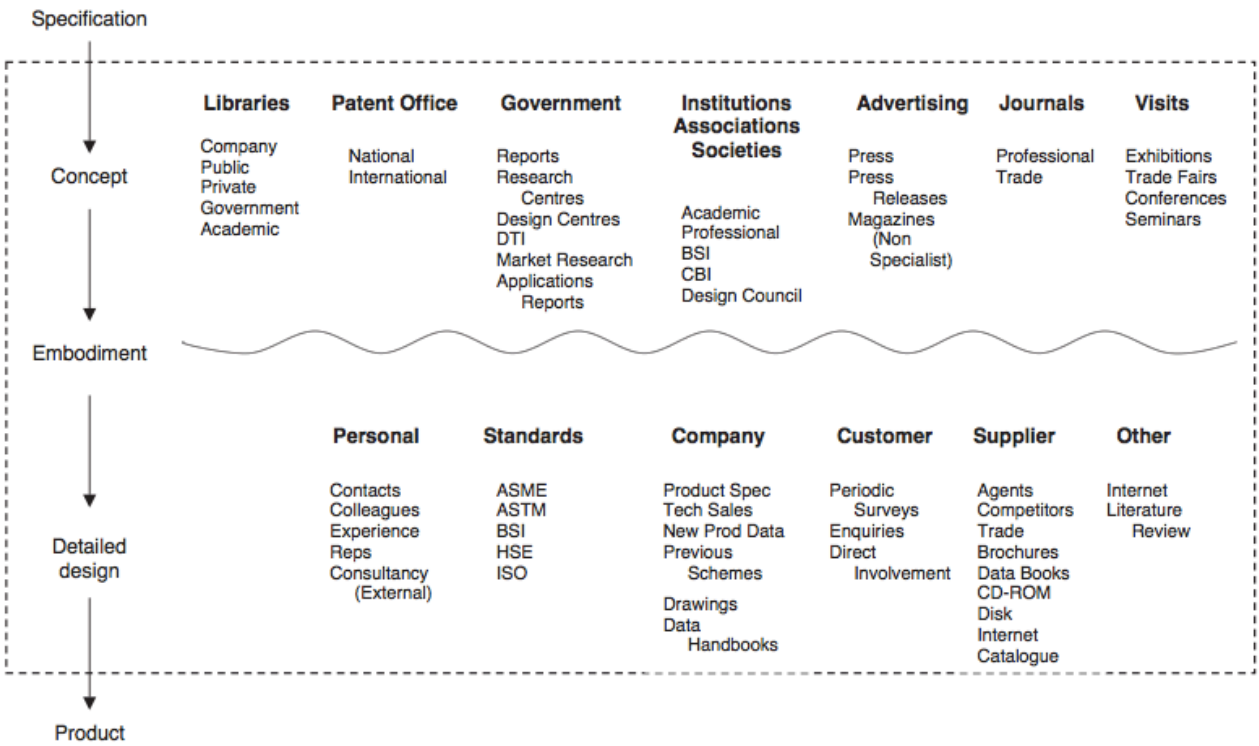


Figure 9: Sources of information and knowledge along the different phases of the design process according to Allen et al. (2002). Image after (Hicks, 2002).

2.3.3 Classification of knowledge into tacit and explicit

From the analysis of Figure 9 it has been highlighted that information and knowledge can be both carried by humans and found in unanimated repositories. The main difference between these two categories stands in the explicit nature of knowledge contained into such “repositories”. In

literature, explicit knowledge represents what can be explicitly stated, while tacit knowledge characterizes what one knows but cannot be expressed in a codified way. As stated by Smith (2001), tacit knowledge is a highly personal and subjective form of knowledge that cannot be found in manuals, books, databases or elsewhere than individuals. In other words

> *"While tacit knowledge can be possessed by itself, explicit knowledge must rely on being tacitly understood and applied. Hence all knowledge is either tacit or rooted in tacit knowledge. A wholly explicit knowledge is unthinkable." (Polanyi, 1967)*

According to the last statement it appears more evident that explicit and tacit knowledge shouldn't be considered as two radically opposing categories, but must be rather framed in a unique body, since it is not possible to produce explicit knowledge without the interpretation and the mastering of concepts in the tacit knowledge domain. To this purpose, Wallace (2007) remarks that for using explicit knowledge (such as a document, a recording, or a work of art) it requires a process of transformation from explicit to tacit knowledge. Indeed also an artificial, passive product of human mind can hold in itself explicit knowledge, but it gets meaning just by means of the individual process of tacit knowing. Gero and Kannengiesser (2004) have described a similar transformation process from the viewpoint of design. Their Situated Function-Behaviour-Structure Framework maps cognitive processes occurring in individuals. The mutual relationships among three different worlds, as depicted in Figure 10, point out the different the cognitive functions that allow to build concepts in the form of tacit knowledge. Such process starts from the experience of something that occurs in the external world and, by itself, carries some information (shape, roughness as well as colour…). The meaning of Function, Behaviour and Structure, for the moment, can be overlooked.

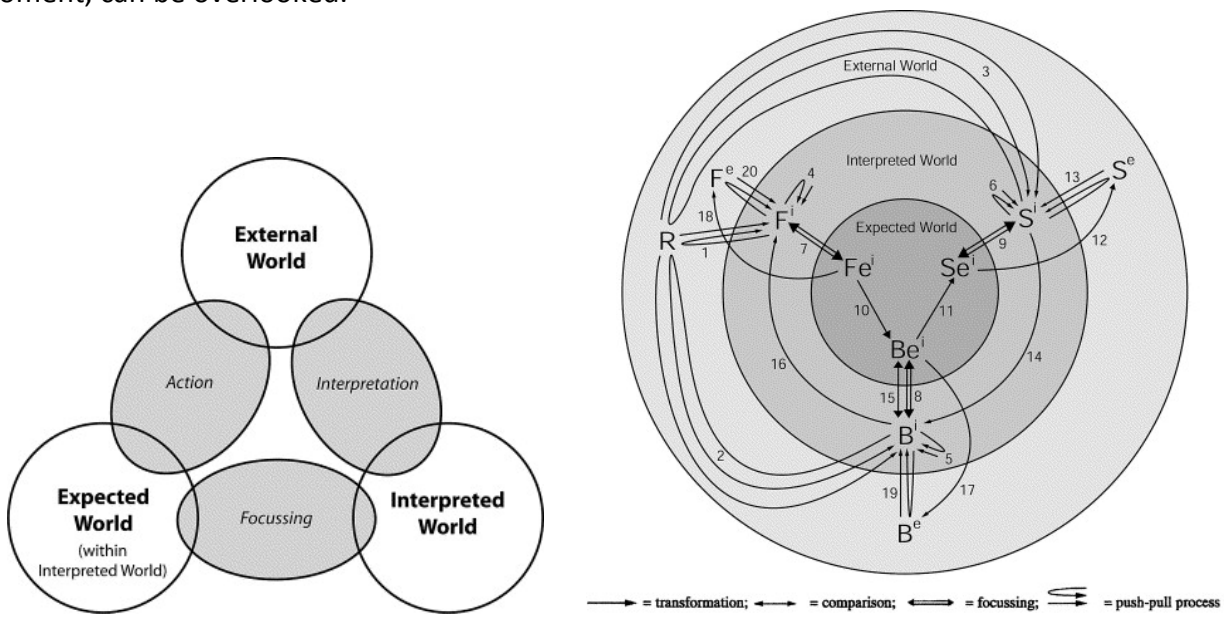


Figure 10: Left: Situatedness - Scheme of cognitive functions as interactions among three worlds. Right: The situated Function-Behaviour-Structure (FBS) Framework, details available in (Gero, 2004).

By using the words of Smith (2001), tacit knowledge

> *[…] is made up of mental models, values, beliefs, perceptions, insights and assumptions. Technical tacit knowledge is demonstrated when people*

> *master a specific body of knowledge or use skills like those gradually developed by master craftsmen. Cognitive tacit knowledge incorporates implicit mental models and perceptions that are so ingrained they are taken for granted. Cognitive models affect how we make sense of events in our world. (Smith, 2001).*

The transfer of knowledge therefore has also to deal with its transformation, and it constitutes a crucial point for design activities that is critical to address. As witnessed by Civi (2000), socialization, combination, externalization and internalization are the processes involved in such a transfer.

Socialization allows sharing experiences among individuals through common models, describing practical facets as well as technical skill; thus improving and reversing elements of tacit knowledge into a bigger framework (Tacit to Tacit). This process enables to improve individual skills to be used in order to attain a desired goal state in design.

Combination, in turn, is the process according to which it is possible to put together different concepts by building a wider set of elements of explicit knowledge (*Explicit to Explicit*). Moreover, it straightforwardly supports the cognitive processes that allow to attain a design goal through the combination of already existing solutions.

Internalization has been briefly described above (Gero, 2004) and it concerns the transformation of what has experienced (read, listened, touched…) in the external world into personal beliefs and reorganized mental models (*Explicit to Tacit*). Since this process entails a learning-by-doing process it is evident that it strongly supports the efficiency of the design process by improving the notions about "*how to do things*".

At last, **Externalization** is the process where new knowledge can be created and articulated into an explicit form (Tacit to Explicit) and it is the most critical to carry out (Civi, 2000). Its purpose is to transmit knowledge and make it reusable beyond the limits imposed by socialization. Its importance in design is paramount since it is possible to find similar types of problems by analogy and address them with strategies and technical solutions that have already demonstrated their efficacy in different contexts (Smith, 2001).

In this perspective, Collins (2010) has pointed out that such processes are critical to make people increasingly skilled in doing things. He remarks that it is necessary to translate tacit knowledge into explicit in order to train people. Moreover, cheap and easy means (prints or talks) are the most indicated to fulfil such a goal. Inside this belief it is enclosed concept that internalization and the externalization processes are therefore two sides of the same phenomena that is knowledge transfer. On the one hand, it is required to increase the knowledge of people through an internalization process; but, on the other hand, to carry out such a goal in an efficient way, knowledge should be organized and externalized in way that allows its "broadcasting". How to capture and transfer such knowledge is, however, still an open issue that poses several research questions. Hicks et al. (2002) state that one of the main problems concerning the formalization of knowledge concerns the identification of the relevant elements to be captured. Besides, one more issue in this regard concerns the extent of this capturing procedure, in order to assure the usefulness of the caught knowledge.

Other studies, in turn, tried to address the issue of how to represent the captured tacit knowledge so to make it explicit. Roth et al. (2010) suggest that in design it is necessary to rely on a unique taxonomy so to represent all the different knowledge of the individual involved in such a process according to their competences regardless of the specific field of application. Perez-Arao et .al (2007) remark that this kind of process should also have the characteristics of being

systematic at the maximum extent, thus implying the necessity to introduce procedures that allow to make this process repeatable.

To this purpose, the introduction of appropriate taxonomies, which are capable of turning the tacit into explicit knowledge and working with repeatable outcomes in different fields of application, allows to use them as a means for questioning individuals about what they know and organize their answers according to the structure of the taxonomy itself. In this sense, given the repeatability of such investigations of tacit knowledge, computers represent a very relevant partner in this maieutic process of knowledge extraction, releasing humans to act as the main actor of this process of capturing. This specific aspect will be regarded with more attention in Section 2.5.

2.3.4 Sources of Tacit Knowledge in the Design process

Design is an activity that requires a huge amount of cognitive resources: from the description of the design space to the decision making process aimed at excluding alternatives in order to converge towards a unique and effective solution (Cross, 2008). The choices among different options are always driven by the need of satisfying specific requirements. Whenever two or more requirements appear as non-mutually compatible, a new problem appears in the design space and the next design move requires a designer's creative leap to solve the problem. In order to identify the most efficient approaches for solving problems in design, Kruger and Cross (2006) studied the design processes carried out by different designers: on this bases they distinguish four different cognitive strategies:

- **Problem driven design -** main focus on problem definition using information and knowledge that is strictly needed to solve the problem, with the purpose of promptly generating a solution;
- **Solution driven design -** little time spent on problem definition and main efforts put in the definition of solution concepts gathering information and knowledge needed to further develop a solution;
- **Information driven design -** generation of solution concepts on the basis of information gathered from external sources;
- **Knowledge driven design -** generation of solution concepts on the basis of prior, structured, personal knowledge, with a minimal amount of information gathered from external sources.

Regardless of the followed strategies, it is clear that gathering information and knowledge from external sources represent a key issue, even for the last approach. Indeed, individuals' memory cannot manage the fast changes occurring in science and technique (Bracewell, 2009), since the size of available information is exponentially growing. This, in turn, means that Knowledge Elicitation (or Externalization) and Information Retrieval may jeopardize the efficiency and the effectiveness of the problem solving process, because it is not always clear what kind of information could be useful for solving problems (Ahmed, 2009).

Therefore, it is here necessary to start by taking into account which ones are the relevant sources of tacit knowledge within the design process, so as to review the current issues for addressing the knowledge extraction from the most relevant players and determine potential opportunities to improve the existing techniques.

Figure 9 shows that several categories of individuals can bring information and knowledge capable to be reused within the design process: Customers, Professionals, Suppliers, as well as Academics and even External Consultants. They all have, at a different extent and on different

aspects, some expertise about the product to be designed and then used. Such expertise makes them a preferential partner for supporting the design process with their tacit knowledge.

Moreover, these different profiles can be characterized according to their role in the development process aimed at innovating existing products. Customers, in this sense, represent a complementary category to the others. Despite all of them can be properly seen a stakeholder of the design process, from here forward customers will be considered as a separate category for sourcing information. Indeed, all the other players hold a different kind of knowledge, more focused on technical issues, that has a crucial role in carrying out the various design stages aimed at attaining a goal. Therefore, such residual profiles owning technical tacit knowledge will be referenced as stakeholders, without the necessity of repeating that they should be considered as stakeholders *from within* the design process.

2.3.4.1 Customers

Section 2.2.1 has already discussed the importance of customers to determine new market segments. Indeed they can be considered as one of the cause, together with the environment in which they are immersed, of the dynamics occurring in market structure. Furthermore, their new and emerging demands are the causes driving such changes.

Marketing, indeed, is gaining a greater importance in industrial contexts because of the adopted strategies for keeping competitiveness**. Customers' opinion, as a consequence, is progressively becoming in many different industrial contexts the predominant driver of innovation.** For this reason it is crucial to understand which are the different methods or procedures to catch the tacit knowledge of customers so as to turn it in a usable set of elements of explicit knowledge that, on the one hand, drives and, on the other hand, limits the introduction of new technical solutions aimed at satisfying demands and needs.

To the purpose of better understanding where to find meaningful information for the design process, two different classifications of customers are presented. Rogers (1983) proposes to link innovation diffusion with customer behaviour. It stems from the consideration that customers adopt innovations in different time frames, as follows.

Innovators are people having a wide availability of economic resources that allow them to posses an innovation as soon as it appears on the market, accepting risks of buying products of higher complexity and poor usability. Their role is crucial for the diffusion of innovative products, processes and services in the market even if their social interactions are not so pronounced.

Early adopters distinguish themselves from innovators because of their improved social integration and their intrinsic ability to put forward their opinions to turn them into common beliefs. They adopt innovations at the beginning of their commercialization (but later than innovators) since their status and charisma is conferred also by the possession of such goods.

Early majority is the segment of people that come into possession of innovations before the average of the population, that doesn't have particular attitude of opinion leadership, even if they are well integrated into the society.

Later majority represent people that generally have a sceptical attitude towards innovation, and that are characterized by a certain scarcity of resources that leads them to come into possession of innovation just when the society exert a certain pressure for adoption. Differently from innovators and early adopters their hesitation in adopting innovations concerns the need of removing all the potential risk of a wrong purchase.

Laggards, at last, do not care the pressure from the society to posses a certain innovation. Indeed, such attitude is partially due to the fact that they refuse to adopt an innovation until all

the inherent risks get removed and also because of an innate scepticism towards new technical solutions.

On the other hand, Von Hippel (1986) pointed out that there is a particular category of customers: lead-users. The point is here turned into the perception of needs and demands, rather than in social interactions. In detail, "*Lead users face needs that will be general in a marketplace- but face them months or years before the bulk of that marketplace encounters them, and […] [they] are positioned to benefit significantly by obtaining a solution to those needs.* These two different classifications by Rogers and Von Hippel are not mutually exclusive; rather, it is evident that lead-users share common features with both innovators and early adopters. The definition of the audience whom opinion has to be examined is therefore crucial for introducing innovations with high potential and, on the other hand, low risks.

For what concerns the role of the customers' knowledge in the design process, the "Voice of the Customer" (also referred as VoC) refers to customer information concerning needs, requirements and expectations (Clausing, 1994). According to the different extents of customer involvement in development processes, Kaulio (1998) recognizes three different situations where the Voice of the Customer addresses its contribution to design. In substance he distinguishes between three different kinds of design processes: *for* the customer, *with* the customer and, in partial contrast to what has been stated before, *by* the customer.

In the first case (*for the customer*), the customer is placed outside the design process, despite the product is conceived consistently with the customer requests. In this situation the customer has no control on the explicit knowledge he produced. Indeed, stakeholders manage them and, more important, they must interpret them according to the specific context in which the development process occurs, thus translating generic statements about desires into technical issue to be addressed during the process. From this perspective, Ulrich and Eppinger (2008) has remarked that, to ease this knowledge capture and make it effective, it is crucial to question users by using a familiar jargon that is easily understandable and limits ambiguity. Moreover they also point out that such questionings should provide written elements that must refer to the function of the technical system to be designed (what it is for), rather than on its behaviour (how the system is), because the latters concern decision that should be made during the design phases by appropriate stakeholders.

In the second case (*with the customer*), the situation changes and the suggestion to carry out an efficient design process by Ulrich and Eppinger gets neglected. Indeed, in this specific kind of design processes, the customer has the faculty of expressing opinions not just concerning the purposes of the entity to be designed, but also about the potential solutions that could address their needs. Generally speaking such approaches require the customer opinion to both understand needs and demands so as to plan the development and, later, to estimate and express satisfaction or discontent about the solutions that the designers has proposed to attain a desired goal just before their manufacturing start. This practice is becoming more and more diffused as witnessed in (McAdam, 2002), (Fuller, 2002) and (Bordegoni, 2011).

In the third case (*by the customer*), the customer has the most active role. Lead-users has the chance to propose their privately developed concepts, thus meaning that they suggest a complete product in terms of functions, behaviours and structures -with reference to Gero's framework (2004)- and this product represents the starting point for the design process assuming that all the customer's tacit knowledge relevant for developing a new solution is enclosed in the proposed solution concept.

Despite it has not been explicitly stated before, the Voice of the Customer is usually captured through the use of questionnaires and aims at recording customer satisfaction. The textbook by Hayes (2010) describes specific issues that should be taken into account while

designing a survey to capture customers' opinion, from how to populate it with meaningful questions, to how to exploit the results in order to build a stronger corporate strategy. Among those, the most relevant issue according to the purpose of this work entails the first step of the questionnaire design.

Figure 11: A general model for the development and use of a customers satisfaction questionnaire (Hayes, 2010).

As depicted in Figure 11; the first step for developing VoC questionnaires needs to clarify which are the customer requirements to be taken into account, namely the relevant features that would characterize the business of the company for which the survey is carried out. Hayes remarks that for companies it is essential to own knowledge about priorities according to the customers' viewpoint so as to determine strategies for customer satisfactions. This witnesses the increasing attitude driving the corporate business according to the perspective of the market, rather than according to technology. For what concerns the instruments to determine in advance the customer requirements, Hayes mentions two non-mutually exclusive alternatives.

The first technique is the so-called "quality dimension development process". It needs to question people involved in the whole business process and that is in close relationships to the service or product. The underpinning concept underlying this choice is that, to determine customer requirements, it is necessary to hold some expertise and it is the key to understand what the customers want. Hayes reports several examples of customer requirements in different fields of technique. However, the specification of the questions in each single domain is left to the different stakeholders within the design process that has to define them just according to their experience, thus lacking in completeness.

The second technique, in turn, is "the critical incident approach" by Flanagan (1954). It aims at capturing customers' knowledge in the form of customer requirements directly from the customer. From a practical point of view, they are put in front of specific situations that require an evaluation about the relevant behaviours (of both technical systems for products and process, of people for services). In opposition to the quality dimension development approach, the stakeholders have here a relevant role just in defining the potential situations where relevant customer knowledge may emerge, so as to identify the satisfaction items that would be evaluated by customers. Such satisfaction items, in turn, define the customer requirements.

In general terms, the following techniques show that the stakeholders within the business have a paramount role in catching tacit knowledge by customers. Besides, with both approaches, they can just rely on their own tacit knowledge to determine customer requirements or situations through which question customers. Indeed, despite the two approaches result in a wide range of domains of potential applications, for practical reasons the definition of such surveys for specific businesses rely on specific checklists or set of customer requirements as already proposed in literature.

Despite it is also relevant to this topic; the process of translating customer requirements into technical requirements will be presented in detail along Section 2.4.2.

2.3.4.2 Stakeholders within the design process

Consistently to their central role within the innovation processes, designers having expertise in domain-specific fields of science and technique represent the most relevant source to capture up-to-date tacit technical knowledge. Such central role is mainly due to their active participation to the development of new technologies and to the design processes concerning the integration of technologies into innovative technical systems. Technical experts, whenever facing problems, usually rely on their tacit knowledge to interpret the physical phenomena underlying the technical system they are analysing, to generate solution concepts for satisfying specific customer needs as well as to evaluate the solution concept they have conceived in order to redefine constraints and priorities along the design process.

Therefore, knowledge elicitation, as mentioned in Section 2.3.3, represents a valuable opportunity to drive the design process by means of specific requirements that can improve both the effectiveness and the efficiency of the design process. The so collected elements of knowledge allow defining both the boundaries of the different design space states and the goal state to attain.

Not surprisingly, the retrieval of relevant tacit knowledge from technical experts is a widely diffused practice in different scientific and technical domains such as information systems, medicine, operations management, education and, the more important to the purpose of this work, design (Miaskiewicz, 2011). The capturing of their opinions and beliefs becomes incredibly crucial in all the contexts and the situations characterized by the scarcity of data and information from which nurturing individual or social tacit knowledge (McBride, 2012). Decision Makers, Designers, Manufacturers, Suppliers and other stakeholders are then also an available source from which drawing from. To this purpose, however, it is important to notice that the actual availability of experts is a crucial issue to address since, according to their role, the time frame in which it is possible to carry out the externalization of their knowledge is radically limited by the incumbent daily businesses that they have to complete (Rohner, 2011).

Thus, for the codification of tacit technical knowledge from experts in industries, several challenges emerge in order to make these practices repeatable, reliable, efficient and, more than everything else, useful.

As said, experts represent an up-to-date source of tacit technical knowledge since they build their competences on practices and experiences. However, several factors can impact the reliability of the captured data because of the presence of relevant biases. The context under which this externalization process takes place may dramatically affect the results because of the abovementioned time pressure. Besides, experts can also bias the outcomes because it is possible to encounter certain reluctance in answering questions during this externalization process. In fact, it is possible that the perception of the elicitation process by experts triggers conflict with the unexpressed need to keep some of the tacit knowledge as secret as possible in order to protect specific individual or corporate interests.

To this purpose, the motivation of experts and their level of understanding the importance of knowledge transfer for the corporate strategy is a factor to cope with. Indeed, an appropriate description of the knowledge transfer purposes may trigger a good disposition in the mood of the technical expert to be questioned. On the other hand, a scarce support by the higher levels of industrial organization may trigger a completely opposite behaviour, thus resulting in outcomes of poor utility and transferability (Rohner, 2011).

Previous experience is one more factor that may also affect the reliability of the captured and externalized knowledge. From this viewpoint, understanding which expert holds the required tacit knowledge imply that is already clear which kind of technical knowledge is necessary. However, an extreme approach aimed at strictly selecting the sources of knowledge may results,

to a certain extent, as a limitation. Indeed, the cognitive process of Transformation in design demonstrate that it is still possible to perform searches for suitable solutions in domains (design spaces) that goes beyond the original description of the design space where the problem state has been depicted. In such cases it is possible that a completely diverse technical knowledge is required to carry out with success the innovation process in design. A high degree of experience, from this side, could represent a good parameter to assure the reliability of the captured tacit knowledge. However, this may lead to potential limitations regarding the capability to release and abstract from the specific context in which the competences have been earned (Vargas-Hernandez, 2012).

It has been already mentioned that this externalization has clearly to deal with the appropriate codification of knowledge and, as for knowledge elicitation from customers, the challenge is represented by the identification of suitable strategies to turn the "*unconscious*" into "*conscious*" and verbalize it (Gaines, 1987).

To this purpose, different channels of communication can be exploited for eliciting knowledge from experts. This aspect is quite critical since communication problems may produce errors in the interpretation, thus compromising the reliability of the resulting knowledge base. Reasons triggering this kind of misleading communications are grounded in the potential misunderstanding due to the stakeholders' domain-specific jargon, which in turn appears to be poorly adaptable to the criteria for knowledge elicitation. As well, a wrongly focused contextualization of the purpose for which the externalization process occurs can also result in conversations poorly fitting with the situation that requires the acquisition of new knowledge (Martin, 2012).

The human-human interaction through face-to-face or telephone-mediated interviews is one of the most adopted strategies. Such interviews can take place between two individuals or in context where panels of experts are involved in meetings (McBride, 2012).

The human-human approach implies, as mentioned by Fellers (1987), that a methodological facilitator, which is skilled in the procedure for acquiring new knowledge and transfer it to an explicit format, is present and in charge of the externalization process. This person 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. In this perspective it is worth noticing that preliminary training with experts can produce better outcomes. For instance, if questioning procedures are used for externalization, it is important that experts learn in advance how to properly answer questions. An improved familiarity of experts with the extraction procedures and techniques is viable to reduce the efforts required by knowledge transfer, as highlighted by McBride et al. (2012). In this sense, the introduction of simulated scenarios describing the context for which the knowledge acquisition is required (as for the "critical incident approach" for customers) represents one potential strategy for achieving a double goal. First, they reduce the risk of a wrongly driven communication between the facilitator and the stakeholder. Second, they also improve the stakeholders' perception of the importance of such an activity.

It is also worth mentioning that to address the need of knowledge elicitation during the design stages, several contributions are available in literature in form of checklists of relevant aspects to be considered along the design process. This specific aspect, being mostly concerned with the development processes aimed at innovating products, processes or services will be extensively discussed in Section 2.4.1.

Surveys and interviews, however, are not the only alternative capable to carry out externalization processes, several examples demonstrate that this issue can be also addressed through the use of Relation Tables where to 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, 2012).

It is now worth recalling that the design process involves a wide range of different stakeholders, characterized by various objectives to be achieved for the attainment of the overall innovation goal. Whenever knowledge externalization occurs in this context, the presence of a methodological facilitator becomes more critical. The words by Martin et al. (2012) support this assumption:

> *Some of the considerations in eliciting expert knowledge include determining how to work with multiple experts and how to combine multiple judgments, minimizing bias in the elicited information, and verifying the accuracy of expert information (Martin, 2012)*

Indeed, such facilitator is also in charge of the achievement of consensus among experts (Ben-Aried, 2011). This issue needs to be accurately discussed since inappropriate means for reaching consensus may produce errors, such as the ones emerging during misleading communications, and thus compromise the definition of a useful knowledge base to rely on. However, it is also worth noticing that the convergence towards a unique definition of multiple visions inevitably neglects the various nuances of interpretation about the same concept.

To this purpose, Delphi method (Linstone, 1975) has been considered as one of the most powerful tool in reducing potential biases due to the polarization of consensus towards specific subgroups or eminent individuals in the panel. This objective is achieved through anonymously and individually asking the members of the panel about the issue to be elicited. The individuals' visions then get shared, reorganized and adjusted by also taking into account all the other vision in an iterative fashion so that finally a certain consensus is reached (three rounds generally).

For what concerns the facilitation of the knowledge extraction process and consistently to what have been remarked for the elicitation of knowledge from customers, even in this case computers express a good potential in easing the execution of elicitation and acquisition procedures. Indeed, the support of computers, in this sense, allows to release from geographical constraints through broadcasting surveys by emails or by enhancing the communication (Martin, 2012) through the addition of video streams to the more common audio-based interactions carried out by telephone. Moreover, standardized procedures for knowledge extraction could represent a good opportunity to implement related algorithms into software applications that aim at substituting the human methodological facilitator.

2.3.5 Sources of Explicit Knowledge in the Design process

In order to complete the analysis, it is now necessary to take into account which ones are the relevant sources of explicit knowledge within the design process, in order to clarify where to retrieve meaningful and useful elements to carry out, with increased effectiveness and efficiency, the design process.

It has been already discussed that, during the design process, technical experts and, moreover, designers exploit their competences to assign meaning to what happens in the external world according to a process of interpretation (Gero, 2004). Indeed, this process occurs both when it is asked to describe a situation where causes of discontentment have to be removed, as well as to evaluate concepts generated along the design activity. However, science and technology are

exponentially developing with increasing levels of specialization and by exploring new domains, so that it is more and more difficult to master all the needed subjects. **As a consequence, tacit knowledge, even if leveraged by a multidisciplinary team of experts, could not be sufficient to tackle design tasks in innovation processes. To this purpose, explicit knowledge represents a valuable support for both experts and non-experts as a means to acquire new knowledge and design innovative solutions.**

> *Explicit knowledge is technical and requires a level of academic knowledge or understanding that is gained through formal education, or structured study. Explicit knowledge is carefully codified, stored in a hierarchy of databases and is accessed with high quality, reliable, fast information retrieval systems. Once codified, explicit knowledge assets can be reused to solve many similar types of problems or connect people with valuable, reusable knowledge (Mareis, 2012)*

Nowadays, the access to explicit knowledge has been nurtured by the introduction of Internet and the World Wide Web. It has created the conditions to share knowledge elements in an effective, easy and quick way. Nevertheless, the availability of an enormous range of sources of information and explicit knowledge also results in some drawbacks pertaining the reliability of the retrieved content. Objective data, even organized in information according to the context in which they have been produced, represents a perfect source to feed design processes, as proposed in Figure 7. According to the logic of "*design as search*" (Simon, 1973), those data and information supports the designer in characterizing both technical issues (such as the description of product characteristics) and customer attitudes (such as statistics about purchases), even if such a process requires an interpretation process through which they enriches both explicit and tacit knowledge. Nevertheless, objective data does not necessarily constitute a reliable source to draw from without limitations. Indeed, it is still necessary to point out that also objective data is not free from biases, just as tacit knowledge, being the collection procedure by itself potential source of perturbations.

On the other hand, Science and Technology allow relying on really authoritative sources of information and knowledge. Textbooks, handbooks and every scientific publication, such as journal papers that undergo a peer-review process, have, at least, better chances to constitute a good and reliable source to plug knowledge gaps. Among the available sources of explicit technical knowledge, patents represent a good opportunity for locating relevant explicit knowledge despite their content does not undergo a peer-review process. Indeed, experts in patent law in the different patent offices make decisions on patents just on the basis of their fulfilment of requirements for patent granting, completely neglecting the actual capability of inventions of really working. Nevertheless, they also represents assets for industrial competitiveness and it is also possible to infer meaningful data at least for what concerns the corporate strategy of competitors or players that are running their businesses in other market segments.

To this purpose it is worth mentioning that patents, as well as scientific papers, contain information that cannot be differently retrieved -it has been estimated that patents contain a huge amount of information not available elsewhere; almost 80% of the whole content (Bregonje, 2007)- and their databases are regularly updated with recent contribution so to enrich and move beyond the limits of the state of the art. Among the opportunities to gather updated information on a given scientific or technological matter, it is worth considering that they also have a particular structure that eases the identification of relevant documents in a given set. Scientific papers and, mostly, patents are organized following a standard structure that enables to carry out searches

according to different characteristics. Patent classification or domain of science; publication date as well as authors or patent assignees and inventors; the key content summarized in the abstract as well as the most relevant keywords are all examples of metadata that allow to organize these information in order to narrow the range of alternatives, so as to ease the searches.

To this purpose, Information Retrieval has a crucial role in design: from the need to plug knowledge gaps, so as to enlarge the borders of the design space, through the retrieval of useful stimuli from available data and information sources, to the identification of already existing solutions to evaluate the novelty of ideas generated along a design process. Requirements, from this viewpoint, can be extracted from retrieved documents so as to improve both the effectiveness and the efficiency of the design process. Beyond the practical application of information retrieval techniques, it has been already pointed out that information retrieved from the external world represent one of the data source according to which human mind structures memory and through which it exploits cognitive processes. Moreover, Aurisicchio et al. (2006) have highlighted that information gathering currently requires a meaningful amount of time spent by designers, especially during the early stages of the design process. Interpersonal communication emerges as a key resource for progressing design problems in a practical way, learning how to design: designers generally prefer to source knowledge and information through informal interactions with their colleagues (the socialization process mentioned in Section 2.3.3). However, it is expected that designers will increasingly have to rely on retrieving information captured and stored independently of human memory as remarked at the beginning of Section 2.3.4 and briefly recalled above. These reasons provide compelling evidence about the need to quickly and correctly formulate queries for the investigation of knowledge databases (Becattini, 2012-b). Indeed, queries (and keywords composing them) currently represent the standard way by which data can be gathered from a wider and wider range available sources. The efficient performances of IR systems, reducing the number of non-relevant information retrieved with a single query, still represents an open issue. The potential support of criteria for eliciting and classifying knowledge elements could feed the identification of meaningful keywords to be employed for searches of scientific and technological explicit knowledge.

2.4 Role of Requirements in Development Processes

This section will go into the details about requirements along the development processes. More specifically it aims at clarifying in which contexts they are necessary and which kind of support they can provide within the design process. The section is subdivided into four different subsections.

The first subsection will start with the description of design methods and procedures from a literature review, in order to define which are the phases of the development processes where requirements plays a relevant role. This description allows to identify which ones are the most relevant cognitive processes involved during the design activities and that may emerge along the different stages of the development process.

On this basis, the other three subsections are organized according to their role in the analysis of design problems (2.4.2); in the synthesis of solution concepts (2.4.3) and in the evaluation of such concepts for moving towards the next development step or iterate the design process (2.4.4).

2.4.1 Requirements in the stages of the development processes

The definition of phases, tasks and cognitive processes concerning the development processes has a crucial role in the improvements of their efficiency. Indeed, it is just by clarifying which steps

should be carried out that it is possible to efficiently address the need of developing new solution with adequate efforts, setting up objectives to achieve and thus reducing unfruitful iterations due to an unorganized process where innovative solution are searched by chance and in an unorganized context.

To this purpose, different scholars have proposed their visions about the product development process. Some of them limit their contribution to the description of the different phases that characterize the process, while some others point out which tasks should be addressed along each step in order to drive them according to prescriptive rules to follow.

Cross (2008), in his book "*Engineering Design Methods – Strategies for Product Design*", carries out a meaningful review of different available approaches for product design. Stemming from his analysis, it will be discussed how the different approaches characterize this process. The purpose is to identify similarities and differences among them and to point out relevant correspondences with the concepts already discussed in the previous sections. Moreover, it is worth noticing that these models can be also useful in describing which phases characterizes the development of new processes.

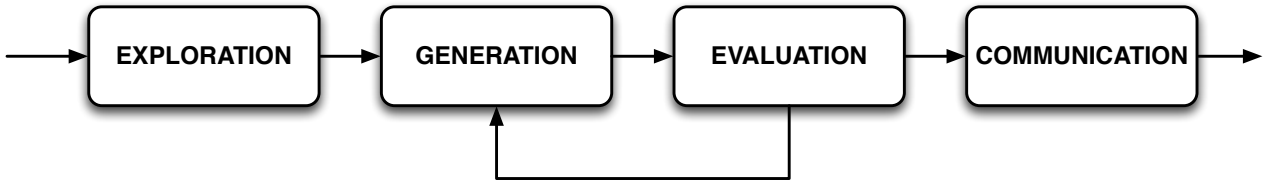


Figure 12: The four different cognitive activities exploited by individuals and groups during the design process together with mutual relationships. Arrows represent flows of information.

Exploration, *Generation*, *Evaluation* and *Communication* are the four phases that, according to Cross (2008), can describe with sufficient details the different activities performed by designers during the Product Development Process (PDP). They are organized in sequence, even if iterations and loops are allowed and expected according to the heuristic logic with which designing proceeds.

Figure 12 shows that the design process starts with the *Exploration* of the design space in order to clarify which are its limitations, somehow setting the limits for searching. This concept of *Exploration* differs from the cognitive process described by Boden (2009), even if some commonalities can be recognized. Indeed, the definition of requirements from needs is, by itself, a creative activity and it occurs according to generative rules. After a proper definition of the design space it is possible to start *generating* solution concepts that address the problem at hand. These outcomes should be properly *evaluated* in order to verify if they have a potential for further development or if they have to be discarded. Moreover, this kind of *Evaluation* is not carried out just on the whole solution concept, but also according to its capability to achieve specific sub-objectives. This allow to keep promising solution concepts so that, in an iterative fashion with the previous phase, it is possible to refine what still does not meet the expectations. Once the evaluation demonstrates that at least one of the solution concepts attains the initial goals, such design proposal is ready to be delivered (thus, *communicated*) to the manufacturing department.

The model proposed by French (1999) is articulated into four phases, as well: *Analysis of a problem*, *Conceptual Design*, *Embodiment of schemes*, *Detailing* as presented in Figure 13.

It is evident that the focus has shifted from *Generation* and *Evaluation* to the detail level of the ideation process. Indeed, the phase concerning the *Analysis of the (a) problem* is directly related to the abovementioned *Exploration* phase. However, the subsequent phases hold themselves both the processes of *Generation* and *Evaluation* and they are distinguished from each other according to the detail level of the design proposal. The *Conceptual Design* stage, indeed, is

described as the stage where concepts of broad meaning are proposed as a direction for attaining the goal. Further developments take place during the *Embodiment of the schemes*, since the initial concepts get sketched and defined with greater details so as to produce a general layout that define how the design proposal will be embodied. *Detailing*, in turn, aims at refining the characteristic parameters of the design proposal are subjected to minor changes. In this context, to clarify in which relationships are the two models, it is possible to say that every time a design proposal is defined or detailed the situation requires the generation of solution concepts capable to address the need; on the other hand, both the decisions to move from one stage of the design process to another, as well as the ones concerning the need to rework on the concept at the same level of details, requires a process of *Evaluation*.

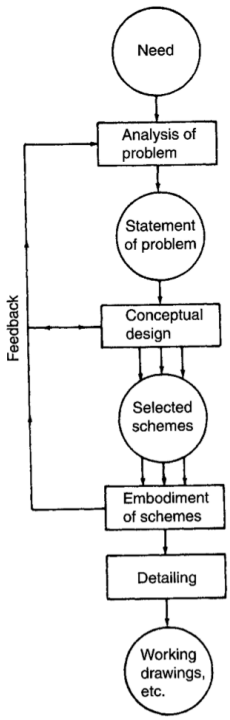


Figure 13: The Product Development Process as described by French. From Cross (2008).

Jones (1984), in turn, proposed three prescriptive steps: *Analysis*, *Synthesis* and *Evaluation*. Even if they plainly have a similar meaning to what Cross has proposed, the objective of such an approach, like all the other systematic prescriptive method, is radically different. *Analysis* stage prescribes to list all the requirements in order to produce a meaningful design specification. During the stage of *Synthesis*, each characteristic of the design specification should be singularly addressed to devise solution concepts for their subsequent combination in a unique solution with minimum design trade-off. The *Evaluation* phase, in turn, specify that the decision about the final design proposal must be taken into account by considering the capability of the design concepts to match the various requirements, including those coming from manufacturing and sales departments.

In turn, Archer (1984) introduced a more characterized prescriptive model that entails six stages: *Programming*, *Data Collection*, *Analysis*, *Synthesis*, *Development* and *Communication*, which can be further organized into three main phases as shown in Figure 14.

The *Analytical phase*, indeed, encloses both the stage of *Programming* and *Data collection*, where it is asked to define criticalities and collect related data in a fashion that is further usable along the whole process. The *Creative phase*, in turn, entails the analysis of the situation at hand by splitting it into sub-problems that allow to build an appropriate design specification (*Analysis*)

that should be tackled in order to define design proposals (*Synthesis*) that get detailed in prototypes to be manufacture and executed for an appropriate evaluation of their performances (*Development*).

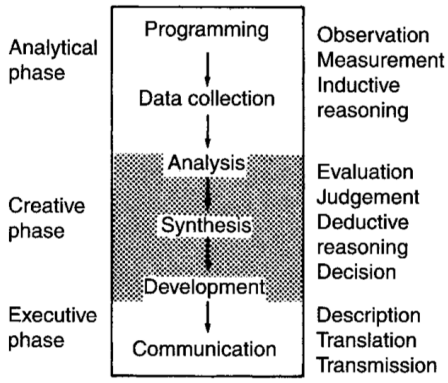


Figure 14: The Product Development Process according to Archer's vision. From Cross (2008).

The *Executive Phase* concerns the production of appropriate documentation for distributing the design proposal to other departments (*Communication*). Despite this process does not explicitly mention the need of carrying out evaluations, they have a paramount role to move forward in the design proposal (right side of Figure 14).

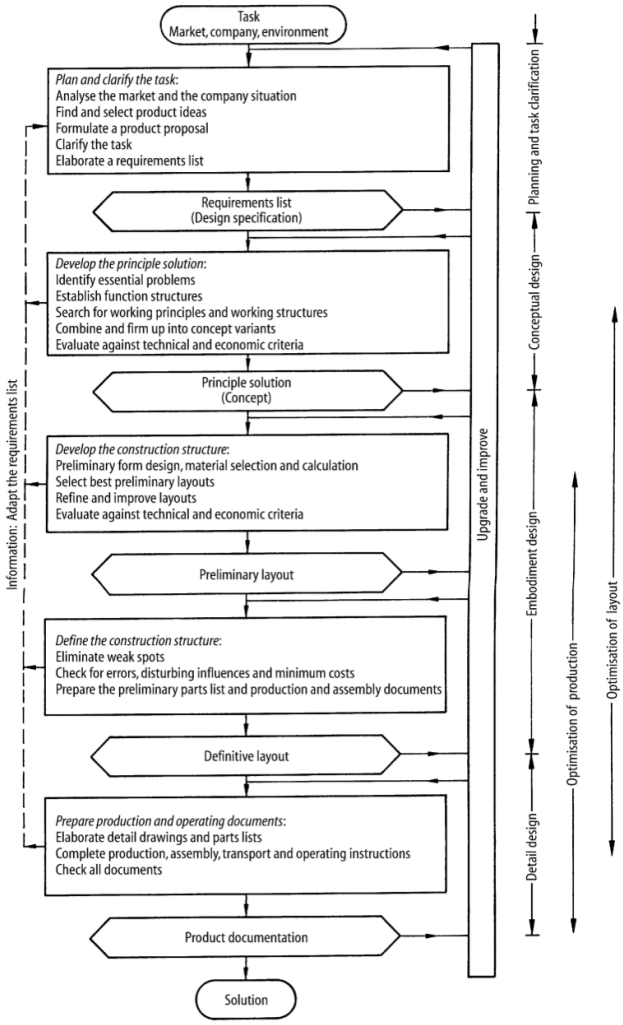


Figure 15: The flowchart describing the systematic Product Development Process according to Pahl and Beitz (Pahl, 2007).

Pahl and Beitz (2007) further improve the characterization of a prescriptive model for design by identifying four characteristics phases along the PDP as shown on the right side of Figure 15.

First, it is necessary to clarify the task at hand (*Task Clarification*) by retrieving all the information that can contribute to the identification of requirements and constraints to be satisfied by the solution concept, so as to produce a complete design specification. Second, on this basis the designer must start looking for appropriate solution principles by identifying the specific sub-problems to cope with (*Conceptual Design*). Such working principles start defining preliminary structural characteristics that are summarized in the concepts of solution. Third, it is necessary to determine more specifically both layout and forms (*Embodiment Design*) of the solution concepts to turn them into a few design proposals that just need to be refined if suitable for achieving the technical and economical goals. Once the definitive layout of the solution has been established it is necessary to detail it, so the fourth phase prescribe to introduce small modifications and moreover, adjustments to the characteristic parameters of the design proposal (*Detail Design*).

The work by Pahl & Beitz has been subjected to modifications and improvement by the German society of Professional Engineers (VDI, the German acronym) and indeed mutual exchanges can be also recorded through the references of their book "*Engineering Design: A Systematic Approach*". Such further details resulted in different procedures that are still developed to address the design process systematically. Figure 16 represent an example of this activity.

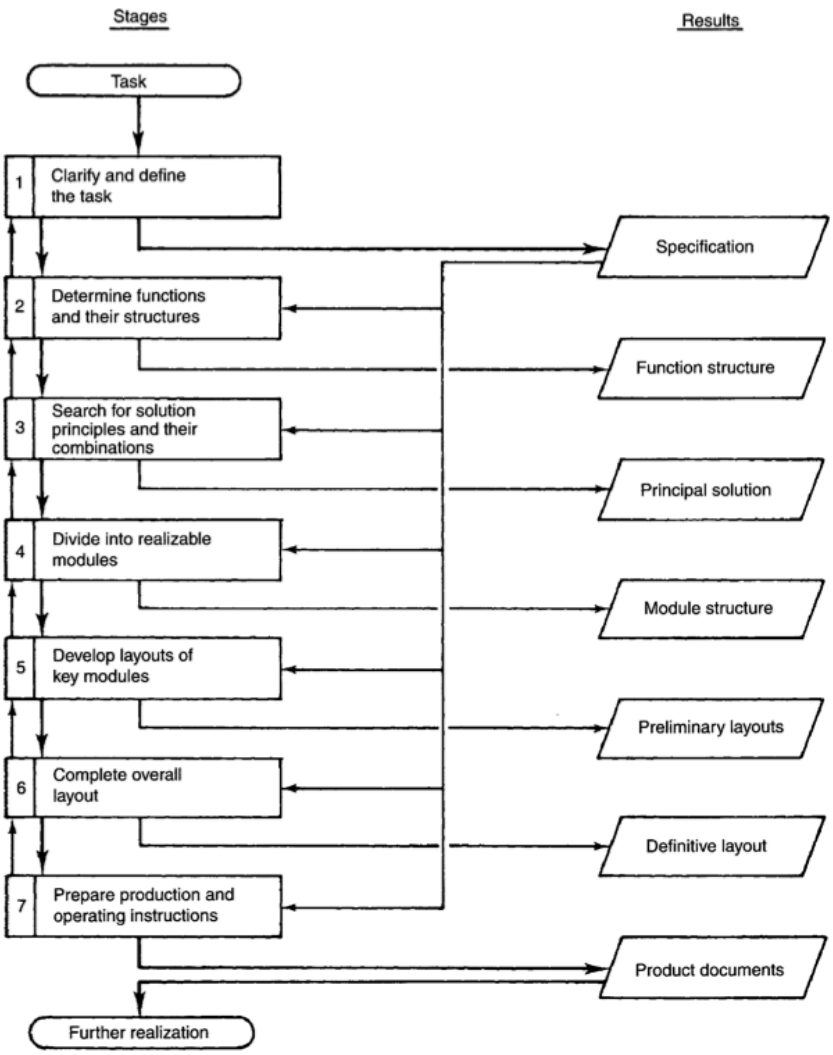


Figure 16: Characterization of design tasks, by the German society of Professional Engineers, to be carried out during the product development processes (Pahl, 2007).

Without entering into the details of the model, it is worth highlighting a few concepts that emerges also by the analysis of Figure 16. First, the PDP is divided into steps that resemble more to task than to phases or stages. Second, the approach is oriented towards the decomposition in sub-problems that allow to modularly design subcomponents to be integrated in the overall solution concepts. Third, the design specification, once defined in the first task, has an active role in all the next stages of the PDP.

March (1984), with a completely different and solution-driven approach, takes into account the way of reasoning along the PDP and clearly remark that *Induction* and *Deduction*, the two most known reasoning processes, are not sufficient to describe the *Synthesis* of design proposals. Indeed, *Deduction* reasoning allows to move from general to particular and *Induction*, on the contrary, takes conclusions about general behaviours according to particular premises. Designing, for March, requires a different way of reasoning that cannot be ascribed within none of the abovementioned two. He calls it *Production* or *Productive reasoning* but it reflects the concept of *Abduction* introduced by Peirce (Buchler, 1978).

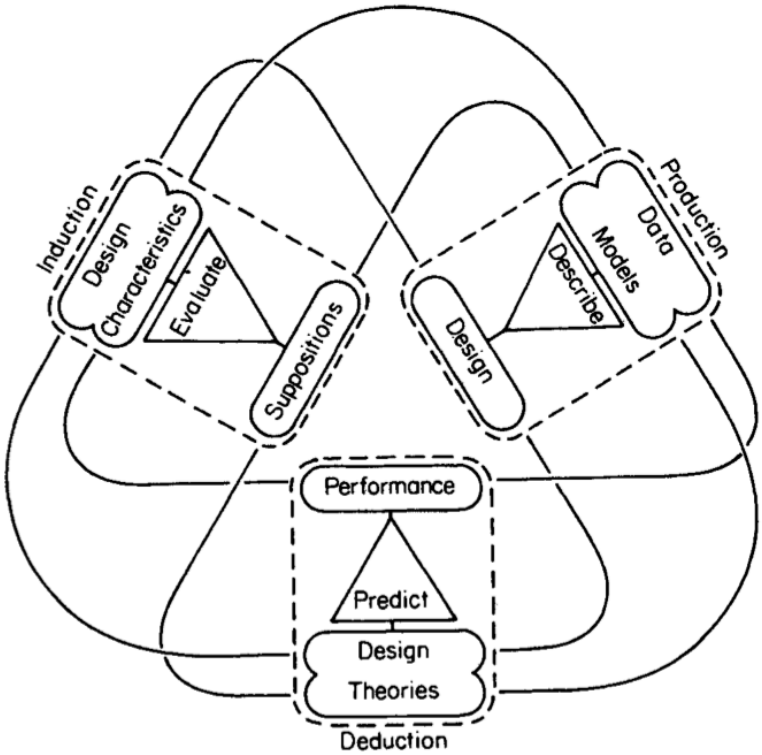


Figure 17:The perspective of March (1984) on the PDP. In details, the role of deduction, induction and abduction in Product Development Process (Cross, 2008)

Abduction/Production better describes the *Synthesis* of concepts and design proposals since it deals with the production of hypothesis, which are doubtless the outcomes of designers' mind that later undergoes a process of *Evaluation,* which include also an, even abstract, simulation, as described by Gero et al. (2004). Figure 17 shows the Production-Deduction-Induction (PDI) model that, in a cyclic manner describe the PDP from the perspective of cognitive processes of reasoning. Into the details, in the PDP, the *Production* phase enables the proposal of design concepts. Such a design proposal allows to move to the *Deduction* phase, where it is necessary to simulate the behaviour of the solution concept in a real context. This simulation sheds light on the performances of the design proposal that, in turn, can now be evaluated through *Induction* for identifying needs of changes and adjustments.

Roozenburg and Eekels (1995) call into question this meaning of Abduction and suggest to specify between *Explanatory Abduction* and *Innovative Abduction* referring to them as, respectively, *Abduction* and *Innoduction.* The former describe reasoning processes that moves from particular to particular, while the latter really describe creative behaviour since it generally address reasoning in which from general considerations one moves to other general considerations.

Moreover also Cross (2008) proposes his method for the PDP. It is articulated into eight different stages, as presented in Figure 18, where they are depicted as boxes inside the boundaries determined by Problems and Solutions.

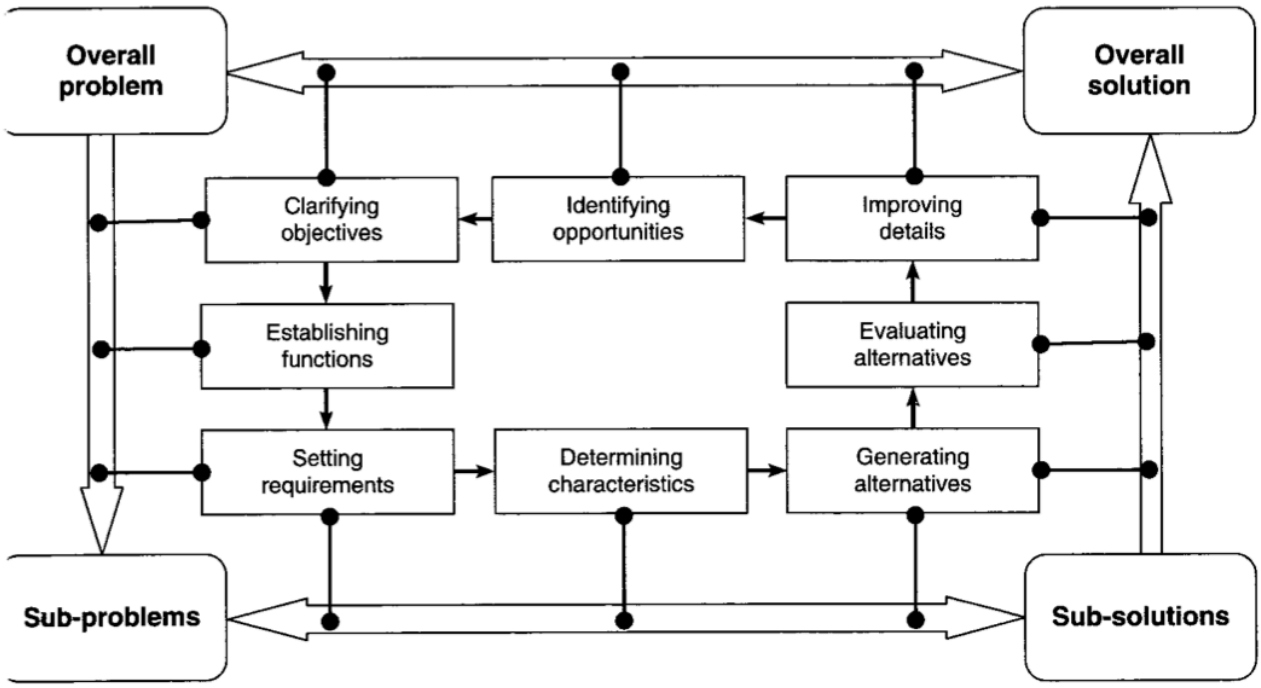


Figure 18: Cross' different stages to carry out the design process. The attention is paid to the specification of problems into sub-problems and the combination of specific sub-solutions into an overall solution. From Cross (2008).

Summarizing the sequence of phases, the process start from the central box on top of the Figure 18 (steps forward anti-clockwise) by recognizing some opportunities for product development (e.g.: a problem to solve as it will be clarified in Section 2.4.2) so as to determine objectives to be achieved through a certain set of functions. Their implementation needs to meet a set of diverse technical requirements. The satisfaction of such set can be achieved through product characteristics to be determined. An appropriate combination of such characteristics allows defining a finite set of design alternatives that constitute the initial proposals. After a process of evaluation, the alternatives that survived the selection get further detailed and considerations about further opportunities of development can be done so as to start a new cycle.

All the models of the PDP (even the P-D-I, whose description started from the synthesis of concepts for the sake of clarity) start with an initial analytical phase during which it is critical to understand which are the problems to address and the requirements that should be met in order to obtain a suitable and valuable solution. The other phases (stages, tasks), on the contrary, shows several discrepancies among the diverse models, mainly because of the different facets that have been taken into account, being them cognitive processes or actions to be taken. Nevertheless it is

very important to specify that all the design phases aimed at the proposal of design solutions require both the *Generation* (*Synthesis*) of concepts and their *Evaluation*.

In the following, the role of requirements will be examined according to three different cognitive activities of the design (Gero, 2004):

1. the initial Analysis of the situation;
2. the Synthesis of concepts for the final design proposal at different levels of abstraction, being them developed to the definition of working principles and preliminary structural characteristics or already organized into a structural embodiment that is viable to be manufactured after some adjustment to meet geometrical characteristic.
3. the Evaluation of solution concepts for both determining further opportunities for the PDP and rejecting unsuitable design proposals.

2.4.2 Role of requirements during the Analysis stages

It has been already stated in Section 2.2 that, independently from the context in which it may emerge, a "situation" is as a state in which someone perceive some discontent because of changed conditions in the environment as well as in the individual itself. Situations, therefore, can be also formulated as problems that arise because a demand needs to be satisfied (Roozenburg, 1995). In this context, the description of the situation and its causal models can be considered as the first step towards the identification of problems, as the entities and reasons underlying discontentment.

Design is in charge of searching and developing appropriate solutions to remove this discontent so that it won't come up again or, in other words, designing aims at solving problems. From a different perspective, situations and problems are in the same relationships as Ill-Structured Problems (ISP) and Well-Structured Problems (WSP) (Simon, 1973). Today it is clearer that this difference stands in the individual skills to turn an ISP into a WSP. Therefore, the individual's subjectivity becomes relevant for the design process, since the greatest part of the creative effort is initially addressed in changing the structure of the problem (Dorst, 2006). To this end, particular regard should be given to the interpretation of the problem, both taking into account the individual knowledge and the followed method. Several methodological contributions have been proposed to structure initial situations into a framework where critical entities and causal relationships are made explicit, as the preliminary condition to start choosing the right problem to solve. Yet, in a way, the core of many of these methodological approaches is aimed at identifying the right objectives, than to choose the "right" design proposal to a wrongly defined problem (Roozenburg, 1995) (Cross, 2008) (Gero, 2012). Indeed, evidences emerged in literature shows that the capability to frame and reframe problems to pair it with a solution is crucial to obtain high-level performances in design (Cross, 1998).

With reference to the concept of turning tacit knowledge into explicit presented in Section 2.3.3, it is possible to determine that the transformation from the perception of a situation to the definition of a problem articulated through Context, Goal and related Objectives corresponds to the process of Externalization. From this perspective, the words by Cross (2008) support such statement:

> *It [a rational method] externalize what you have to do, so that you do not have to try to keep it all in your head, and so that you do not overlook something. It formalizes the process, by making a record of items that can*

be checked-off as they are collected or achieved until everything is complete. (Cross, 2008)

According to Roozenburg and Eekels (1995) such initial situation should be examined according to a hierarchy of aims and purposes in order to produce a meaningful design specification, as depicted in Figure 19.

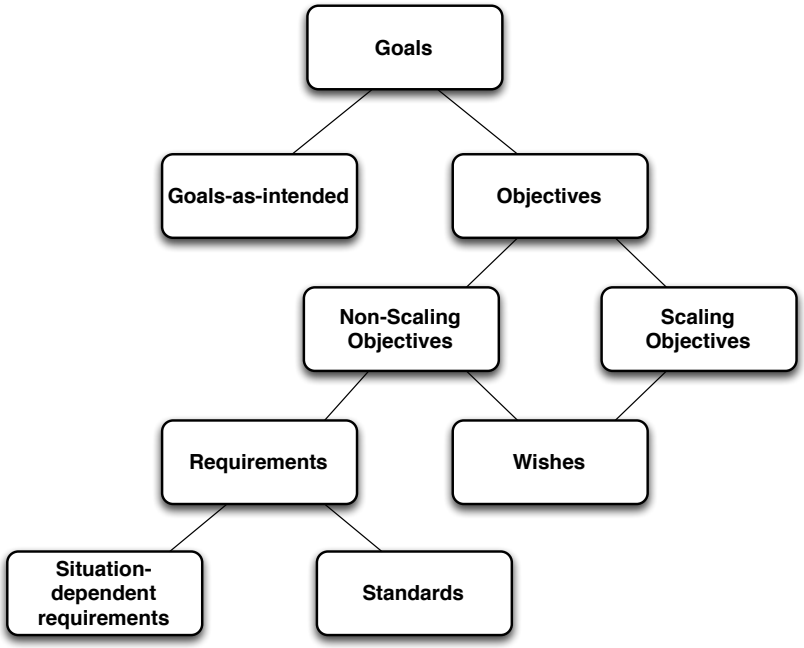


Figure 19: Hierarchy of goals and objectives as proposed by Roonzeburg and Eekels. From (Roozenburg, 1995).

Goals represent the target to be achieved in the form of future desired situations where discontent is not present anymore. *Objectives* are statements aimed at clarifying what has to be done in order to attain the goals. They are divided into *Scaling* and *Non-Scaling Objectives*. The latter category collects all the objectives that a design proposal just meets or not and are, thus, measurable (at least in qualitative terms). On the contrary, the other category is its residual, but it does not mean that it is useless. Indeed, through Scaling Objectives it is possible to rank all the diverse proposal emerged during the design process. This consideration leads to the definition of *Requirements* and *Wishes*. All the *Scaling Objectives* can be categorized as *Wishes*, meaning that also *Wishes* are a means to rank the different design proposals. *Requirements*, on the other hand, collect just the *Non-Scaling Objectives* that have to be met as a necessity, so as to distinguish good solutions from solutions to be discarded (the others enriches the set of wishes). At last, requirements can depend on the specific situation to be addressed, as well as derived from technical standards as established by authorities. To build the design specification, they propose to collect all the stakeholders according to the context in which the product to be developed should work, so as to identify objectives in terms of wishes and requirements. A support for their definition can be obtained through the support of checklists. The objectives undergo a process of simplification in order to get rid of redundancies and form specifications, so that it is possible to design by just thinking about performances. Then, they get organized according to a hierarchy and target values for each requirement included into the specification are set in order to also ease the evaluation of solutions.

On the contrary, *Demands* and *Wishes* are the different denomination that enables the characterization of requirements in compulsory and non-compulsory for the satisfaction of a *Goal* according to the vision of Pahl & Beitz. Also according to their viewpoint, demands from the problematic situations have to be translated into measurable "performance requirements". The size of the design specification can be further enriched through checklists.

As said, both in (Pahl, 2007) and in (Roozenburg, 2005), checklists for supporting the integration of the requirements are suggested. They effectively allow enlarging the design specification by triggering questions to the various stakeholders involved in the PDP. They address different concepts along the product lifecycle, such as performances, maintenance, size and weight, … For a complete description of these two checklists, please refer to Appendix B.

In this respect, a similar classification of aims and purposes has been also developed by Cross (2008). In regard to the method proposed by Pahl and Beitz, the method of Cross defines the complete set of requirements after the identification of the functions to be carried out for the achievement of a goal, which is a task that should be carried out during the Conceptual Design phase (Pahl, 2007). This could be probably due to the fact that Cross considers the development of a design proposal (and thus the design process) not necessarily as a straightforward search that moves from the problem state to the goal state. To his vision it is rather a process of matching the two spaces (problem and solution) in an iterative fashion until a satisfactory pair has been identified. This process is deemed to be highly creative and goes under the denomination of "co-evolution of problem and solution" (Dorst, 2001).

Nevertheless, in the method of Cross the step of *Clarifying Objectives* is carried out after the formalization of the design brief, during the step for the *Identification of Opportunities*.

> *The formal starting point for the design of a new product is the design brief (Cross, 2008).*

Such design brief is a document collecting the set of information coming from customers (real or simulated with the User Scenario Method) and setting what the new product have to be and to do for solving the problem. Being it defined at the beginning of the project, it doesn't take into account potential proposals of solution. On the contrary it considers the *Context* where the problem has emerged as well as the *Goal* to be achieved. It also set which are the conditions to satisfy the design goal by *Constraints* and defines the *Criteria* for evaluating the design proposal that will emerge during the PDP. With reference to the classification of aims and purposes by Roozenburg and Eekels, Criteria and Constraints have a detail level similar to Objectives. Criteria correspond to Scaling Objectives. On the other hand, Constraints (Cross, 2008) partially overlaps the concept of Non-scaling Objectives (Roozenburg, 1995), since they have compulsorily to be met by the design proposal.

Objectives, according to the meaning assigned by Cross, can be further specified through dependences and parental relationships. His Objective Tree Method requires a discussion about the design brief within the design team that, on this basis, have to prepare a detailed list of objectives to be subdivided into a hierarchy, according to their importance. A diagram of the relationship among the objectives shows which strategies are more indicated to address a given problem.

The Function Analysis method, in turn, is aimed at defining the functions of a new design. Their identification should be done at a high level of abstraction, just considering a function as a black box converting inputs into outputs. Functions should be also decomposed into sub-functions and organized according to a hierarchy characterized by parental and time dependencies. At last,

components for carrying out elementary functions should be listed by taking into account than more than a component (structure) is capable of carrying out the same function.

At last, the Performance Specification method is intended to populate the design specification by starting with objectives and functions generated in the previous steps of his design method. Before defining the design specification it is necessary to determine the viewpoint for the whole PDP since the design specification can significantly change according to the level of generalization (more general is the viewpoint, higher the freedom of the designer). Requirements can be then determined in terms of performances as quantitatively as possible, with reference to objectives to be achieved and to functions to be performed.

In this context, it is worth mentioning the OTSM-TRIZ Network of Problems (Khomenko, 2007). As for what concerns the three stages of Cross, such method start addressing the same kind of clarification process in the analysis stages of the PDP. Indeed, the Network of Problems is a graph whose nodes represent both Problems and Partial Solutions (they are depicted differently from each other, see Figure 24 in the following). Their connections provide a hierarchical structure of the problem situation together with various alternatives to solve it. In detail it consists in the decomposition, when possible, of the main problem into as many nodes as the number of sub-problems. The edges of the graph link problems with arrows according to parental and causal relationships. The edges link also Partial Solutions to both the originating problem and, in case, the new caused problem. Once the Network of Problem is complete according to the visions of the diverse stakeholders, it is possible to elicit the design specification from the Problem nodes. Indeed, each sub-problem identifies an expectation that has not been completely satisfied and, therefore, an objective to attain or a requirement to be met. The role of Solutions within the network will be discussed in Section 2.4.3.

The issue of translating customer requirements into technical requirements is addressed by the Quality Function Deployment (QFD) method (Akao, 2004). It is organized with a chart (Figure 20) called House of Quality (HoQ) because of its shape resembling a house with a pitched roof.

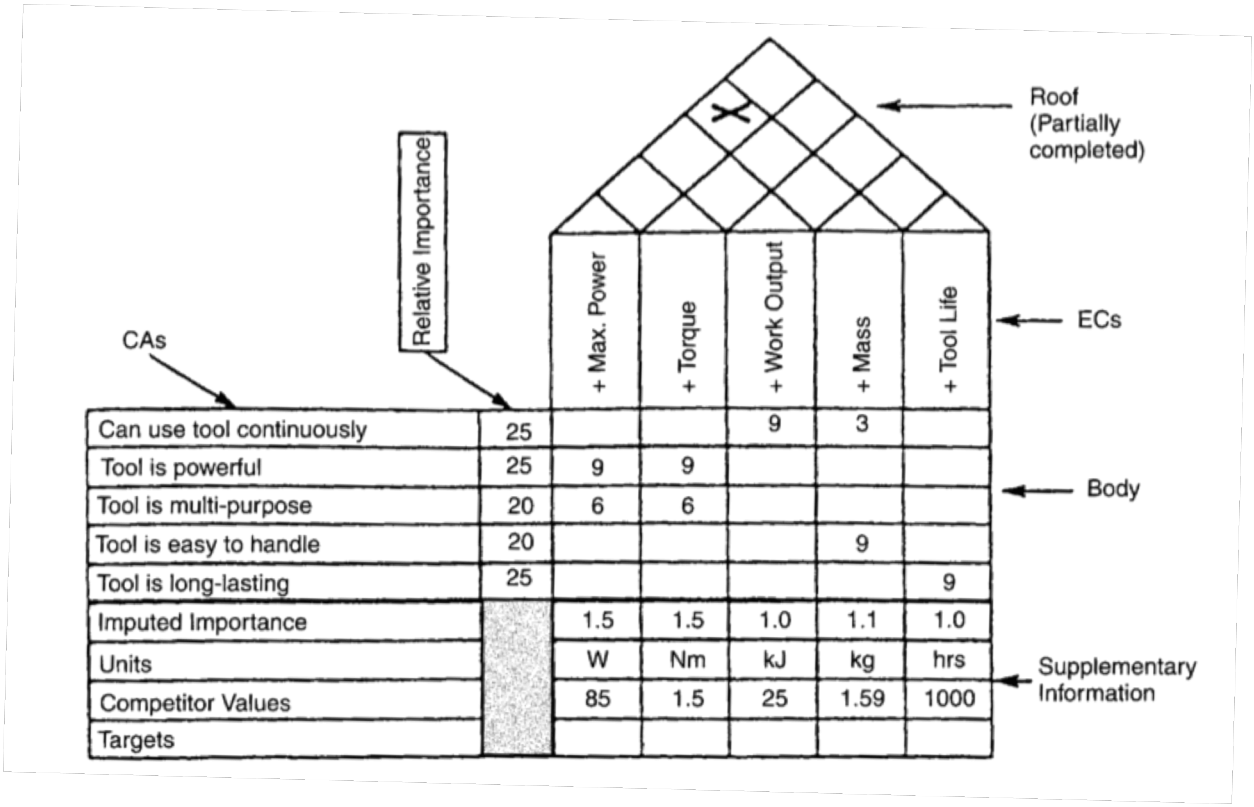


Figure 20: An Example of application of QFD through the House of Quality. From (Cross, 2008).

With reference to Figure 20, this method aims at mapping *Customer Attributes - CA* (requirements) and *Engineering Characteristics - EC* (technical requirements) for the product. The former are organized in rows and the latter in columns. Moreover, QFD allows to rank customer requirements according to the perceived level of importance, to requirements and wishes as well as to more sophisticated classifications (Kano, 1984) (Matzler, 1998). Cells in the Body of the House of quality link Customer Attributes with Engineering Characteristics. At last, the Roof of HoQ allows interactions among Engineering Characteristics to be determined. At the bottom of the Body different characteristics can be recorded, such as a ranking of importance among Engineering Characteristics, their Unit of measurements as well as the value achieved by the leading competitors.

This method, however, does not address the definition of technical requirements. It rather maps the relationships between customer and technical requirements as a means to drive the PDP. Both types of requirements must be defined in advance and technical requirements, according to the prescriptions, should be evaluated in reference to the characteristics of the products developed and commercialized by competitors.

After this examination it is clearer that the design specification, namely the list of requirements to be met by the design proposal has a paramount role in driving the PDP with effectiveness and efficiency so as to do the right thing before doing the things right. In Section 2.2.2 it has been remarked that requirements are crucial for the definition of the boundaries of the design space, as well as problem and goal state. Moreover, this set of requirements is also useful to drive further developments of the project as well as negotiation with suppliers. The implementation of requirements lists within knowledge management systems represent a valuable chance for reusing previous knowledge to search for new solutions (Pahl, 2007).

According to this last consideration, it is worth mentioning by items the desired characteristics of a design specification, in order to highlight both potential lacks in current practices and opportunities for the development of new methods and tools for the identification and the characterization of requirements. Such characteristics, according to the vision by Roozenburg and Eekels, follow:

- **Validity -** as the capability of the contained requirements to discriminate the extent of the achievement of a certain objective from which they have been defined;
- **Completeness -** as the capability to cover all the objectives in the different domains where stakeholders are involved;
- **Operationality -** as the capability to assign a measurable variables to the objective to be achieved, so that avoid subjective evaluation;
- **Non-redundancy -** as the capability to avoid the presence of double items having the same meaning;
- **Conciseness -** as the capability to contain just the meaningful requirements without neglecting important facets to be taken into account (not too much, not too little);
- **Practicability -** as the capability of requirements to be tested according to the available information and funds to carry out simulations.

In this regard, the existing checklists does not address these characteristics, since both the one proposed by Pahl and Beitz and the Pugh's one presented in Roozenburg and Eekels (1995) (Appendix B) simply do not allow, by themselves, to determine a design specification having the above mentioned characteristics. Designers or the facilitator in charge of extracting knowledge from experts have to deal with these issues by means of their own experience and skills. Instruments for supporting facilitators in the definition of a design specification with the abovementioned characteristics will support the PDP so that it can be carried out with better effectiveness and efficiency.

2.4.3 Role of requirements during the Synthesis stages

Before taking into account the specific role of requirements into the stages of the PDP where new ideas and concepts are generated, it is worth considering the specific tasks that, according to the vision of Pahl and Beitz, are crucial in both Conceptual and Embodiment design phase, as reported in Figure 21 and 22.

The phase of Detail Design is purposefully neglected from this analysis since the contribution of requirements is poorly exploited for determining significant system characteristics. Such phase is more related to adjustment of design parameters for the embodied solution in order to comply with target values.

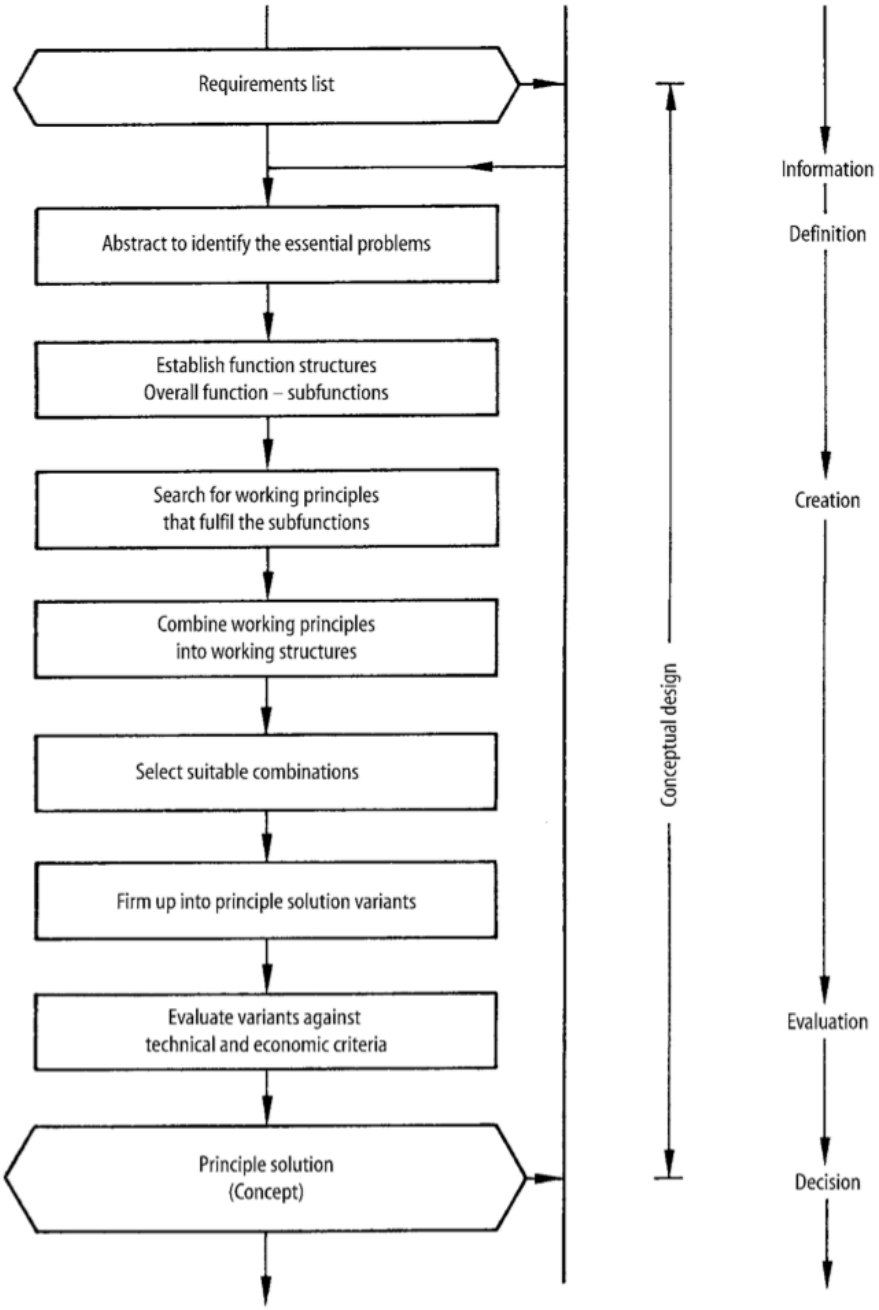


Figure 21: The different activities characterizing the Conceptual Design phase according to the viewpoint of Pahl and Beitz, (Pahl, 2007).

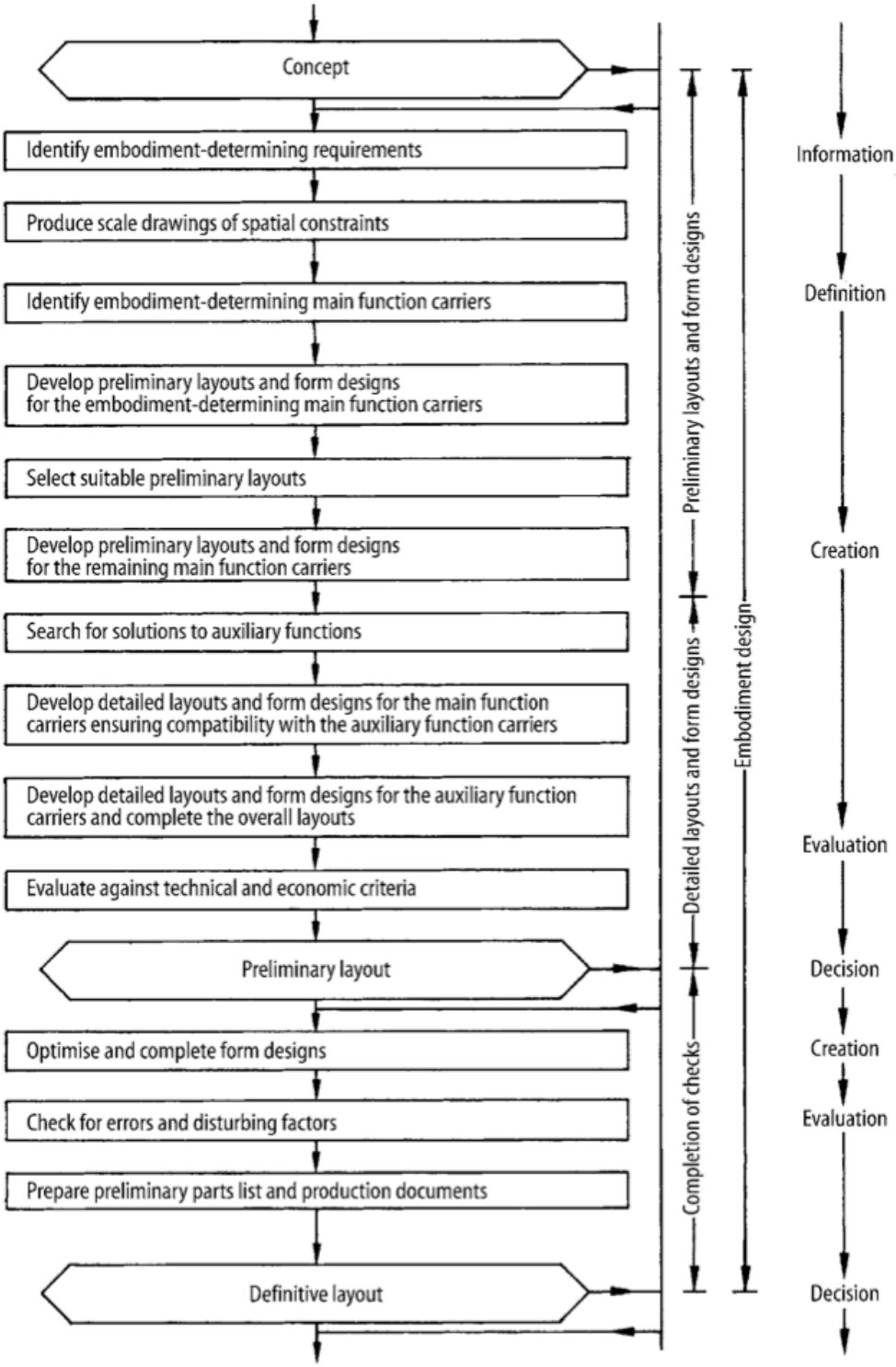


Figure 22: The Embodiment Design phase according to the viewpoint of Pahl and Beitz, together with the related activities (Pahl, 2007).

To this purpose, the definition of possible directions to be explored during the ideation phases is something that strongly depends on the definition of a problem, since it is the list of requirements that drives the PDP as depicted in Figure 21. Turning requirements into a design proposal, indeed, has to deal with the generative process of ideation for which specific creative patterns have been already identified in terms of Combination, Exploration and Transformation (Boden, 2009). Indeed, it is necessary to understand what are the restrictions under which a solution should be searched and found. These restrictions, commonly referred also as constraints, are also part of the

problem definition since they narrow the ranges of available opportunities for solving the problem itself. An over-constrained problem will probably introduce too many restrictions that limit individual's creativity and, on the contrary, a poorly constrained situations will just address a few objectives and related solutions will be poorly applicable to the situation at hand. Such considerations support the necessity to start the Conceptual Design stage by abstracting the situation at hand so that it is possible to release to common beliefs due to the solution-oriented vision of designers, thus enlarging the range of opportunities for development with an appropriate definition of constraints for the design space. Indeed, as briefly mentioned in the previous section, it is frequent, as recognized by Maher in her seminal work of 1996 (Maher, 1996), that during the design process there may occur several iterations between the analysis of the problem (i.e. the definition of the problem space) and the synthesis of partial solutions (i.e. the subset of variables capable to satisfy several objectives). Carrying out the ideation phases without taking into account the structural characteristics of solutions, thus focusing on functions and working principles, is the key for an effective and efficient PDP (Ulrich, 2008).

The subsequent phases, therefore, pertains to the definition of

- Functions (what the system is for);
- Behaviours (what the system should do); and
- Structures (what composes the system)

that can be possibly implemented into a conceptual design proposal capable to satisfy the conditions set as a reference target for attaining the goal state (Gero, 1990) and (Gero, 2004).

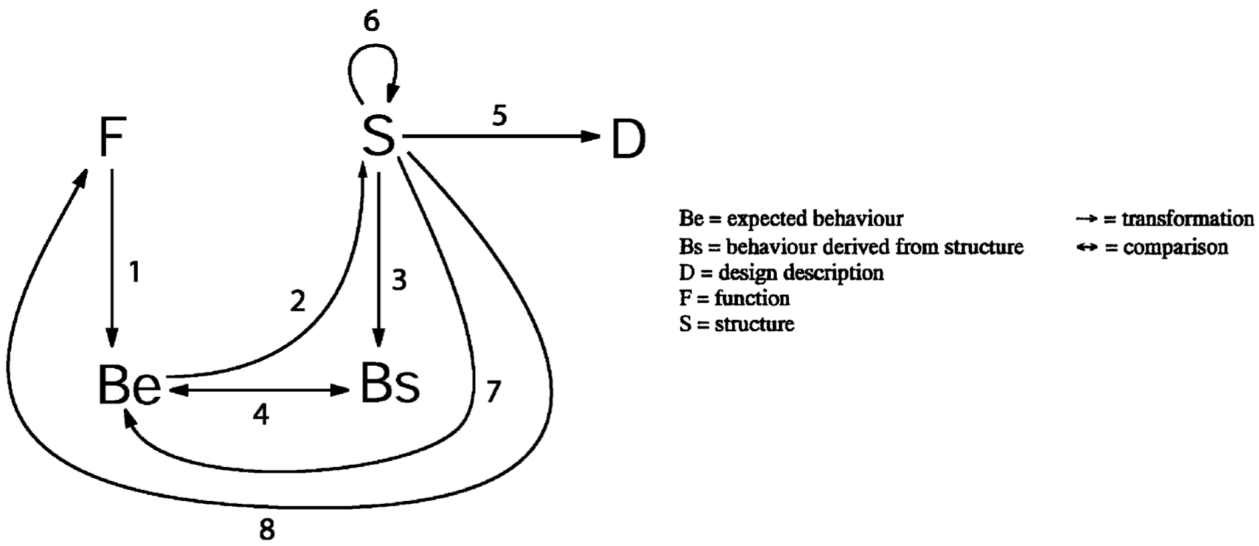


Figure 23: The Function-Behaviour-Structure Framework (not situated) as proposed by Gero (1990).

More into the details, the definition of Functions as black boxes transforming inputs into outputs (as suggested by Cross, but also by Pahl and Beitz as well as Roozenburg and Eekels) is directly addressing the need to think about what the system is for, rather than thinking about how to achieve a certain goal. In such a way it is possible to concentrate the attention not just on a single way to perform a function, but on the wide range of working principles that can be appropriately combined so as to define one or more appropriate Behaviours for the design proposal. Moreover, Figure 21 and Figure 23, also shows that it is necessary to reflect on the potential Structures (working structure) that enable to match the Expected Behaviours.

Such kind of search for solutions from the one hand contributes to the refinement of the requirement list according to the different decisions that are made during each stage of the PDP

and, on the other hand, drive the search for potential technologies to be implemented into the design proposal. In details, with reference to the creative processes described by Boden, two different strategies can be recognized as for searching new technologies, in the author's opinion. Both in case of the redesign of an existing but obsolete product and in the design of a product from scratch it is necessary to evaluate the suitability and the potential of existing technologies.

This kind of search can be carried out within the boundaries of the technological domain set up through the definition of the problem space. In this case the list of requirements represent a set of criteria for the identification of appropriate technology that provides the opportunity to substitute the one(s) currently adopted by the competitors or, more in general in the domain. Such process of search for opportunities of "Technology Substitution" is directly connected with the cognitive process of Exploration through which the design space is searched for the definition of solution concepts capable to address some of the requirements.

On the other hand, such search can be also carried out outside the boundaries defined through the problem and the goal state. Such search concerns the identification of technologies allowing the achievement of the same or similar objective in radically different domains of application so that it is possible to transfer such technology within the conventional domain of application of the product to be designed. Even in this case the list of requirements represents a set of criteria to discriminate technologies according to the objectives that they can satisfy, without considering specific structures through which they are implemented. The process of search for opportunities of "Technology Transfer", in turn, is directly related to the transformation of the design space, since some requirements that are characteristics of the domain of application of current solutions can be neglected so that the constraints of the design space can be redefined into a new shape that also set a new goal state.

Moreover, the substitution and the transfer of technologies often go with the practical impossibility of a direct implementation within the desired technical domain. In this case barriers for the implementation of radical technology shift emerges and can be recognized as the main limitations for product development. According to this perspective, the search for solution is even more radical because it addresses the need of understanding what limits the evolution of a given technology, thus slashing the chances of successful development. The list of requirements, in these cases, can be exploited as a means to determine potential design conflicts since they are the reasons that determines the practical impossibility of implementing new technologies within a domain or, worse, to develop completely new ones. The determination of these barriers addresses the need of forecasting the development of new technologies as expressed by Kucharavy (2007).

To this regard, from the one hand it is crucial to identify the right objectives to satisfy and, on the other hand, it is decisive to understand which are the design variables to work with in order to obtain the desired results. TRIZ (Altshuller, 1984), Russian acronym for "Theory of Inventive Problem Solving", and OTSM-TRIZ (Cavallucci, 2007) among the others, address this kind of issue. One of their key concepts is that a problem can be observed both from the point of view of conflicting objectives and of conflicting design parameters. On the contrary, without the presence of a conflict, the problem at hand does not represent a real problem and immediate actions can be carried out to remove discontent from a situation. The aforementioned OTSM-TRIZ Network of Problem and the OTSM-TRIZ Network of Contradiction (Khomenko, 2007) are instruments for mapping problems and solutions in complex situations by means of appropriate hierarchy. The latter is a subsequent interpretation of the Network of Problems and integrates information about the contradictory requirements. The nodes of this bipartite network are constituted by parameters represented as Control Parameters and Evaluation Parameters. The latter correspond to the requirements of the technical system under development, the former correspond to design variables through which attaining the desired objectives. Methods and tools from the TRIZ body of

knowledge also support the solution of problems formalized as contradictions between two conflicting requirements as well as non-mutually compatible values for the same design variable, with the purpose of avoiding trade-offs as pointed out by Jones (1984) among his suggestions for an effective and efficient PDP.

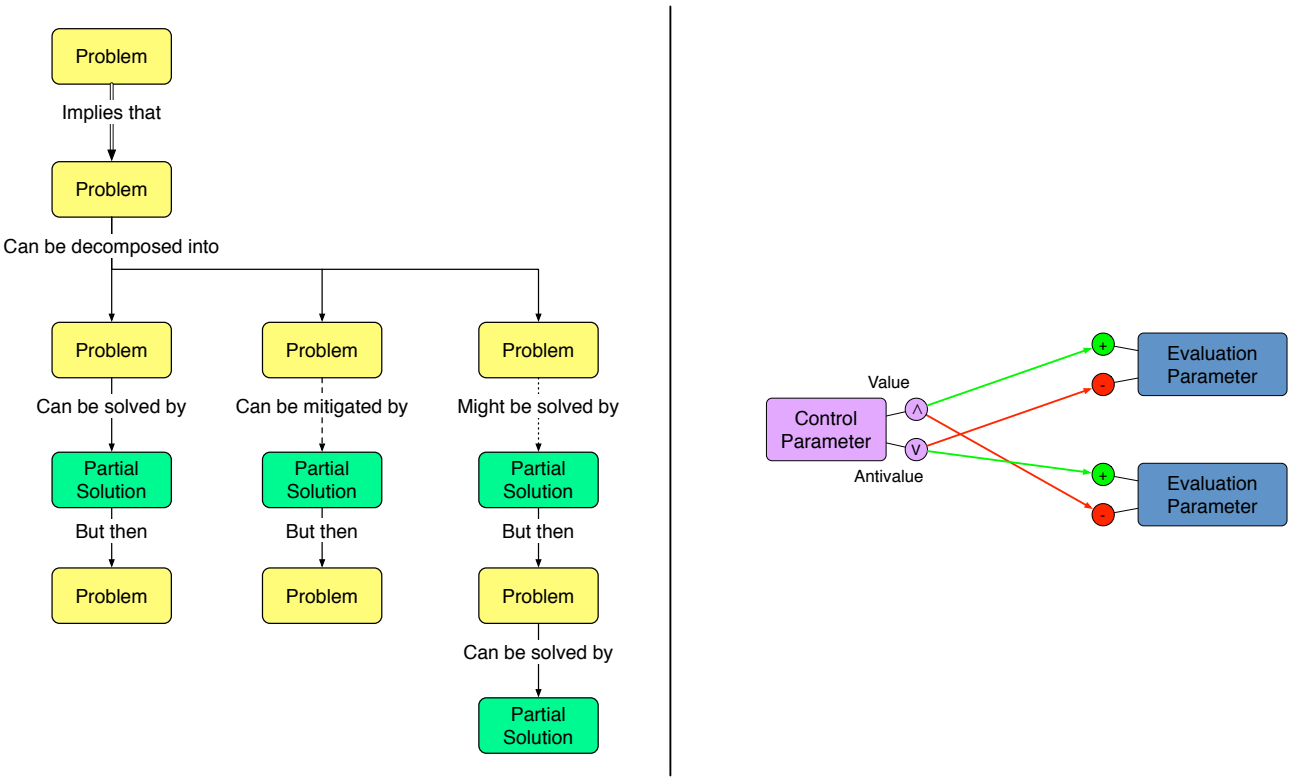


Figure 24: Left - characteristic nodes and links of a Network of Problems. Right - characteristic nodes and links of a Network of Contradictions.

Within this context it is worth mentioning that a less structured chance for highlighting conflicts between technical requirements and thus determining priorities within the PDP is the rooftop of the House of Quality from Quality Function Deployment (Figure 20). Qualitative relationships are represented in cells intersecting both technical requirements (Melgoza, 2012).

One of the last steps concerning the creative process to be carried out during the Conceptual design phase concerns the chance of combining different solution principles for the different requirements into a few concepts of solutions to be further developed. To make this kind of combination, some methods have been exploited in development contexts and the most acknowledged is probably represented by Zwicky's Morphological Chart (Zwicky, 1957) of which an example is presented in Figure 25.

It allows creating a map of all the alternative concepts (organized in columns) addressing the different sub-functions to be carried out by technical system under development in order to achieve the objectives (organized in rows). Cells, therefore, contain very specific solutions to very precise requirements that can be thus embedded and combined into a design proposal that have to be further developed during the Embodiment Design stage (Figure 22).

Since the ideation activities to be carried out during the Embodiment Design phase follow an analogous logic to the ones of the Conceptual Design, before concluding the analysis, it is just worth focusing on the role of requirements that has not been considered yet in stages of Synthesis.

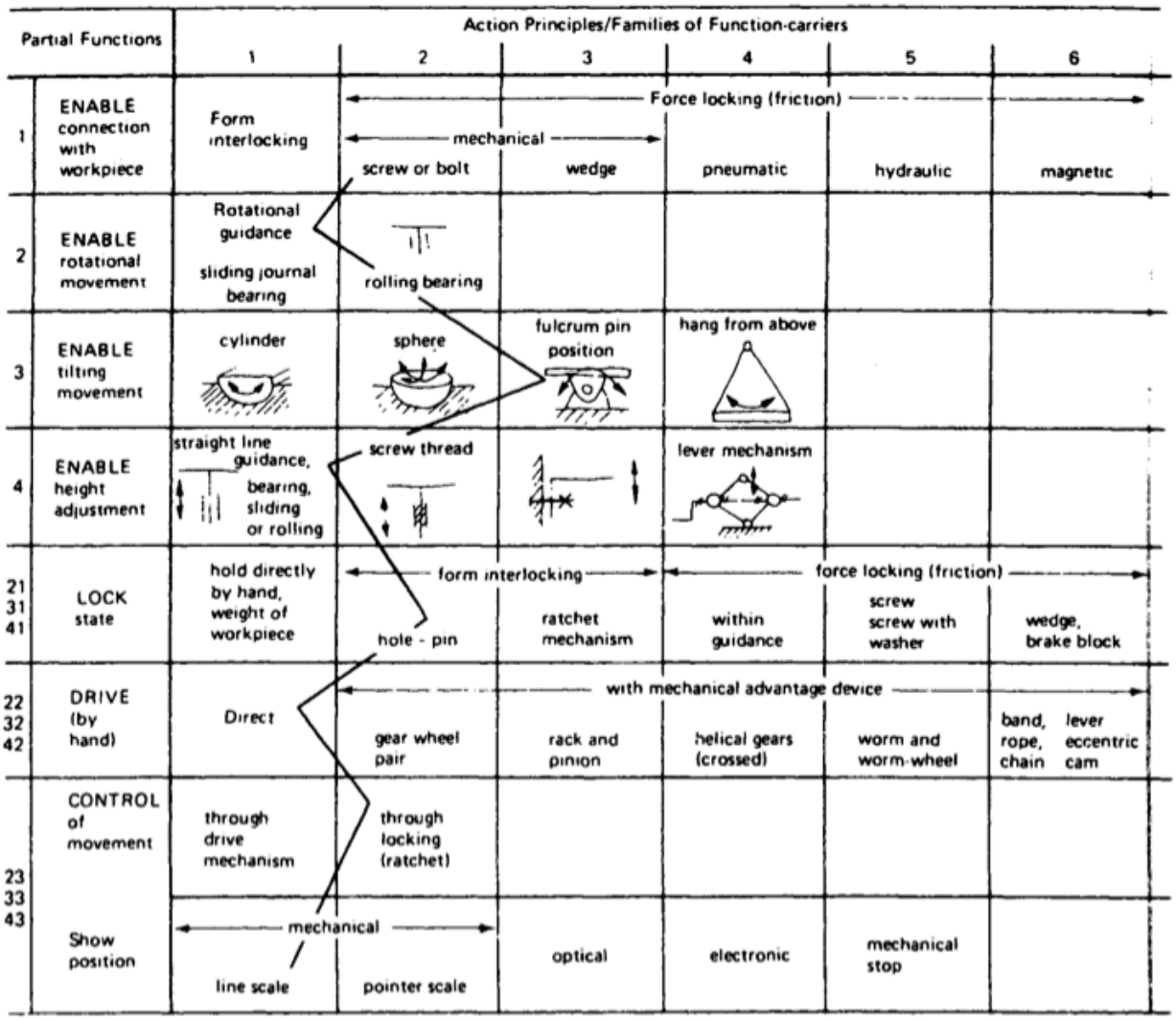


Figure 25: An example of Morphological Chart. The zigzag line moves through cells as for selecting the different design proposals addressing specific objectives. From (Cross, 2008).

The definition of a concept almost completely estabilish the technological boundaries of the design proposal. However, several requirements obtain a paramount importance during the Embodiment Design Phase. Pahl and Beitz, to this purpose, mention three different kinds of embodiment-specific requirements: Size-determining requirements, Arrangement-determining requirements and Material-determining requirements. These requirements, if not already included into the requirements list, should be collected by means of an appropriate checklist (Appendix B) that follows the logic of the ones already mentioned for the Analysis phase. Moreover, Spatial Constraints represent further criteria for the development of complete solutions that just need to be detailed.

Particular attention, indeed, to the available instruments for driving the development process according to specific purpose objective and that goes under the name of Design for X. X assume various denominations with reference to the specific objectives to be taken into account according to the context in which the new product have to work. Among the Various objectives of Design for X there are: Minimization of Wear, Ergonomics, Aesthetics, Production, Assembly, Maintenance, Recycling, Minimum Risk, Standards, Minimum Cost, Quality, Environment, and the list grows with time as new objectives become shared among different domains of technique.

These approaches are not aimed at determining requirements, rather at driving the PDP according to specific guidelines that allow an almost straightforward satisfaction of the posed objectives.

2.4.4 Role of requirements during the Evaluation stages

The evaluation of design proposals occurs according to analogous criteria in the three different phases (Conceptual, Embodiment and Detail Design) of the PDP. Several criteria have been already mentioned in Section 2.4.2, indeed the distinction among Requirements and Wishes already represent a quantitative method to determine if a design proposal can be accepted or rejected and discarded and, among the ones that are suitable to meet requirements, which one represent the best alternative to be manufactured and commercialized.

However requirements play also a role in the evaluation of design proposals in terms of creativity, which is a relevant issue distinguishing innovations as described in Section 2.2.2. Besides, different constructs characterizing creativity have been proposed both for the purpose of evaluating the effectiveness of good solutions and for a better understanding of methods for creative design (for a review about constructs detailing creativity please refer to the work of Dean, Hinders and Rogers (2006)).

Recently the idea that something creative must own the characteristics of *novelty* and *usefulness (Amiable, 1996)* is gaining a wider consensus even if, according to slightly different perspectives, the same constructs could also be interpreted respectively as *originality* and *appropriateness* or *value*. Regardless the denominations, these construct just address some characteristics of a creative design proposal, rather than general characteristics of creativity. Moreover, several issues concerning the validity of the usefulness construct to characterize non-engineering designs, such as the ones concerning artistic or aesthetically new products, are still open, at least for what concerns the methods for its measurement.

Maher (Maher, 2010) introduced also *surprise* as a distinct features of a creative artefact: it is a feature that is based on expectations and so is a function of the attributes of the potentially newly developed artefact in comparison to other, already existing, artefacts (like novelty), but also depends on a projection or expected value that lies outside the description of the artefacts (like usefulness). According to these three constructs she has also started developing a metrics allowing to make relative evaluations of product creativity in a conceptual (design) space through AI systems. Brown, to achieve a similar objective, (Brown, 2012) has studied potential correlates between surprise and creativity to introduce these findings into an AI system to self-evaluate its own performances.

Chakrabarti and Sarkar (2011), on the other hand, propose a method that allows carrying out a ranking of products according to their creativity, thus introducing an, even ordinal, evaluation. Such a method is based on the constructs of novelty and usefulness. The former is evaluated by comparing the generated solution concept (or developed product) to the existing alternatives already developed. The latter, indeed, surprisingly neglect the capability of the design proposal to meet its requirements and take into account indicators such as the *popularity* and the criticality *of the need* the new product aims at satisfying; parameters that can be only evaluated after that a solution concept has entered the market. Therefore, despite a certain consensus towards the main characteristics to be evaluated, a creativity measurement method capable of considering the various dimensions in products, processes and individuals and producing repeatable and reliable outcomes is still lacking.

On the contrary, according to the author's opinion, novelty, usefulness and surprise can have a very important role in selecting the most promising design proposals. From this perspective usefulness or appropriateness are already evaluated through the capability of the newly

developed technical system to meet requirements and wishes. Novelty and surprise, in turn, could be related to the emergence of new requirements that gets satisfied but customers had not taken that into account once the demand for solving a problematic situation emerged. Nevertheless, this supposition would require adequate testing to be considered true and it goes beyond the purposes of this work.

Within the context of the classification of objectives among requirements and wishes, the classification proposed by Kano et al. (1984) shed a new light on the differences among customer requirements. This classification distinguishes between three main categories of requirements: Must-be, One-Dimensional and Attractive. Must-be requirements are those who have to be necessarily met through system performances to determine customer satisfaction and whose absence (or a poor fulfilment of objectives) triggers the refusal of the product by purchasers. Attractive requirement, on the contrary, are those impacting just positively on the appreciation of the customers. Their presence is not felt as necessary but triggers good feelings and can create, as for the denomination, attraction for purchases beyond the performances of the product. At last, One-Dimensional requirements can be characterized as an intermediate category between the aforementioned two. The capability of the product to meet such kind of customer requirement linearly impacts on customer satisfaction: the higher the level of performances, the higher is the satisfaction of customers and vice versa.

Moreover the identification of solution concepts can be carried also through methods that aim at ranking solution concepts (ordinal or cardinal rank), according to appropriate criteria (based on requirements) so that it is possible to determine which one is the most suitable for implementation. A complete review of such methods goes beyond the purposes of this work, but several ones having this purpose can be found in (Roozenburg, 1995), (Pahl, 2007) and (Cross, 2008).

2.5 IT Tools and Computer-Aided Systems for the management of requirements for the Product Development Process

In the previous Sections it has been underlined that computer could give a strong support to the processes of knowledge acquisition and to the innovation actions carried out by industries. The potential benefits deriving from the implementation of automatic means for supporting the transfer of knowledge as well as the collection of relevant information will be discussed in the following. Most of the focus will be directed on the support of such systems for the Product Development Processes leading industries towards commercial success through innovation.

Some scholars have investigated the possibility of creating an environment where creativity is not only stimulated, but also fostered. According to their visions, among the different players having a role in creativity, ICT tools can carry out and facilitate several functions. Lubart (Lubart, 2005) states that computers can be partners in creative processes, such as the one occurring during design:

- by facilitating the management of the working process, encouraging the perseverance of designer in the research of innovative solutions;
- by easing the communication between design team members, since circulation and integration of ideas play a relevant role in the creative process;
- by aiding the designer with a coaching activity, acting as an expert system that guides the user throughout cognitive processes;

- by cooperating in the creative process, thanks to the Artificial Intelligence systems that contribute to ideas generation.

However, assessments on the efficacy of such computer systems in supporting the various development processes are still lacking of sound evidences. Nevertheless, several ICT instruments have been so far developed to support creative design activities. Some of these ICT products have been proposed as commercial software claiming to support the designers' creative processes for generating innovative ideas. Even the performances of these systems have been just evaluated from a qualitative point of view, but the main drawbacks of some of them are well recognized by several authors (Cascini, 2004 and Leon Rovira, 2009) and opportunities for further development have been clearly highlighted by Cavallucci (2011).

Nowadays, Computer-Aided means supporting Product Development allow managing the complexity of current technical systems by representing product data far beyond the geometrical features of the product itself. Plenty of commercial systems fulfil industrial demands allowing to model system parts and to plan their manufacturing processes. Furthermore, the growing potential of multi-physics simulations allows also analysing the product behaviour upon different conditions and different environments (Danjou, 2007). Post processing software allow to interpret simulations with the objective of identifying which part in system geometry needs to be redesigned according to the intended purposes. In other words, Computer-Aided systems allow mapping the relationships between design variables and the expected behaviour of the designed system, through the analysis of a virtual prototype. However, the definition of objectives to measure, so that it is possible to infer customer satisfaction, is still poorly supported and in most cases depend just on the interpretation of data by the designer.

On the contrary, the early phases of the design process, namely product planning and conceptual design, are still far from being effectively assisted by computer applications (Brunetti, 2000). However, several contributions (Wang, 2002) (Scaravetti, 2005) show that the early phases of the product development process may radically affect up to 70% of the whole lifecycle costs because of their significant impact on the manufacturing processes and product quality, respectively affecting industrial productivity and customer satisfaction. The same authors strengthen, in turn, the need of extending the computer-aided system domain towards the support of product planning and conceptual design stages, with the purpose of determining robust design choices, leading to a more appropriate description of product shapes and materials. Wang et al. (2002) remark that the causes of poor support for those design phases concern the fuzzy definition of design requirements and constraints characterizing a so-called "soft" concept model, showing, by its own nature, lacks in terms of electronic visualization and communication. Therefore, the management of the complex, interdisciplinary, informal and still uncertain data on which the whole product development is based, represents the most critical issue for a computer tool.

In terms of system preliminary modelling, the architecture of a Computer-Aided system represents a key factor in order to both integrate it with the downstream Product Lifecycle Management applications and to increase the efficiency of the whole PDP, accomplishing the goal of reducing lead time at the maximum extent. According to this perspective, great efforts have been made in this domain to improve the functionality of Product Data Management systems. They assist Product Lifecycle Management stakeholders in their own field of expertise, by collecting and the managing the information and data flow with the objective of making them available also to other members of the design team, exactly when needed. In this regard, these Computer-Aided instruments also aim at empowering concurrent engineering practice. They create a collaborative environment where members of the design team can share more easily knowledge elements (Grebici, 2007). Nevertheless, they partially achieve these goals and,

moreover, they show some other deficiencies both in terms of performances and efficiency (Liu, 2001). From the one hand, due to their broad scope, they constantly need to be updated in order to face the challenge of a quickly changing world of knowledge and, on the other hand, they lack in usability: teams or individuals need a significant amount of time before mastering the software applications, while collaboration is improved just within a local, rather than global, perspective. Despite web-based systems partially compensate these lacks and widely diffused in the last decade, their use in supporting the early phases of product design is still limited.

Furthermore, enterprises can rely on tailored PDM systems, depending on the technical field of their products (e.g. Mechanics, Electronics, as well as Computer Science) (Eigner, 2010), as it results by several efforts produced for determining what kind of modelling technique could provide the best benefits in each specific domain. Nevertheless, regardless the specific field of application, both those modelling domains converge towards the same objective: the definition of product/system requirements as the milestone for targeting the Product Development Process. According to this perspective, several similarities can be recognized between modelling techniques for software and physical products: systems, actors and use cases pertaining to the Unified Modelling Language well diffused for software, can be declined according to the exigencies of modelling artefacts, specifying, for example, what is their target of consumer, what purpose they have to fulfil and what characteristics should it have for satisfying both the objectives. Indeed, in (Eynard, 2006) a recent and extensive contribution of PDM modelling based on UML is presented.

As said, current CAD systems focus on physical and geometrical modelling, resulting in an insufficient support for describing the abstract features that will drive the development of design choices. Indeed, such decisions are currently in charge of the designer: first, he/she must identify the main requirements to be fulfilled; then, what technical functions must be carried out and what principles should be used for such purposes; just finally, what are the geometrical characteristics of the embodiment capable to deliver the expected functionalities. In this context, the computer-aided analysis of requirements, their management and their elicitation represent a thriving field of research. The Computer-Aided Requirements Management (also presented as CARM) field partially addresses this issue. As a support for concurrent engineering, Fiksel and Hayes-Roth provided one of the first inputs within this domain (Fiksel, 1993). They consider the chance of using dedicated ontologies for managing product requirements, even if their focus seems to be mainly on the definition of requirements for stakeholders within the Product Development Process. A further and more recent contribution in this field has been proposed by Brace et al. (2012).

In (Tseng, 1998) it is presented a method aiming at product definition through the analysis of customer requirements already satisfied by existing artefacts. Moreover, the potential evolution of the product to be developed is taken into account by technological trends, product migration as well as competition. However, this approach cannot be considered completely systematic and, moreover, it narrows down the opportunity due to new demands that customers may express or recognize once a product has been launched in the market.

From a different viewpoint, recent demands for environmentally sustainable products become a pressing exigency for industries (Ameri, 2005), thus new requirements appear as relevant within the design process. Most of the available techniques are aimed at evaluating the effect of geometrical modelling in terms of the environmental footprint of technical systems (e.g. according to their CO2 emission), in the framework of Life-Cycle Assessment (e.g.: Song, 2010).

For what concerns the conceptual and embodiment design stages, diverse contribution propose different product modelling techniques for easing the decision-making process in design, also trying to ingrate them into a broader context of PLM, even if such evaluation and decision process is still carried out by the designer. Plenty of approaches are based on functional

modelling: an exemplary application in this field is available in (Tay, 2002), where the modelling technique is aimed at linking together the functional (abstract) and geometrical (concrete) characteristics of a product as a means for managing product complexity at different level of description, thus focusing on design intent. Conversely, in (Chechurin, 2011) it is shown an opposite approach: functional modelling is integrated within a commercial CAD system with the objective of easing component trimming and the identification of existing conflict. This TRIZ-based approach represents an interesting example of integration of tools within the Product Lifecycle Management, but seems to be mostly tailored for already embodied systems and provides just small support for supporting the analysis and the development of new concepts.

Recent advancements in literature (Kim, 2011) present a software prototype whose architecture is based on System Modelling Language, a subset of the UML. This kind of approach provides a viable direction of development towards the integration of Computer-Aided systems supporting the whole design process, since it allows to associate the impact of design variables on requirements, but the definition of product requirements is completely in charge of the designer and not supported at all.

Moreover, it is also worth mentioning that within the methods supporting conceptual design with an intensive human involvement, which are currently deemed to be more reliable (Rohde, 2008), a dialogue-based system represents a chance for embodying the innovation application. The human–computer dialogue field is claimed to be a rather developed technology (Popescu, 2007) and questionnaires administered in a digital form are widespread and increasing. The choice of employing a computer based dynamic questionnaire lies upon their speed in being carried out (Laghos, 2007) and suitability within information retrieval systems (Quarteroni, 2008). As well, the questionnaire administration conditions (paper based, rather than computer and web-based) do not consistently influence data quality (Hardré, 2006).

The literature clarifies that natural language processing is widespread and employed in different engineering domains, as reviewed in (Chiu, 2007). The research opportunities emerging within design field by linking natural language to engineering and technical concepts (Zeng, 2008) resulted in an increased interest on questioning techniques.

Eris (Eris, 2003) has thus introduced new question categories within well-established taxonomies, by observing the nature of commonly asked concepts within the design process. The observations he had carried out gave rise to generative design questions, i.e. explorative queries representing the designer's diverging way of thinking, that investigate possible outcomes and embodiments of a system, as well as the ways to achieve the desired outputs. The attempts of applying question–answer techniques within design process are quite diffused.

To this purpose, Wang and Zeng present a prototype capable to propose questions to elicit product requirements from customers' answers (Wang, 2009). It also organizes them in a graphical fashion for helping designers to elicit the customer's real intent and to collect complete product requirements. However, this system is just at a prototypal stage of development and, by authors' admission, needs to be further tested and improved so that it is possible to proficiently use it in different contexts. Moreover, all these systems have never been integrated in the Computer-Aided perspective of Product Lifecycle management. Question–answer tool are also employed in the final design stages, to carry out the verification of the product requirements (Shneidermann, 2006) but less efforts have been paid towards the employment of such tools within conceptual design. However, it has been proved that dialogue-based interface allow to remove the jargon of specific methodologies by the employment of natural language. The literature clarifies that natural language processing is widespread and employed in different engineering domains.

Andersson (2004) employs a question–answer tool to be employed in the final design stages, such as the verification of the product requirements. Fewer efforts have been paid towards the employment of such tools within conceptual design. Although Sosnin and Sosnina (2005) assess that question–answer techniques have observed growing importance in conceptual design and that these dialogue-based systems show considerable development margins, their employment is narrowly limited to knowledge retrieval means.

A particular branch of question–answering sequences in the field of conceptual design has been developed to support Conversational Case-Based Reasoning (CCBR), an extension of the Case-Based Reasoning paradigm (Aha, 2001). CCBR, by submitting the user a set of questions to assess the given situation in order to search relevant information, is especially suitable for handling unanticipated situations (Rinderle, 2005). The most relevant advantages of CCBR are related to its capability to incrementally elicit the problem formulation through the interactive dialogue with the user (Lòpez de Màntaras, 2006), as well as their flexibility of use and the ease of implementation (Aha, 2001). Unfortunately their employment domains rarely overlap with engineering design.

From a more commercial perspective some ICT tools, based on radically different design approaches, are presented. Such an analysis mainly focuses on their limits by considering two opposite approaches for supporting the Product Development Process. The first one concerns brainstorming as a means to describe the limitations of intuitive and unstructured methods for problem solving in design. The second one, on the contrary, considers the limitation emerged in the context of the implementation of structured and systematic methods for creative design within computers.

Brainstorming-based software, such as CMapTools, Paramind, Idea Fisher Pro, Idea Generator Plus… allow the user to manage, rather than driving, the design process by linking the generated ideas in a network, where it is possible to introduce hierarchical relationships (CMapTools). They introduce automatically generated stimuli by proposing a set of alternatives based on the substitution of words in user-generated sentences and propose some heuristics to generate design alternatives by asking general-purpose questions, as a means to simulating ideation, rather than extracting knowledge (Paramind and Idea Fisher Pro). Idea Generator Plus, differently from the others, allows also the evaluation of generated ideas versus predetermined criteria (namely system or customer requirements) but, like all the other brainstorming software, its trial-and-error or solution-driven approach, based on thought-provoking techniques, may lead to the generation of a great number of concepts requiring time-consuming analyses and significant human efforts to be checked and implemented. These systems are suitably usable both by individuals and teams and potentially more appropriate for creative industries (advertising, aesthetic design, …) where less design restriction enlarge the applicability of the ideas.

TRIZ-based software such as Creax Creation Suite, Ideation Workbench, Invention Machine Goldfire, … actually integrate instruments and models of the TRIZ body of knowledge and organize them in a quite rigid structure, thus highlighting objective to be achieved on which the designer has to ground his analysis in order to solve the problem. This leads to a reduced capability of the individual (or of the team involved in the design task) to use such a kind of software, if not previously trained with the elements of the theory and a few experience on its practical use. Despite such instruments can be seen as general-purpose software, they do not allow capturing all the relevant requirements in design.

3. Methodological proposal

This section presents the original contribution of this work. In details, it deals with two mutually correlated activities that have been carried out in order to answer the industrial exigencies to support the innovation processes with improved effectiveness and efficiency. The section is structured into three parts.

The first one aims at clarifying which is the overall goal of the research, also by recalling the current limitations emerged from the analysis of the state of the art and the specific objectives to be met.

The second ones presents and original set of criteria for the elicitation of tacit knowledge from experts according to a specific structure that is capable to map the requirements of a technical system for both the innovation of products and processes.

The third part, in turn, describes the development of an algorithm for supporting the identification of problems at the beginning of development cycles. Such an activity integrates the one proposed in the second part of this chapter by integrating the defined concepts into a dialogue based algorithm for questioning experts and eliciting their knowledge, resulting in the identification of conflicting requirements to be addressed during the problem solving process with higher priority.

3.1 Overall goal of the activity

The importance of both the market and the technology in respectively pulling and pushing the emergence of innovations has been widely discussed along the Section 2. It has also been clarified that, regardless of the market-pull or the technology-push approach towards innovation, such processes concern designing new solutions for giving concrete answers to new or already existing demands. In this context, it is more and more critical to identify the right objectives for innovations, since the competing conditions under which various industries develop their new solutions deal with investments and incomes. In order to reduce the former and increase the latter it is, therefore, necessary to work with great effectiveness, by choosing the right directions for development, and efficiently, by having appropriate means for reducing the efforts for the definition of a new solution to be launched on the market.

From this perspective, knowledge plays a paramount role for carrying out the various cognitive-demanding activities during the design processes. Both customers and technical experts represent relevant sources of knowledge and can determine which are the requirements to be met for the development of a successful innovation. However, these knowledge elements are often not clearly expressed and are just perceived by the individuals; in other words they pertain to the sphere of tacit knowledge. It is therefore critical to develop appropriate means for eliciting knowledge from all the players having a paramount role in innovation processes, so as to avoid the adoption of trial-and-error approaches that result in expensive strategies that not necessarily pledge the objectives.

According to the existing perspectives about the design process, requirements are the main criteria for both being capable of setting targets and discriminating good promising solutions against those having a poor potential. Therefore, their elicitation from tacit knowledge represents a challenge, since the existing practice for this purposes have demonstrated to be lacking in terms **of flexibility of use in different contexts and, on the other hand, of catching the wide range of objectives to be achieved in a measurable and complete fashion.**

In detail, this research aims at defining means for supporting the elicitation of knowledge from experts and their related classification in meaningful categories, so that it is possible to overcome the current limitations emerged from the analysis of state of the art. Existing technical

standards and checklists, indeed, allow mapping a very wide range of requirements. The former are very focused on specific fields of technique and, as a consequence, they result to be poorly adaptable to a various range of exigencies. Checklists, on the contrary, try to address this issue with a broader perspective, being more general and by taking into account different issues concerning the development of a product. However, their capabilities in defining a design specification do not necessarily pledge with the characteristics of completeness, validity, non-redundancy and conciseness as pointed out by Roozenburg and Eekels (1995) and discussed in Section 2.4.2.

From a different perspective, the "Design for X" guidelines address the needs of a wide range of technological domains, but they are mostly focused on the definition of best practices to design products so as to satisfy a 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).

In this context, this research aims at releasing, on the one hand, from the specific domain of application of standards and checklists and, on the other hand, from the single objectives of Design for X as presented in Figure 26. This objective can be achieved by introducing a description of criteria at a higher level of abstraction (than checklists) for the elicitation of knowledge from customers and stakeholders. Thus, it is possible to both address the different facets of the whole development process and use them as a strategy to pose questions to the different players having a role in designing. In other words, this research aims at developing an appropriate organization of knowledge that allow to both identify and classify the content of requirements for the design process.

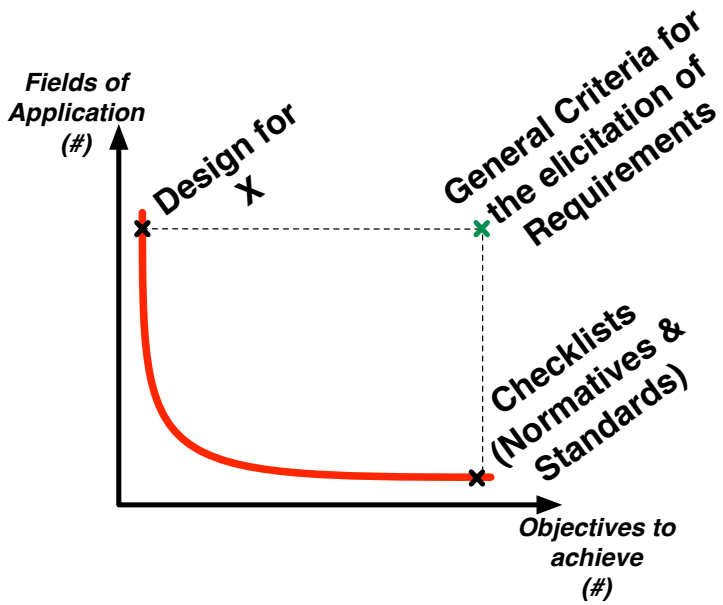


Figure 26: The definition of general criteria for the elicitation of requirements (green cross) from holders of relevant tacit knowledge as a means to address both the needs of different domains of technological development and the capability to catch and represent a wide set of design objectives to be achieved.

Through the identification of criteria for supporting the definition of requirements in diverse situations and for a wide range of purposes, it is possible to address the need of having an instrument that is usable with great flexibility in different situations and in different domains of technology. In such a way, it is possible to support both Product Development Process and the Development of new manufacturing processes through the identification of available

opportunities due to the presence of alternative technologies competing in carrying out the same functions. As well, such a definition and classification of requirements also enables the search for opportunities to transfer some technology from different technical fields as already discussed in Section 2.2.2.

Moreover, such an organization of knowledge also allows to define the characteristic elements for feeding a Network of Contradiction (Khomenko, 2007), in order to identify priorities within the design conflicts to be addressed during the PDP or as a method to identify barriers for the evolution of technical systems, thus supporting the forecasting of new technologies (Kucharavy, 2007).

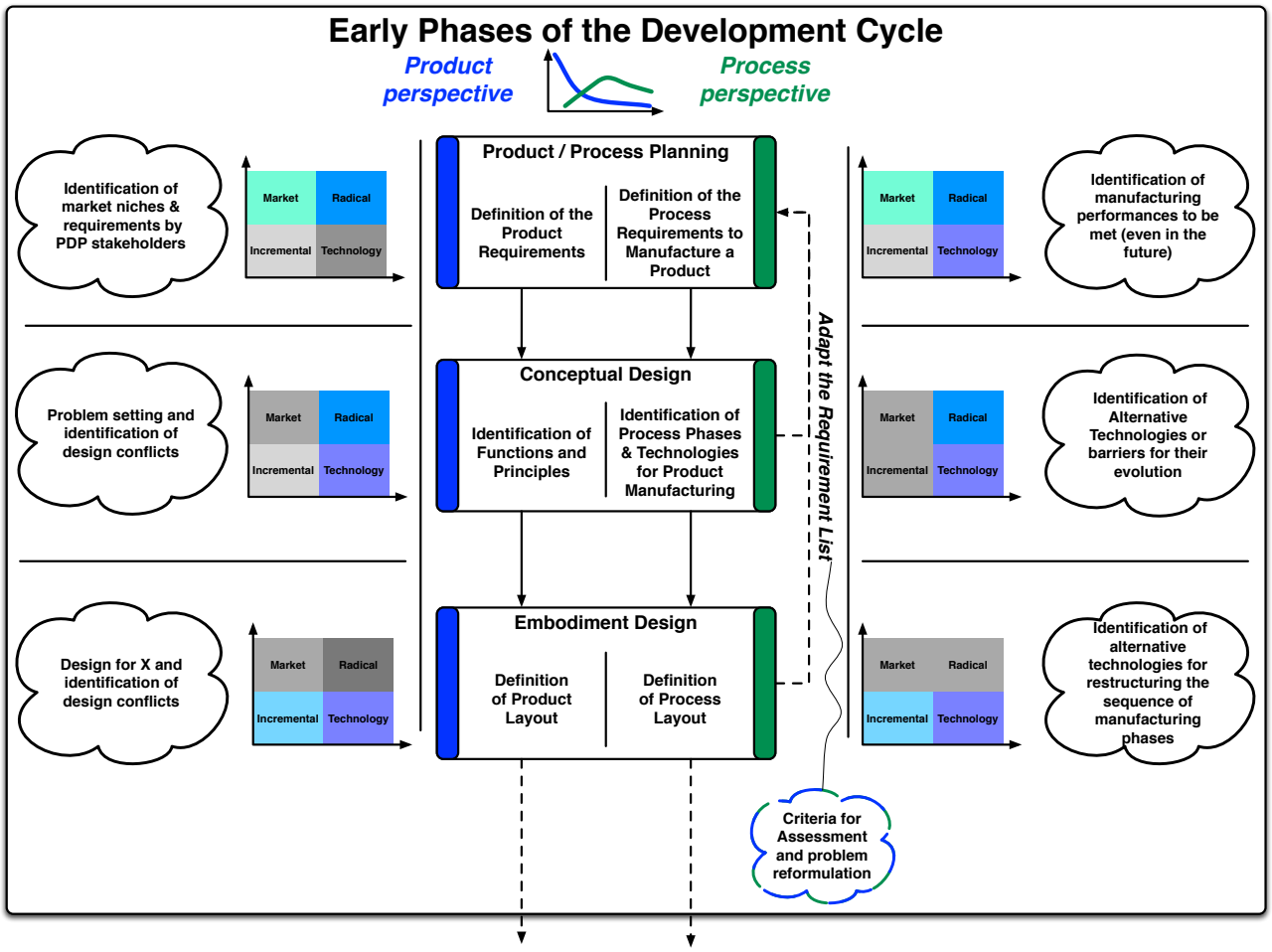


Figure 27: The role of requirements in the first three phases of the Product Development Process (in blue, left side) and the interpretation of the same stages for the development of new Manufacturing Processes, together with the related role played by requirements (in green, right side).

According to this perspective, the author proposes a parallelism for what concerns the development of new Products and related manufacturing Processes, for two main reasons. First, the innovation of Product and Processes has to be considered as a unique phenomenon driven by the same dynamics, where mutual influences affect both developments, as suggested by Utterback and Abernathy (1975). Second, also the innovation of Processes can follow a systematic approach for their renewal.

The left side of Figure 27 depicts the different stages of the Product Development Process and the role of requirements as they have been widely discussed in Section 2.4. The right side, on the contrary, proposes the same three different stages according to the interpretation of a

development activity concerning manufacturing Processes. Within this context, the analytical stage of *planning*, for Processes, concerns with the definition of the characteristics that a manufacturing technology should have in order to satisfy the desired outcomes; which are, in turn, driven by the characteristics of the Product to be manufactured. The Synthesis stages, as for Products, concern the exploration, the combination and the transformation of the design space within the logic of "design as search". Such cognitive approaches, being them generally described as characteristics of creative design (Boden, 2009), are therefore also valid for the search of potential technologies to be developed or implemented for manufacturing products, thus concerning the process side of innovation as described in Section 2.2.2.

The main distinction between the Conceptual and the Embodiment design stages for the development of innovative processes, as for products, concerns the extent of the impact of the design choices carried out during the development process. During the Conceptual design phases it is possible to determine, according to the needs to be satisfied, the nature (characteristics and capabilities) of the technology to be implemented (Technology Substitution and Technology Transfer) as well as the barriers to be overcome for eliminating the causes preventing its implementation (Technology Forecasting). The Embodiment stage, once technologies for manufacturing products or semi-finished products have been defined in previous phases, allows carrying out just minor interventions on the whole manufacturing process. However, in this stage the sequence of steps for manufacturing products can be also rearranged or partially modified (e.g.: some other technology may disappear) according to the identified technological alternatives.

Minor are the chances of modifying and changing the concepts of products or processes during the design processes, and minor are the expected results in terms of innovations. This is the reason why the innovation scenarios (technology push vs. market pull) reported in both sides of Figure 27, links the earlier phases of the development cycles with innovations of major extent, while the embodiment design stages just allow carrying out technological or incremental innovations.

Besides the considerations concerning the *flexibility* in using the criteria for both products and processes (also in different fields of technological development), it is also worth mentioning that the definition of such criteria should enable the generation of requirements that match at the maximum extent the characteristics defined by Roozenburg and Eekels for an appropriate definition of the design specification.

Into the details, these criteria must be capable to drive the definition of requirements so as to satisfy the need of *completeness* and *non-redundancy* for the design specification. The first objective has to be achieved by stimulating experts in taking into account also the facets that are not commonly explored, even through the adoption of existing multi-purpose checklists such as the one suggested by Pugh (1991). The second objective, in turn, has to be achieved by setting the viewpoint and the boundaries for carrying out the elicitation, so that concepts having facets in common can be expressed as distinct requirements pointing to specific objectives. As a consequence, also the *conciseness* of the design specification should be referred to a specific perspective according to which carrying out the elicitation of requirements.

Except for what concerns *operationality* and *practicability* of the design specification, which, according to their definition, mainly depends on the context in which the design process has to be carried out, it is crucial to pledge the *validity* of the elicited list of requirements. Therefore the criteria for elicitation must also trigger the definition of requirements that can be measured in terms of, at least, dichotomous values. In such a way it is, thus, possible to link requirements to the satisfaction or the dissatisfaction triggered by, respectively, their good and poor achievement.

Moreover, the analysis of the state of the art carried out along the previous section has highlighted that experts surely hold the necessary experience to populate a design specification, but their duties within the corporate structure limits their availability for carrying out the elicitation. This imply that, among the objectives of this research, the *ease of use* should be taken into account with great attention in order to produce something that is really usable in industrial context.

At last, among the objectives, it is necessary to mention the *repeatability* of outcomes in terms of the largeness of the design specification. In other words, the criteria should demonstrate to really support those who exploit them and not just single individuals. Such an issue can be examined through measuring the capability of defining a wider range of requirements that, without the use of criteria, won't be ever taken into account. On the contrary, expectations in terms of repeatability seems to be a meaningless goal if evaluated in terms of the specific content of different sets of requirements elicited from different individuals. Tacit knowledge is, by its own definition, personal and therefore the specific expertise plays a not negligible role in differentiation.

3.2 Development of a set of criteria for the identification and the classification of requirements

3.2.1 Definition of a reference framework for a uniform definition of requirements

According to the above-discussed objectives, the development of criteria for the elicitation of requirements capable to drive the design processes has to face several challenges.

The first challenge concerns the definition of the criteria so that they allow knowledge elicitation to be carried out with direct reference to the innovation issues as well as to the evolution and the development of technical systems in a "complete" and systematic way.

In this sense, the author recognize in TRIZ, the Russian acronym for Theory of Inventive Problem Solving, a good opportunity. As the name says, it is a theory for solving design problems and its approach is aimed at avoiding design trade-offs, as already mentioned along the analysis of the analysis of the state of the art (Altshuller, 1984). The whole description of the theory, its methods and instruments goes beyond the purposes of the present research, hence, in this context, just the relevant elements will be briefly mentioned for the sake of clarity. Other details, where they can enrich the description, will be presented in Appendixes. In general terms, this theory is connected to innovation issues both because it concerns the solution of design problems, but also because its concepts are grounded on the empirical results derived from the evolutionary analysis of a huge amount of patents. They have been analysed with the purpose of recognizing regularities and therefore laying some foundational concepts about technical systems evolution. Indeed TRIZ is based on three postulates (Cavallucci, 2007) about such evolution:

1. Technical Systems evolve according to recognizable patterns, so laws of technical system evolution can be inferred (eight laws have been recognized so far).
2. The driving force of the evolution of technical system is the overcoming of contradictions, namely design conflicts, among system parts and/or system objectives.
3. The evolution of a technical system takes place according to the specific situation at hand, meaning that it is possible to let a system develop just if appropriate conditions are present, thus if resources for its functioning are available.

The complete description of the eight laws inferred from the analysis of patents and mentioned in the first postulate of TRIZ theory goes beyond the purposes of this work and won't be reported here. For the sake of completeness they will be presented in Appendix C.

However, the fourth Law of Engineering System Evolution (LESE from now on) will be briefly presented here, since it has been chosen by the author as the reference point from which to start the development of the criteria for describing the complete set of characteristics potentially influencing the innovation of a technical system (further details and in Appendix C).

Such law is also known as the "law of ideality increase" or "the law of the increase of degree of ideality" (Altshuller, 1984) and affirms that technical systems evolve in order to improve their performances in carrying out *Useful Functions* and, on the other hand, towards the reduction of emerging side effects (*Harmful Functions*) as well as towards the slashing of costs (*Resources consumptions*) to be paid in order to make it exist and work. These three classes of concepts serve as a means for catching the potentially relevant changes occurring in technology or demanded from the market. Moreover, they represent mutually exclusive classes and have been therefore chosen as the main reference classification for defining the requirements of technical systems.

Moreover, with the purpose of producing criteria for the definition of system requirements having the characteristics of completeness, non-redundancy and conciseness it is important to define a common viewpoint for referencing the whole analysis. As suggested by the reviewed contributions about engineering design methods, the conceptual design phase deals with the definition of functions required to satisfy the objectives for which a technical system requires has to be designed. Thus, for carrying out an effective and efficient design process, it is of paramount importance to define requirements so that it is possible to understand which kind of function can satisfy them. In Conceptual Design, the word "*function*" assumes the meaning of "transformation of an input into an output". The EMS (acronym for Energy-Material-Signal) model is widely adopted in engineering design for this purpose, as witnessed by, e.g.: Pahl and Beitz (2007), Cross (2008). This model considers a function as a "black box" transforming flows, organized into three categories: energy, material and signal (Figure 28). From both the perspectives of products and process, each technical system is developed for the purpose of transforming something that naturally wouldn't change (or vice versa: to keep stable something who as the tendency to vary). Therefore, such preliminary definition of the function of the technical system, according to the purpose it is designed for, allows obtaining a shared viewpoint for the subsequent elicitation of requirements.

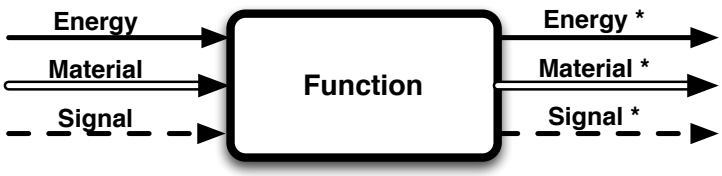


Figure 28: The Energy-Material-Signal model

Such preliminary definition does not limit the possibility of further dividing the overall purpose of the technical system into several sub-functions. This specific issue can be addressed by a modelling technique already developed by Cascini et al. (2008) and which is not part of the original contribution of this research. Details on this modelling technique are presented in Appendix D.

With reference to the need of producing measurable requirements (*validity*), it is proposed to define the requirements in terms of Evaluation Parameters, according to their meaning within the boundaries of OTSM-TRIZ. Evaluation Parameters, indeed, are an abstract representation of requirements to be met by a given technical system. They are intended to characterize the

presence of conflicts in design according to the values assumed by design variables having an influence on them. Conflicts (*contradictions* in TRIZ jargon) appear among Evaluation Parameters, at least two, in terms of non-mutually compatible satisfaction. In other words, the assignment of a certain value to a design variable (Control Parameter) that affects both requirements generates satisfaction for the one (green circle) and dissatisfaction for the other (red circle), as depicted in Figure 29.

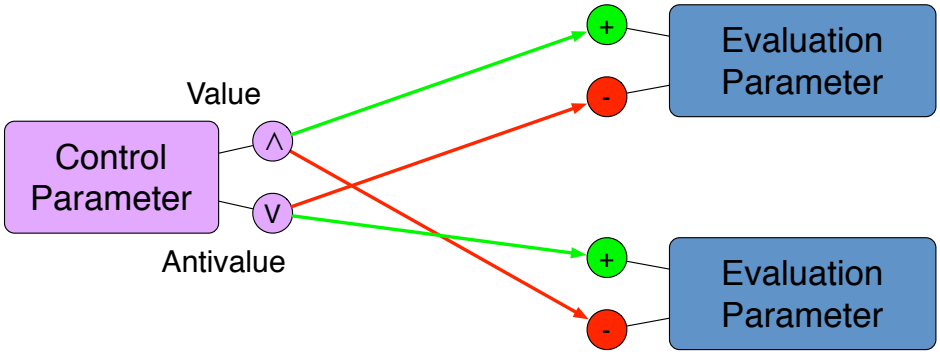


Figure 29: Evaluation Parameters in the OTSM-TRIZ model of Contradiction. The opposite values assigned to the Control Parameter determines the satisfaction (green circle) for an Evaluation parameter and the concurrent dissatisfaction (red circle) for the other Evaluation Parameter

According to such a description, it appears evident that Evaluation Parameters can be measured in terms of, at least, a dichotomous variable. Moreover, depending on the context and the detail level of the analysis, it is also possible to determine threshold values according to discrete or continuous scale of measurements for distinguishing between satisfaction and dissatisfaction.

3.2.2 Definition of the set of criteria for the elicitation of requirements from tacit knowledge.

According to the choices illustrated above, Evaluation Parameters can be chosen to characterize the Useful Function performed by TS, the onset of Harmful Functions as well as the need of Resources for the system to work. However, before going into the details of the criteria for the elicitation of system requirements, it is worth considering in which kind of domain (among Functions, Behaviour and Structures) the capabilities of a technology can be searched or determined.

With reference to the FBS framework proposed by Gero (1900 and 2004), it appears evident that what concerns the delivery of Useful Functions pertains at a greater extent to the Function level, being it intended as the purpose of the technical system.

On the contrary, the presence of side effects and the need of resources as well as details about Useful Functions do not lie on the same level of Function, since they emerge according to what the system does in practice and according to what compose the system, as a means to deliver the Function. For this reasons they pertain to the sphere of Behaviour and Structures.

This implies that requirements -concerning the capability of the system to both prevent the emergence of undesired side effects (Harmful Functions) and the limited consumption of Resources to make the system work- cannot simply be considered in reference to the EMS model presented before.

Nonetheless, this issue is not contradicting the overall framework presented above as a reference to ensure a uniform analysis in terms of completeness, non-redundancy and conciseness. Indeed, the research for appropriate technologies to be implemented into technical

systems has to be preliminarily carried out according to the Function they have to perform (e.g.: Pahl, 2007). Then, once several alternative and competing technologies have been identified and selected as promising for further development according to their capability to carry out the function, it is necessary to reduce the range of alternatives by also comparing them according to

- the capability to achieve the main useful function as required by the technical system;
- the extent of drawbacks potentially emerging by their introduction; and
- the needed resources for system functioning.

For this reasons, system requirements concerning Useful Functions can be initially identified, as mentioned, in reference to the EMS model describing the transformation from input to output (or from Object to Product, in TRIZ Jargon). Nonetheless, some of them can be determined also according to the capability of the selected technology to address diverse exigencies that depends also on the specific behaviour through which a function is carried out. To this purpose it could be beneficial to understand what components are crucial for the functioning of the technical systems. This kind of examination can be eased through the use of the Minimal Technical System model, that distinguishes the main four components of a technical system: the Tool, the Engine, the Transmission and the Control elements (as referenced by LESE #1, available in Appendix B). However, the modelling through the Minimal Technical System for catching requirements is not compulsory, even if it may ease the identification of system requirements. On the contrary, the definition of requirements concerning the Harmful Functions and the Consumption of Resources should follow different criteria that take into account general features capable to describe the presence of side effects and reasons underlying costs.

3.2.2.1 Classification of requirements concerning Useful Functions

In general terms, the requirements concerning Useful Functions have been divided into four sub-classes: Threshold Achievement, Adaptability, and Sensitivity to External Conditions as well as Controllability, as follows:

- **Threshold achievement**: requirements describing the capability to impact the object of the function with the expected extent (Figure 30);
- **Adaptability**, (Figure 31) further subdivided into
    - **Versatility:** requirements characterizing the capability to adapt the behaviour of the technical system according to different operating conditions;
    - **Robustness**: requirements accounting the capability of the technical system to obtain the same (stable in values) desired outcome under varying inputs;
- **Sensitivity to external conditions**: requirements concerning the capability of the technical system in carrying out its function regardless of the conditions of the environment in which it is immersed (Figure 32);
- **Controllability:** requirements about the capability to set system characteristics and parametersso so as to obtain a desired result according to user's will (Figure 33).

This subdivision allows all the potential facets, according to the EMS model, that may affect the delivery of a certain function to be mapped: the outcomes are then evaluated according to the target to be achieved, the initial conditions of the flow to be transformed, the context in which this transformation occurs as well as the capability to modify the target from inside the technical system upon request.

A more detailed description of the criteria for the classification of requirements according to the abovementioned structure follows. For the sake of clarity, examples in for the function "to clean clothes" are presented where meaningful.

Threshold Achievement

This criterion (Figure 30) represent the main driver in searching new or alternative technologies, since they allow to point out which are the reference values that the design proposal is expected to achieve, for each flow of the EMS model to be transformed by the function. They both define which is the target to attain and provide means for looking to available solutions capable of such achievements. They take into account both the quantity of flow that gets transformed by the function and the quality of such transformation, meaning the specific parameter of the flow that gets changed by the function.

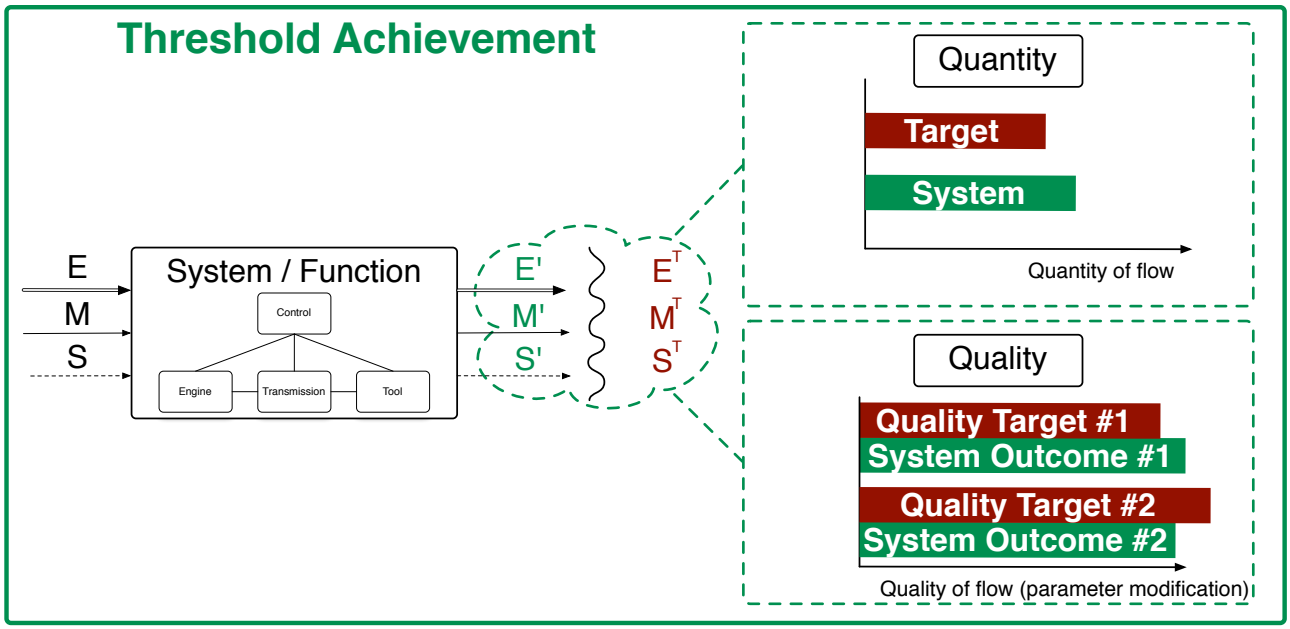


Figure 30: Graphical representation of the criteria for the elicitation of requirements concerning the capability of the system to reach target values, both in terms of quantity and of quality of flow.

<u>*Quantity of the product*</u> (Figure 30, top)*:* Each function has the capability to transform the object of the function itself in the desired product. Thus, this parameter assesses the quantity of this transformation in terms of maximum theoretical productivity of the existing technical system (e.g.: pcs/hour). This parameter wants to estimate "how much" quantity of the object gets transformed into the product. (e.g.: the amount of clothes that a washing machine can treat at a time with a washing cycle)

<u>*Quality of the product*</u> (Figure 30, bottom)**:** Each function changes or stabilizes at least one of the features of a given object in order to transform it in a desired product. The parameter "quality of the product" is thus meant to describe the capability of the system to deliver the function as requested in terms of quality. In other words, while the parameter related to quantity wants to assess "how much" the function is carried out, this parameter is intended to assess "how well" the function produces its results in reference to the desired outcomes. (e.g.: the amount of residual stains, odours and pathogens on clothes after a washing cycle as well as the kind of stains that can or cannot be removed…)

Adaptability

Both the concept of *Versatility* and *Robustness* included in the "*Adaptability*" criteria should be considered according to the capability of the technology to obtain stable values of quantity and the quality of the flows, in reference to what has been already discussed for the criteria for define requirements about the achievements of threshold values (Figure 31).

Adaptability and Robustness could be interpreted according to the meaning that Control Theory currently assigns to them. Nevertheless, this is not the case, because differences there exist. Therefore it is widely recommended to strictly adhere to the indication suggested by the criteria for the elicitation of requirements. The concepts of "*Versatility*" and "*Robustness*" proposed in the hereafter are surely depending on the Function level, since they still concern to the transformation of an input into a, say, repeatable output. However the different capabilities of technologies to obtain more or less robust or versatile results pertains to the domain of the Behaviour, since the achieved values depend on the way the function is actually performed.

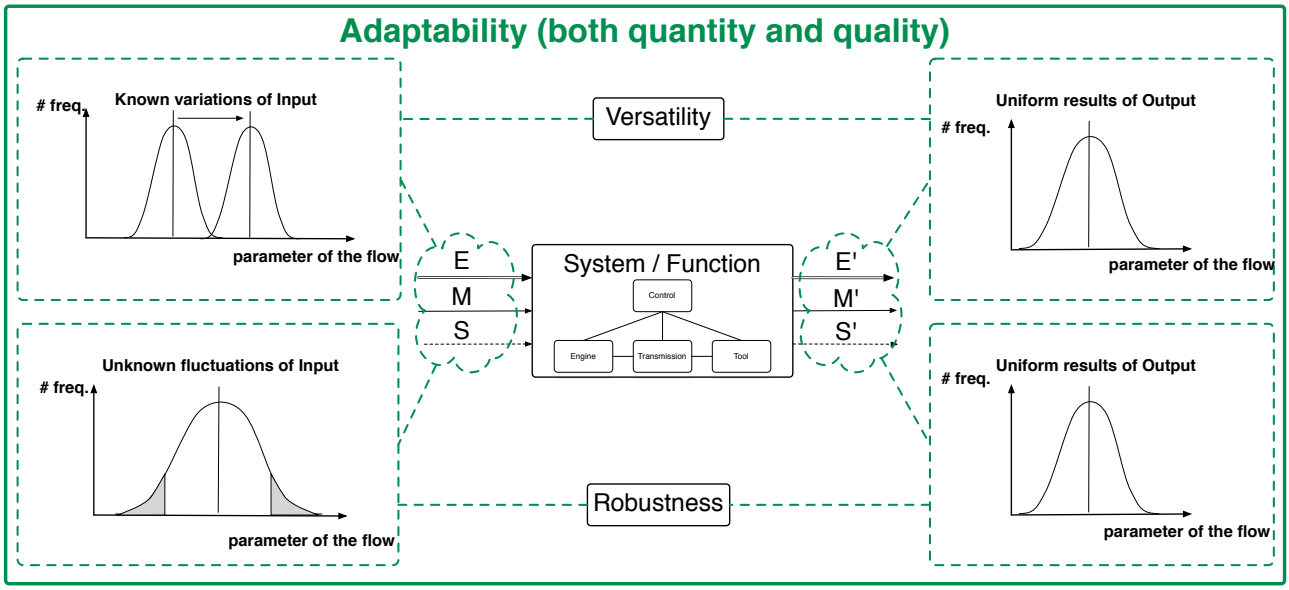


Figure 31: Graphical representation of the requirements concerning the capability of the technical system to adapt to different incoming flows, by obtaining repeatable results.

<u>*Versatility*</u> (Figure 31, top)**:** Takes into account some of the variations of the working condition under which the technical system carries out the function. In detail, it focuses on the capability of the system to produce standard outputs regardless the input object has been willingly changed in some of its properties. Thus, this parameter describes the capability of the system to work with different objects according to various exigencies, producing outputs of standard quantity/quality (e.g. the capability of a washing machine to carry out cycles, simultaneously or not, with different kind of textiles such as wool, cotton, …).

<u>*Robustness*</u> (Figure 31, bottom): Takes into account some of the variations of the working condition under which the technical system carries out the function. It deals with the capability of the system of producing standard outputs even if the input flow (the object) has non-standard characteristics due to unpredictable fluctuations in the batch to be treated. This parameter describes the capability of the system to work with different inputs, producing outputs of standard quantity/quality. (e.g. the capability of a washing machine to carry out a cycle with clothes of different dimension, such as tablecloths and napkins, or with a different kind of decoration, such as printed or embroidered…)

Sensitivity to external conditions

This criterion aims at defining requirements concerning the capability of the technology to carry out the function regardless of potential influences emerging in the environment in which the technology itself is immersed (Figure 32). In other words it is a criterion that allows triggering consideration about the context in which the users of technical system to be designed will exploit its functionalities, consistently with what has been pointed out by Cross (2008) for what concerns the Design Brief. Even for this specific criterion the focus is on the function, even if the sensitivity to external condition changes from technology to technology, thus depending on the specific behaviour they implement.

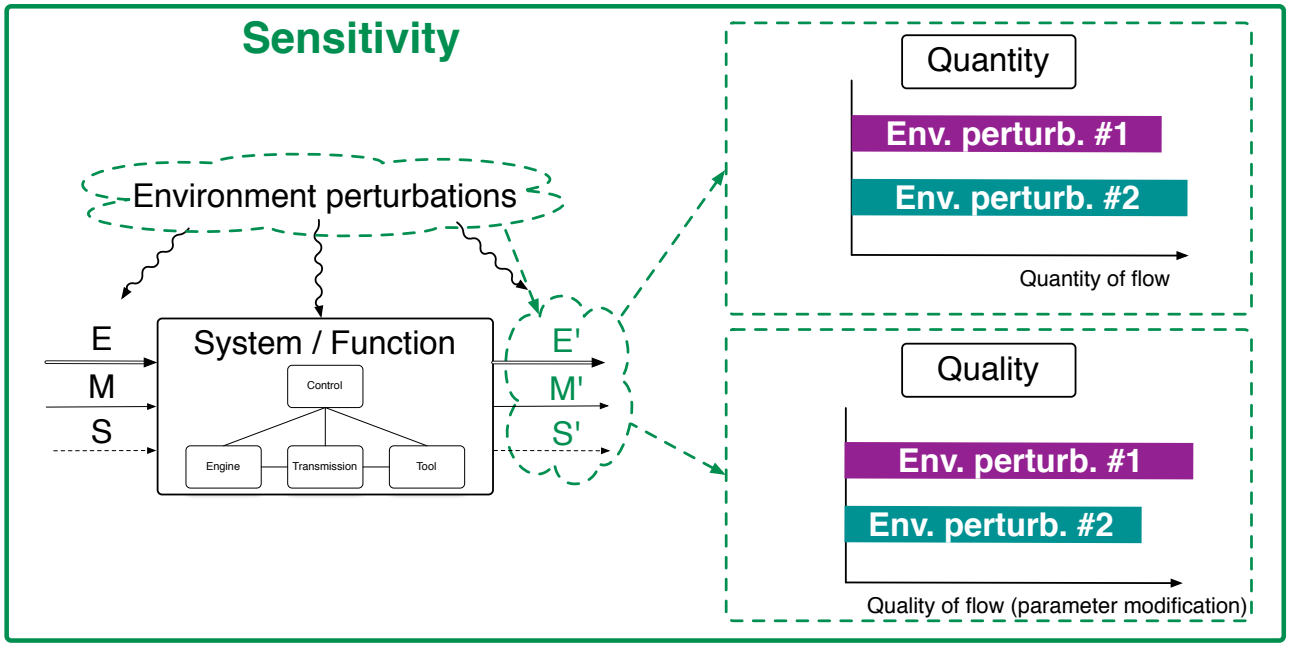


Figure 32: Graphical representation of the criteria concerning requirements pertaining to the sensitivity of the technology to the external conditions that may potentially affect both quantity and/or quality of flows.

Sensitivity to external perturbations - quantity (Figure 32, top): Describes how external perturbations may affect the outcomes of the function. In detail, it is aimed at measuring how much changes in system surroundings may affect the quantity of flow that the function processes with success in order to obtain the desired product. In order to make this evaluation/assessment it is necessary to consider non-changing characteristics of the input flow. (e.g.: the capability to wash the same amount of clothes regardless of particular external perturbations that may alter the working conditions)

Sensitivity to external perturbations - quality (Figure 32, bottom): Describes how external perturbations may affect the outcomes of the function. In detail, it is aimed at measuring how much the changes in system surroundings may affect the quality of outgoing flows processes with success by the function in order to obtain the desired characteristics of the product (since it changes at least one of its parameters). In order to make this evaluation/assessment it's necessary to consider non-changing characteristics of the input flow (e.g. the capability of a washing machine to keep the required washing temperature regardless the external condition in order to remove the same amount or kind of stains)

Controllability

This criterion aims at defining requirements related to the capability to regulate the functioning of the technical system according to varied demands. In other words such a criterion concerns the definition of requirements describing the capability of technology to set different target both in terms of quantity (amount of energy, material or signal) and/or quality of the flow (meaning specific changes for the parameters characterizing the flow). As for most of the other criteria, even this criterion pertains to the capability of obtaining outgoing flows having certain characteristics, thus relates to the purpose of the technical system and its Function; however, this capability does not just depend on incoming and outgoing flows, but on the specific principles (Behaviour) according to which the technology allow to control the outcomes.

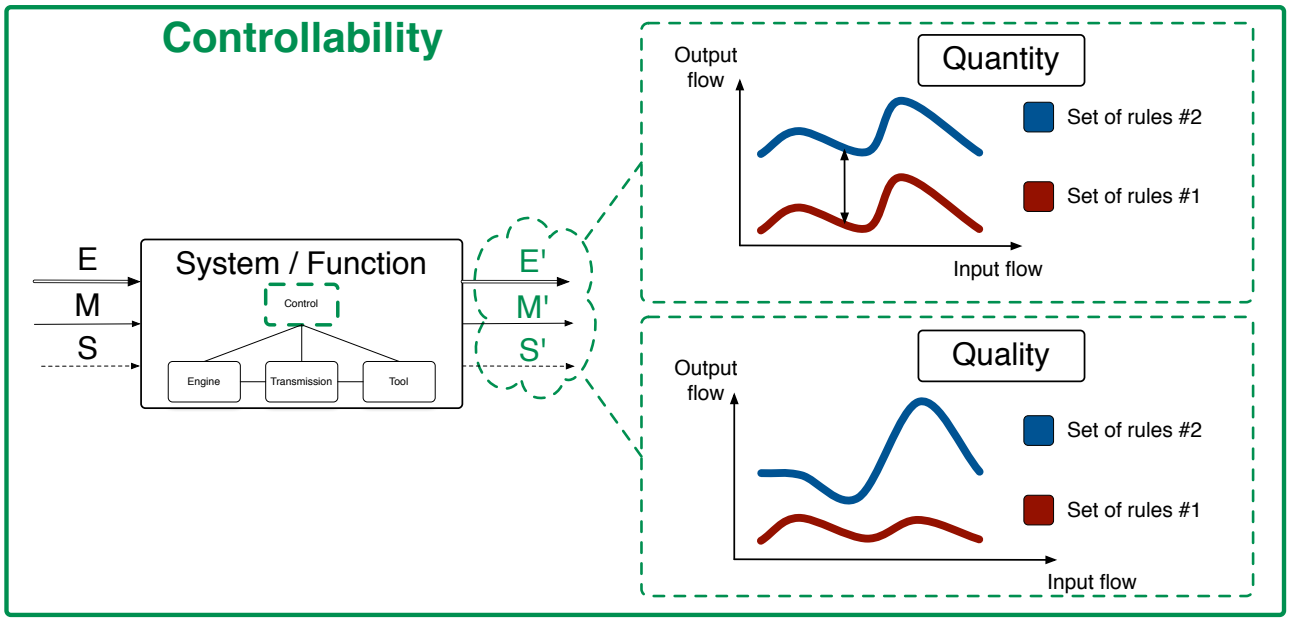


Figure 33: Graphical representation of the criterion for the identification of requirements about the capability of a function to modify the characteristics of the outgoing flows.

Controllability of quantity (Figure 33, top): Aimed at evaluating the capability of the system, to be set and regulated according to specific rules and values in order to obtain a given quantity of the product. Thus, also this parameter deals with the opportunity to control the system in order to produce a particular result. It should be evaluated by considering non-changing characteristics of the input flow. (e.g: the capability of a washing machine to be set in order to carry out a washing cycle with a full load or half load)

Controllability of quality (Figure 33, bottom)**:** Aimed at evaluating the capability of the system to be set and regulated according to specific rules and values in order to obtain a product with given characteristics. Thus, it deals with the opportunity to control the system in order to produce a particular result. It should be evaluated by considering non-changing characteristics of the input flow. This parameter can be split in more detailed parameters, one per each feature of the product of the function. (e.g.: the capability of a washing machine to be set in order to clean clothes obtaining different characteristics at the end of the process, such as setting the spinning speed or cycle temperature)

3.2.2.2 Classification of requirements concerning Harmful Functions

As stated at the beginning of Section 3.2.2, Harmful Functions appear in reference to the specific technology that gets used for a certain purpose (e.g.: cooling with a traditional vapour-

compression cycle requires a compressor that produces noise. Peltier cells, on the contrary, allow the same function to be carried out, but do not produce any noise). To this purpose, the requirements aiming at the prevention of harmful functions need to be elicited according to a slightly changed logic.

The main reference is still represented by the Useful Function, as the main objective to be achieved by the design proposal. Once the different competing technologies fulfilling such a purpose have been identified, the potential harmful interactions may occur among a finite set of entities, if described at a general level. Therefore, the criteria for the definition of the capability of technology in avoiding the emergence of Harmful Function is divided into three different sub-classes, considering negative impacts on:

- the object of the Main Useful Function (e.g. an undesired side effect caused by the same mechanism adopted to deliver the MUF or as its consequence);
- the system and subsystems integrity (e.g. an undesired side effect on the technical system as a whole or on its parts);
- the external environment (e.g. an undesired side effect that compromise some environmental conditions or damages some of the elements that pertains to the world in which the technology/technical system is immersed in).

The complete range of potentially harmful interactions is presented in Figure 34. The Useful Function carried out by the technical systems is represented through a straight and green arrow. On the contrary, curvy red arrows characterize Harmful interactions.

According to this classification, it appears as almost impossible to determine in advance which are the potential effects occurring as a consequence of Harmful Functions. Nevertheless, their complete definition is also meaningless, since the same function (and its effects) can be considered as Useful and Harmful, depending on the contexts in which it emerged (e.g.: Eddy currents are undesired in a wide range of contexts, however they are also exploited purposefully in other applications, such as induction cooking).

Nevertheless, in the following, a description of some potentially harmful effects is presented with the objective of clarifying the meaning of potential interactions occurring among the technical system, the Object or the Product of the technical system itself (namely, Input and Output flows of the Function modelled as a black box) and the Environment in which the technical system works. Such effects shouldn't be considered as an exhaustive description of the phenomena that can potentially appear.

Also in this case, examples from the world of technologies for clothes cleaning are presented where meaningful and applicable.

Harmful Functions of the Technical System against the Object or Product

Object integrity: Refers to the potential emergence of undesired effects due to the function delivered by technical system on the structure of the object that has to be transformed into the product. Thus, this parameter is meant to assess the undesired effects that may completely spoil the integrity object and fatally compromise the product of the function. This parameter can be split in more detailed parameters, one per each spoiled feature. (e.g. presence of clothes whose textile gets spoiled by the drum or whose colour gets contaminated by other clothes)

Product Wastes: Deals with the undesired part of the object that is not transformed as desired by the function, thus it is related to the presence of debris or waste resulting e.g. from metalworking operations. This parameter can be split in more detailed parameters, one per each specific kind of waste (not applicable to the function "to clean clothes" by means of a washing machine).

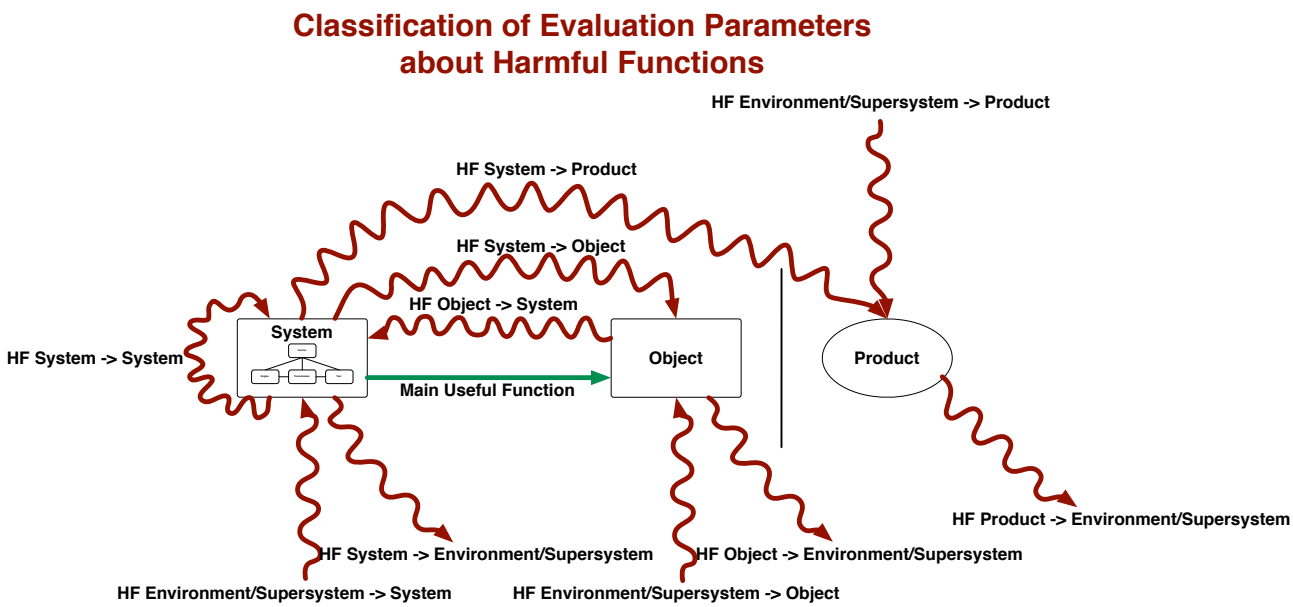


Figure 34: Graphical representation of the potentially Harmful Interactions occurring among couples of elements from the technical system, the object/product of the function, and the Environment. Curvy red arrows represent Harmful Functions, the straight green arrow is the Main Useful Function performed by the technical system.

Harmful Functions of the Environment against the Object or Product

Sensitivity to critical External Conditions: Relates to external condition, as the one already mentioned in the section about requirements concerning to the delivery of a useful function. Even in this case the parameter is meant to assess the sensitivity to perturbation in the environment as well as to critical condition. Differently from what concerns the above-mentioned parameter, this one deals with all the features that are not related to the delivery of the useful function, thus it's worth to detail this parameter by taking into consideration those ones that are not addressed by the Main Useful Function and detailed thorugh the initial EMS model.

Harmful Functions of the Object against the Technical System

Mechanical resistance: Aimed at estimating the capability of the technical system to bear the load due to the stresses produced by a specific counter-action of the object of the function before, after and during its delivery as well. This parameter can be further detailed by taking into consideration phenomena such as deformation and fatigue resistance. (e.g. resistance of the drum dampers)

Wear resistance: Relates to the action that the object of the function delivers in an undesired way on the system itself by means of a physical action. Impacts of particles, as well as friction, are often causes of abrasive or erosive wear. (e.g. resistance of the drum bearings)

Harmful Functions of the Technical System against itself

Reliability: Refers to the occurrence of system failures. It is meant to assess the importance of failures in the system. Nevertheless this evaluation doesn't have to take into account the amount of the time spent to fix the system, since it will be evaluated by means of a different parameter, but exclusively the negative consequences of system failures. (e.g.: importance of a non-working detergent dispenser - failures of detergent dispenser)

Expected life of the system: Intended to evaluate the capability of the system to keep its integrity and capabilities of function delivery along time. Almost all the technical systems have a

useful amount of time before the greatest part of its components abruptly start to age and failures appear at a great extent. (e.g.: duration of the whole appliance)

Harmful Functions of the Environment against the Technical System

Corrosion resistance: This parameter, sometimes, may be partially or completely synergic with phenomena due to the undesired actions of the Object onto the system; it takes into account the potential damages due to the action of agents (usually coming from the environment, but they may also pertain to the object of the function) that may alter the chemical composition of parts of the technical system.

Resistance to critical external condition: May include the EP previously examined. It allows to describe all the other mechanisms of damage emerging in the technical system due to certain critical values of external condition such as the loss of colours by clothes under the action of UV radiation coming from sunrays. (e.g.: capability to resist to limescale deposition on the ohmic heater).

Harmful Functions of the Technical System against the Environment

Noise production: Deals with the estimation of the noise produced by the technical system during the function delivery. Sometimes noise can be considered as a desired product; nevertheless this parameter wants to focus on all the undesired noise such as specific undesired frequencies. (e.g. presence of noise during water removal by spinning)

Heat discharged towards the environment: Focuses on the amount of heat released towards the environment since it may contribute to the global warming phenomenon. It can be further detailed by taking into account direct effects due to heat discharge (e.g. a condenser of a steam-based power plant) and also due to indirect action of function by-products (such as the amount of carbon dioxide released towards the atmosphere). (e.g. the heat discharged with drained water)

Environment Pollution: Evaluates the effects on the environment of the pollution due to the function delivery by the technical system. Each undesired agent, that may constitute harm for the environment, goes under this class. Heat and noise, as seen before, are evaluated by means of specific parameters and don't have to be considered among these effects. (e.g.: the effects of wastewater on streamlines).

User Safety: This parameter takes into account the presence of potential severe harms for the user, if any, of the technical system. (e.g. potential harmfulness of the glass window in the washing machine door because of its temperature)

Comfort and ergonomics: Even if this parameter, from a certain point of view, is strongly related to user safety, it focuses on the capability of the system to be used without bothering anyone, producing significant pain for the body or long-term illness due to wrong postures. (e.g.: comfort for loading; impose uncomfortable postures to the users)

Harmful Functions of the Object or Product against the Environment

Pollution by product wastes: As mentioned before for what concerns the technical system, it is worth to take into account the potential harms for the environment due to the action of product wastes. Thus, this parameter is meant to assess if product wastes may generate some undesired consequences and can be further detailed by specifying what characteristic of the environment can be compromised and/or what agent causes such effect. (e.g.: presence in drained water of small plastic pieces torn away from clothes during spinning)

3.2.2.3 Classification of Requirements concerning the Consumption of Resources

It has been already and widely discussed that each system can be characterized according to the function(s) it delivers, meaning the changes that it carries out on *Energy*, *Material* and/or *Signal*. Before each system becomes a "system", it is raw material that undergoes the same modification of flows by other technical systems carrying out their functions. It follows that every property or parameter of the different flows can contribute to represent things according to the different level of detail selected. Such property and parameters represents the reasons why some material is chosen against others for design, some energy sources represents better opportunities than others and so forth.

Besides, each system, being it technical or natural, needs to exploit some resources for its existence. Moreover, if it is also animated so as to carry out some functions, the resources increase in number and type. In other words, everything that exists needs at least some *Space* into which manifests itself and, if those entities are also animated, they play at least a dynamic act which expresses their animation, thus requiring also *Time*. These two dimensions represent the continuum into which all things are immersed, as taught in each Physics class.

According to this perspective it is quite useful to characterize the kind of resources concerning the needs of the technical system in order to provide the benefits they have been designed for. Since both the time and the space dimensions represent a universal starting point into which things can be classified and EMS ontology has been used for defining the function of the technical systems by the involved entities; it is proposed to use this classification to map the different resources required by a technical system. It is worth noticing that these two classifications may appear as not mutually exclusive, since all the flows can change during time and occupy some space (even zero is a value for describing room required). This is partially true, since changes occurring in the materials, energy or information may have also a role in slashing or increasing the consumption of space and time, but the effects of such changes are different and should go under different categories.

Moreover, since the contribution of customers and different stakeholders is expected within the design process, such examination has also to be carried out by considering the whole lifecycle of the technical system according to both the different stages of his life and a hierarchical level in space. Such hierarchical levels are three, and organized into:

- *Sub-System* (namely resources directly pertaining to system parts);
- *System* (resources that are not exploitable by themselves, but with the combined action of system parts); and
- *Super-system* (resources pertaining the environment into which the technical system exists) as depicted in Figure 35.

As stated at the beginning of Section 3.2.2, the consumption of resources may radically vary from technology to technology, even for the same function (e.g.: a traditional vapour-compression cycle requires vapour and electric energy for cooling, Peltier cells, on the contrary, carry out the same function by means of electric energy and metallic elements). In this regard, the boundaries of the analysis are again driven within the activity required to carry out the Useful Function of the technical system to keep the same level of completeness, non-redundancy and conciseness, but according to the specific Behaviour characterizing the technology under examination.

In the following, a set of potentially relevant Resources to be consumed by technical systems is presented. The purpose is to shed light on the way the criteria should be interpreted and not an exhaustive checklist. Examples about the resources consumed for "cleaning clothes" are provided where meaningful. Resources concerning *Signals* are referred as *Information* in order to distinguish among classes through capital letters and avoid ambiguousness with *Space*.

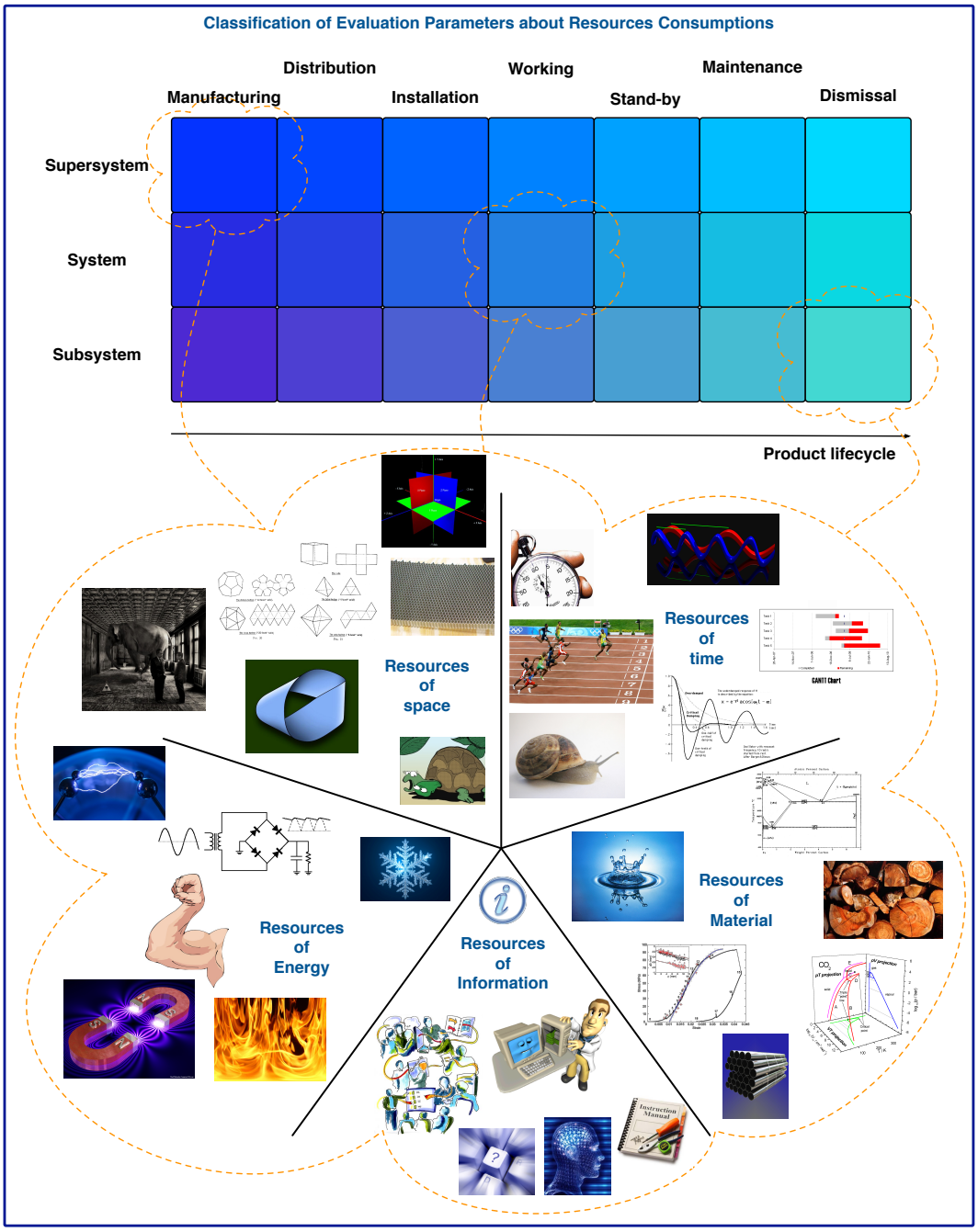


Figure 35: Graphical representation of the different classifications proposed for the consumption of resources. Top - an example of the different stages of the product lifecycle. Bottom. The five different dimensions into which classify the resources needed in different stages of the life of the technical system.

Space

Accessibility: Related to the quantity of space required to allow the users to approach the technical system without encountering obstacles and to properly interact with it during function delivery. (e.g.: room required for loading)

Encumbrance: Relates on the space required by the simple presence of the technical system. (e.g.: room taken up by the appliance)

Storability: Deals with the space required to store the system and the product under investigation in a place where they are just collected before their employment somewhere else. It

can be also detailed by taking into exam the space required to temporarily place the product of the function.

Space required for installation: Aimed at assessing the required amount of space to install the technical system and the auxiliary ones. (e.g. room required to connect the appliance to water pipes and electrical grid)

Space required for dismantling: Evaluates the amount of space needed in order to allow access to workers that have to disassembly the technical system and, of course, the amount of space that the technical takes up by itself. (e.g.: see above)

Time

Quickness in function delivery: Measures the time required to carry out the function. In other words it takes into account the amount of time required in order to modify the object of the function into the product. (e.g.: duration of a washing cycle)

Time for maintenance/failure fixing: Assesses the time that is usually required in order to bring back to full functionality the technical system after a failure or a common intervention of maintenance. It may also be detailed by considering different failures as well as their frequency (e.g.: duration of maintenance interventions)

Number of processes/treatments required for obtaining the product: Focuses on the product of the function. It is meant to assess the amount of time required to obtain a certain product by means of more than one processing phase of the same function. (e.g.: number of rinsing cycles)

Time for assembly: Whenever the technical system requires an initial installation in a specific location it is necessary to spend some time in order to prepare it for working. This parameter is meant to assess such amount of time. (e.g.: time required for connecting the appliance to water supply and electric grid)

Time for dismantling: Whenever a technical system ends its useful life, it is required to dismantle it in order to free the required space for its replacement. This parameter is meant to assess such amount of time. (e.g.: time required to disconnect the appliance from water supply and electric grid)

Availability: Refers to the amount of time to be waited before the technical system is ready to deliver its function. Moreover, it can be further detailed by distinguishing among the time to be waited for one specific technical system and for the whole equipment delivering the function, thus taking into account system redundancy and similar choices. (e.g.: the time required to heat water to the desired level)

Information

User awareness: Estimates the amount of information that the user of the technical system should possess before the system starts to function in order to understand what is the mechanism of that function (e.g. vocational seminars…). (e.g.: user awareness about the kind of textile to be treated, in order to choose the right washing cycle)

Competence of maintainers: Expresses the amount of information required that each maintainer should have in order to fix the flaws of the system that may emerge after or during use.

Ease of use: Deals with the amount of information that a common user must manage in order to correctly govern the function delivery

Ease of installation: Refers to the amount of information required to put together all the parts that contribute to the function delivery.

Ease of disassembly: Refers to the amount of information needed to separate components of the technical system once it is going to be replaced by a new one.

Ease of upgradability: Concerns the information required in order to change some subsystems or to improve the existing ones by means of new features.

Complexity (variety of parts…): Takes into account the complexity of the technical system, thus considering the amount and the variety of system parts as well as the mutual connection they share.

Material

Portability: Aimed at estimating the capability to easily move the technical system; nevertheless in this case it is important to take into account just the aspects related to physical quantity such as density since geometrical quantities have been taken into account with space resources. (e.g. the weight of the appliance)

Required consumable/disposable material: Evaluates the amount of disposable material required for the function delivery (e.g. water for metal cutting). It can be further detailed according to the different types of needed material. (e.g.: amount of detergent required for washing)

Independence from other product: Takes into account the capability of the system to work without requiring different material to be treated by auxiliary functions. Such parameters should be carefully examined whenever it's required to make comparisons between competing technologies; in this case it is suggested to detail this parameter by specifying what products are necessary for function delivery. (e.g.: the need of using a detergent or a fabric conditioner)

Reusability of items: Takes into account the capability of the technical system to work by means of already used items. It can be further detailed according to the nature of the item to be reused. (e.g. the capability to reuse cleaning agents, such as the chips of the Xeros ltd. washing machine)

Recyclability/Reusability of the whole system: Examines the capability of the whole technical system to be directly reused or reprocessed in order to be recycled.

Energy

Energy/Power required for working: Takes into account the overall amount of energy required to complete the transformation between object and product. Thus it is required to take into consideration the energy specifically required for the main useful function and the amount needed by the auxiliary function. It can be expressed both in terms of energy and power. (e.g.: energy needed for a washing cycle)

Dependency on a certain type of energy: Describes the different types of energy that are required by the technical system in order to deliver the main useful function and auxiliary functions. If the system doesn't require any specific type of energy the parameter can be considered "as-is", else it can be detailed by expressing the type of energy required on which it is possible to make quantitative estimation (whose results should be consistent with the above-mentioned parameter) (e.g.: capability to use hot water coming from solar panels or boilers rather than heated by ohmic devices)

Number of energy transformation: Deals with all the different energy conversions that take places in the boundaries of the technical system, also by taking into consideration the transformations that occur in auxiliary systems.

Efficiency: Specifies the results of the energy transformations; focusing on "how well" such transformation is carried out. It can be further detailed by considering the overall efficiency and the efficiencies of each energy conversion.

Number of workers: Describes the amount of manpower required in order to carry out the function. It can be further detailed whenever the workers play different roles in the function delivery.

An extensive application of these criteria for eliciting and classifying knowledge about requirements is presented in Section four.

3.3 Algorithm for the definition of the design space as a means to identify requirements for solution concepts (OPEN-IT project)

OPEN-IT was a project partially funded by the ERA-SME EU programme. Among its objectives, there was the definition of an ICT tool capable to support innovation actions by Small and Medium Enterprises.

Therefore, the development of the algorithm for the ICT module supporting the analysis of technical innovation problems has been seized as a good opportunity, within the boundaries of this research, to verify if the proposal to identify, classify and use requirements for driving the problem solving process in design can produce further benefits if assisted through the use of a computer.

Moreover, the demonstration of the efficacy of such algorithm also allows preliminary considerations to be made about the chance of releasing from the need of a human facilitator carrying out the elicitation of tacit knowledge. This opportunity also allows new paradigms to be introduced into the structure of the ICT tools, so as to verify to which extent the current capabilities of Computer-Aided systems in supporting the early phases of the PDP can be shifted.

The definition of an algorithm for supporting problem analysis and driving the early steps for the identification of possible direction for searching solutions, also allow changing a little bit the focus from the exclusive description and classification of requirements. From their use for searching and evaluating technologies to be implemented into new product to be designed from scratch, to their identification for precise objectives as the ones to be addressed during the Synthesis stages of the design process.

Nevertheless, the logic of the whole classification contained within the criteria has been introduced into the algorithm in terms of different paths for the exploration of the design problem at hand. The definition of the main characteristics of the problem, indeed, is carried out by looking for the two non-plainly compatible requirements among these paths, so as to identify priorities within the PDP for attaining goals capable to better trigger satisfaction, consistently with what has been discussed in Section 2.4.3.

In order to better exploit the potential of individual creativity and cognition, the structure of the algorithm has been developed by identifying the main limitations of current Computer-Aided means supporting the early stages of the PDP. As depicted in (Becattini, 2010) it has been developed a reference model for the implementation of the analysis module of a TRIZ-based Computer-Aided Inventive Problem Solving system that is presented in Figure 36. TRIZ has been chosen among the available theories and methods for creative problem solving since it allows to drive with higher effectiveness and efficiency the problem solving process, because of its logic oriented towards the overcoming of conflicts rather than accepting trade-offs among requirements; consistently with Jones (1984) that identify proposals of improved potential as the ones that have less compromises as possible. Besides, it is worth mentioning that within the TRIZ body of knowledge, one instrument allows the problem solving process to be assisted as a

sequence of steps. It is called ARIZ, Russian acronym for Algorithm for the Solution of Inventive Problem and its overall logic is embedded into the algorithm as well (the ARIZ85-C version is presented for completeness in Appendix F).

Moreover, the latest advancements obtained by OTSM-TRIZ through the definition of models of the problem solving process, also support the development of the algorithm in order to assist cognitive processes with improved capabilities of abstraction (Hill Model), so that it is easier to identify barriers to be overcome (Tongs Model) and converging towards a satisfactory solution (Funnel Model). The description of these models is presented in Appendix E.

It is also worth recalling that, as discussed during the analysis of the state of the art, dialogues and questions represent a good strategy for eliciting knowledge from people. Therefore it results convenient to structure the algorithm as a dialogue-based sequence of questions aimed at exploring the different facets of individual knowledge.

A systematic succession of questions is viable to support the investigation of the problem, allowing even to highlight the least codified aspects, that otherwise would be hardly taken into consideration. The fine-tuning of the questioning procedure can advantageously foresee differentiated logical blocks focusing on various facets of the problem. The logical succession can thus guide the user towards the identification of criticalities and conflicting issues and subsequently to the search of useful technical and scientific information.

The following subsection describes the overall structure of the model by illustrating the functions and main characteristics of its logical blocks. The proposed algorithm is presented, for improving the readability of this part, in Appendix A. All its steps are presented in tables organized according to the logical blocks that compose it.

3.3.1 General description of the structure of the algorithm

The dialogue-based system is structured for helping at first the user in exploiting his know-how by suggesting problem solving paths, which do not require external expertise to be implemented.

Thanks to the investigation of the parameters affecting the undesired issues arising in the system, the designer can individuate factors to be modified in order to reformulate the problem as a typical case. Moreover, among the outcomes of the innovation system, the algorithm provides indications for suitable problem solving alternatives through different TRIZ tools (Altshuller, 1984), e.g. separating in time/space, trimming useless or low-valued components, opportunities to turn the undesired effect into a useful output, re-thinking the ways to perform the main function or to deliver the same benefits.

However, as already mentioned in the previous paragraphs, the formalization of the problem should also aid the knowledge search. As recalled in Section 2, the knowledge search within the expertise domain has to be preferred to the information retrieval in external fields, due to an easier and quicker implementation of the ideas generated, although adapting solutions from different technical contexts represents a good trigger for radical innovations. In each case the search for new knowledge should be carried out just when the abstraction process has been completely and successfully performed, i.e., when a so-called physical contradiction has been correctly formulated (two plainly non-mutually compatible values for the same design variable).

Within TRIZ, the high innovation degree of the solutions originated when overcoming a technical conflict between requirements is well acknowledged, as well as the role the potential of solving principles commonly employed in different technical areas.

In order to identify the proper requirements to be addressed by the problem solving process and to cover all the options for problem solving and knowledge search, the framework of the algorithm includes a set of logical blocks aimed at examining different aspects of the system to

be designed and/or improved according to the criteria proposed in Section 3.2. The network of links among the blocks and the single nodes of the algorithm determine an extensive bundle of paths and cycles to refine the problem formulation, depicted in Figure 36.

In order to ease the usability of the innovation system and the formalization of the problem, the following measures have been taken:

- the nodes of the algorithm are just open questions, multiple choice (Yes/No) or simple communications, intended to provide proper hints in performing the problem solving process;
- the questionnaire employs a common terminology, avoiding TRIZ jargon;
- the text of the questions and of the suggestions resorts to previously introduced terms and items;
- some answer examples are provided, as well as their grammatical form, in order to clarify the purpose of the open questions and to provide a more sound text in the downstream nodes of the algorithm;
- the questioning procedure is rich in checks in order to verify the correctness of the user's inputs and to provide a feedback to the user about the outcome of the dialogue.

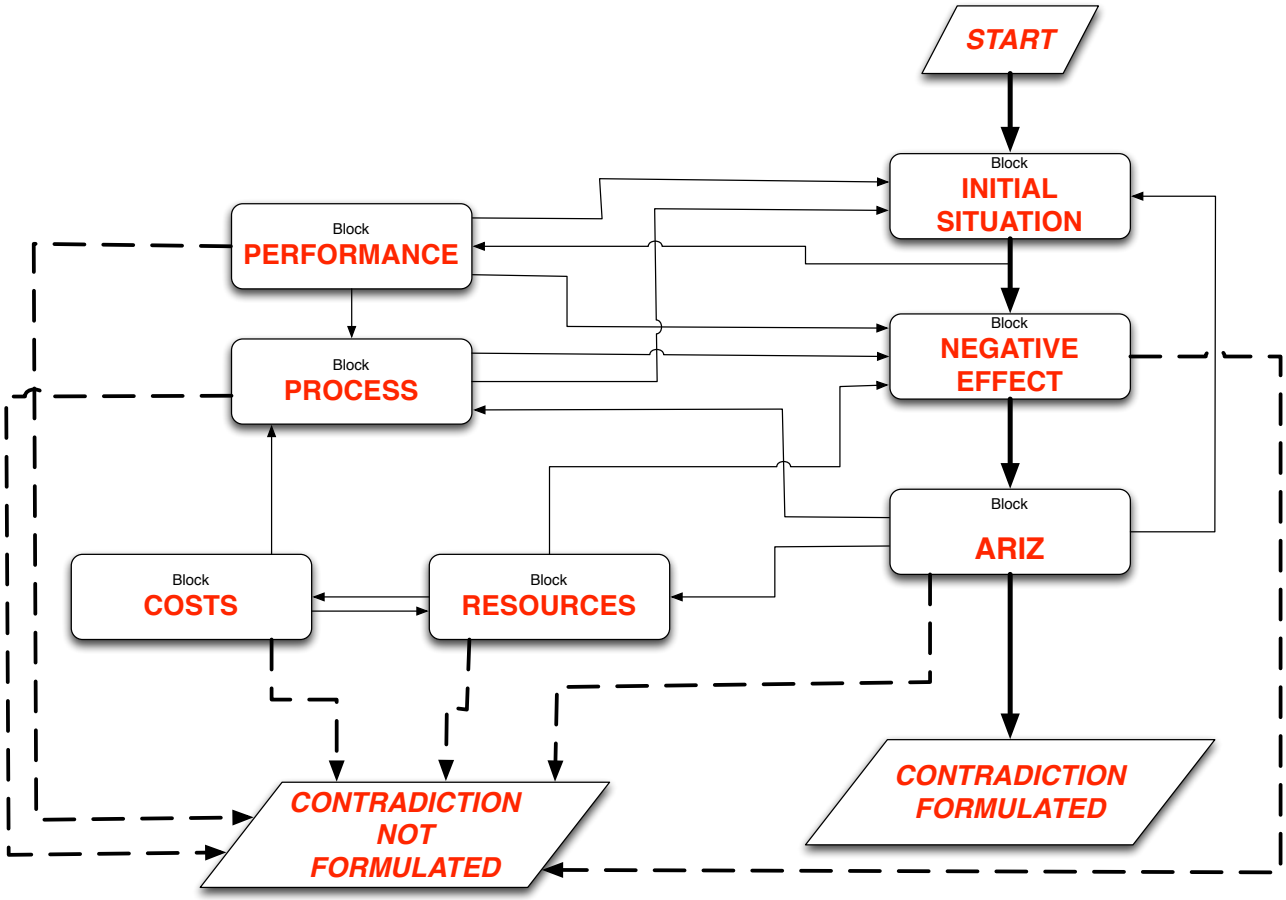


Figure 36: The overall model for exploring and eliciting the knowledge of the individual in order to carry out an effective and efficient problem solving process

With the objective of addressing the user towards the most proper description of the situation, the algorithm performs a preliminary distinction among tasks concerning the presence of negative effects or drawbacks, the required implementation of new useful functions and the enhancement of systems with relevant performances achieved at an unsatisfactory level. The individuation of an undesired effect should lead to the investigation of the features and the phenomena that provoke

it and subsequently to the formalization of a physical contradiction, grounded on a design variable leading to mismatching outputs according to the value it assumes.

However, even when the user does not address the formulation of the problem through the task concerning the elimination of a harmful output, several attempts are carried out with the aim of redefining the model of the system under investigation. The objective is to lead the user towards the formalization of a negative effect responsible for the unsatisfactory or missing functions and, eventually, towards the identification of a contradiction in terms of both requirements to be satisfied. The most straightforward path for formulating the contradiction, remarked in Figure 36 with thicker lines numbered 1, 2 and 3, involves the accomplishment of three logical blocks, intended to assess the initial situation (labelled as IS), entailing the description of the technical system through the specification of a wide set of features and correlations, with the aim of overcoming psychological inertia, by highlighting also more latent aspects, to define the arising undesired effect (NE) and to identify the conflicting requirements (AR).

However, further ways are foreseen to depict the problem, since several matters can hinder a thorough description of the system under investigation; moreover, a lack of knowledge might occur even within the field of expertise. In case of any circumstance hindering the definition of a contradiction, the algorithm is designed to investigate a wide set of features viable to constitute the core of elements and terms to suggest solution paths or to be sought in proper knowledge bases. The wide description, together with the reformulating attempts, is aided by other logical blocks of the questionnaire, inquiring the designer to analyse the circumstances that determine missing or just partially achieved functions (PE), to pinpoint the resources needed by the system to work correctly (RE), to focus on the reasons that imply high costs (CO), to investigate further problems arising during the manufacturing of products or the delivering of services (PR). Eventually, the cases that determine the absence of a contradiction in TRIZ terms, highlighted in Figure 36 with dotted lines, include the following:

- the user has not seized any possibility to modify the studied system, the phenomena that determine an unsatisfactory achievement of the values required to the Useful Function, or, worse, the perception of the missed objectives (line 4);
- the attempts to identify a parameter entailing conflicting requirements have failed (line 5);
- the user has not succeeded to individuate a proper characterization of the undesired effect in terms of required resources (line 6), high costs (line 7) or problems having reference to any stage of the system lifecycle, whose features are influenced by the design and manufacturing/delivering process (line 8); such characterization is viable, within the questioning procedure, to deepen the description of the system and consequently to re-formulate the problem;
- certain individuated criticalities are not considered worth to be further analysed (line 9). As explained above, especially in such cases, addressing the problem solving path and knowledge search within the industrial domain of the system to be designed is advised.

Moreover, in order to allow a wide testing activity, the algorithm has been implemented in a web platform available at the following URL http://www.smeinnovation.net. Thanks to this choice, each tester holds the possibility to extensively proof the dialogue based system and the analysers can observe the whole set of results, working on a single computer.

The so built web application, which has required a strong collaboration with experts in the field of computer programming that were partners of the OPEN-IT project and implemented it, allows one to reuse, in the formulation of downstream questions, the terms and concepts introduced by the users, thus providing a clearer explanation of the system's requests along the dialogue between the human and the computer. In the perspective of linking the TRIZ-based

problem solving procedure with a knowledge search, as for example proposed in (Cascini, 2007), a web application results the most convenient resource to speed up the information retrieval process.

A more detailed description of the logical blocks and their connections is provided in the following subsections.

3.3.1.1 The logical block initial situation (IS block)

The questioning procedure starts with this block, whereas a preliminary description of the initial situation is performed. The block (Figure 37) is aimed at defining at first the technical system to be analysed, its overall goal (meant as the motivation of its existence, the achievements and the outcomes of its use in terms of the desired modifications of a certain state/condition in the world (Vermaas, 2009)) and the main function it performs. The beneficiary of the system and the object subjected to the main function of the system are clarified. The designer is then asked to characterize the technical device under investigation following the hierarchical logic of the System Operator (Altshuller, 1984), as briefly mentioned in the section concerning the consumption of resources. Thus it is possible to delineate the most relevant components, the proper environment to perform the function, the operative conditions, in other words the entire context into which the technical systems under investigation is immersed. The user, in order to thoroughly describe the initial situation, is also required to delimitate the operative space and time involved when the function is delivered according to the logic of ARIZ. Subsequently the choice of determining the most proper task for the problem under investigation is carried out.

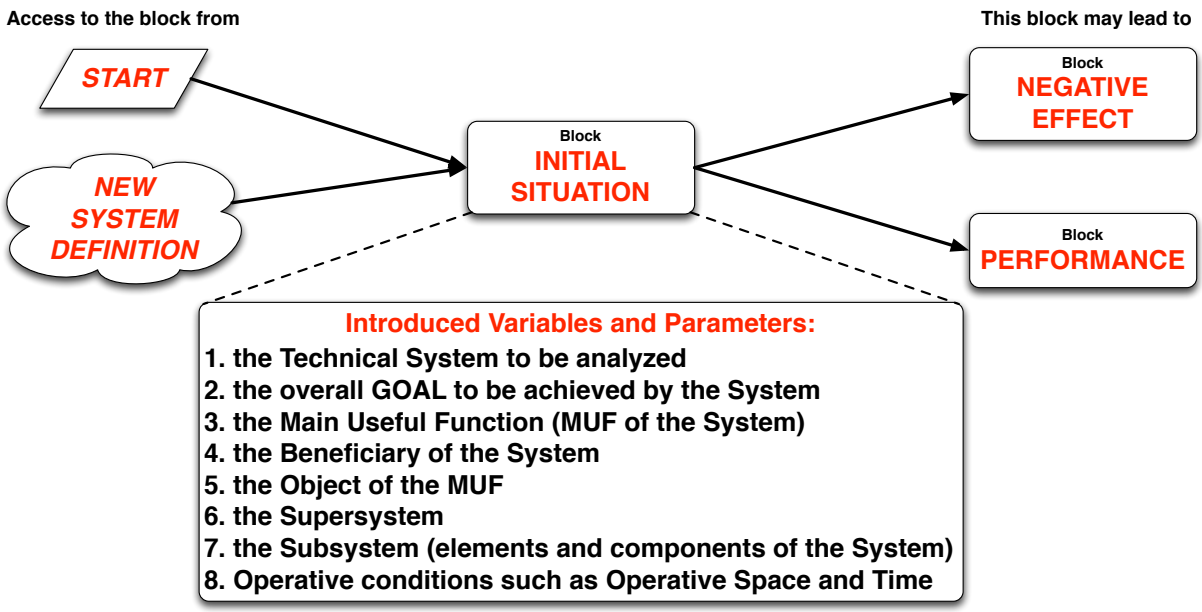


Figure 37: Logic of the Initial Situation block - variables and available paths for the analysis.

With reference to Figure 36, if the designer acknowledges missing functions or functional requirements partially achieved, he/she is addressed towards the block Performance (line 10), otherwise he/she is redirected to the block Negative Effect (line 1). Table A-1 in Appendix A illustrates the described logical block, including the text of the questions submitted to the users, the nodes that follow in the procedure, the variables that are introduced by the user. The identification of these parameters, highlighted in the last column, constitutes a first abstraction step according to the Hill model (Appendix E); the parameters are subsequently reused in the following questions, where they appear in the square brackets. Table 1, as well as those depicting

the other logical blocks, clarifies whether the single nodes require an open text answer (Assignment) or the choice between two different options (Decision). In the second case, the subsequent node depends on the provided answer. The Assignment steps without any requested variable represent communications to the user, mostly anticipating the concepts that will be subsequently required.

3.3.1.2 The logical block negative effect (NE block)

The block aims at investigating the undesired effect that arises in the system, as well as the negative consequences and impact. The user is required to indicate, besides the previous items, which element hinders the achievement of the Most Desirable Result (the fulfilment of requirements) by determining the appearance of the negative effect (Tongs model, Appendix E), the operative space and time of such harmful function, alike in ARIZ steps 2.1 and 2.2.

A further check is carried out in order to verify whether the element responsible for the undesired effect can be removed from the system without any particular consequence. The accomplishment of the NE block leads the user towards the set of questions that are meant to define the requirements of the solution through the overcoming of a contradiction (AR block, line 2 of Figure 36). The block is depicted in Table A-2 (Appendix A), according to the previously introduced formalism.

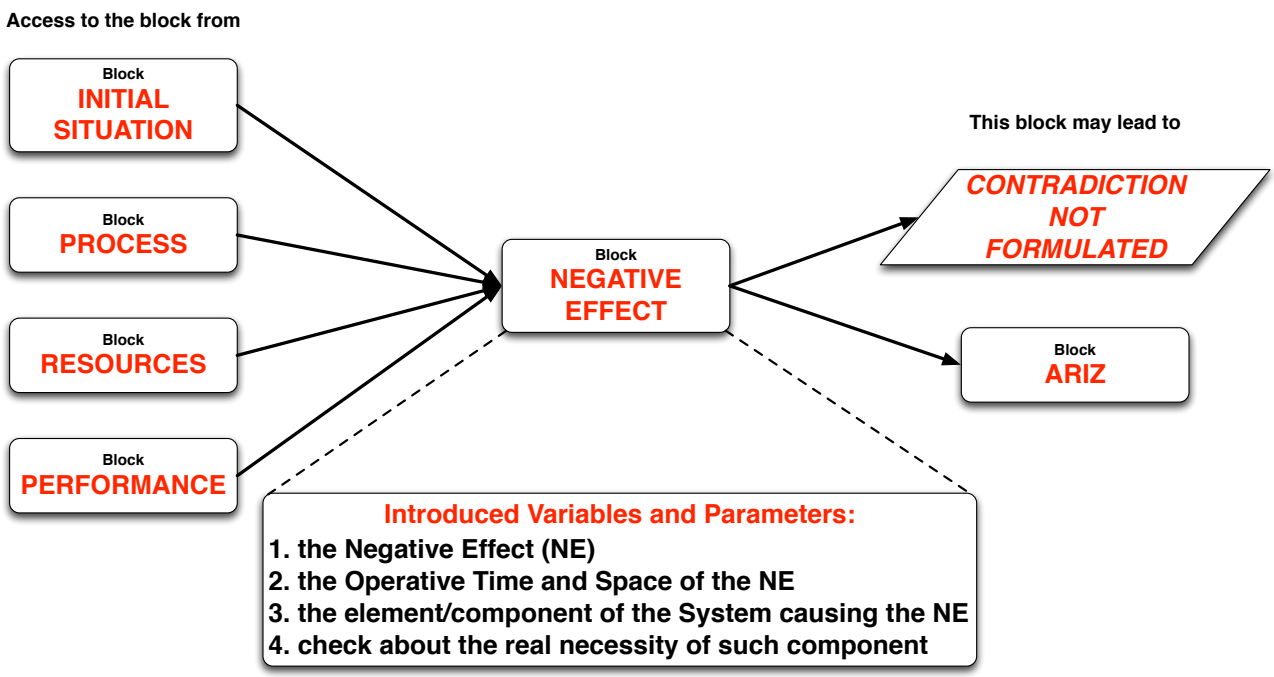


Figure 38: Graphical representation the Negative Effect logical block. On the left side blocks from which the analysis can be derived, the list of introduced variables within the questioning procedure. On the right, the two available path to which the Negative Effect block can lead.

3.3.1.3 The logical block contradiction (AR block)

The block (Table A-3, Appendix A) is supposed to allow the definition of a physical contradiction in TRIZ terms. This step represents the final point of the abstraction process, depicted by the top of the Hill model (Appendix X). The user is requested to focus on the parameters, concerning the previously identified element that influences the extent of the negative effect. The consequences of modifying the parameters, in the sense of reducing the impact of the negative effect, are evaluated up to revealing the decrease of a desired output.

The positive effect that is impaired by a modification of the chosen parameter, as well as its operative time and space, are properly defined along the logical block. The mismatching behaviours faced as a result of increasing/decreasing the chosen control parameter constitute the core formulation of the physical contradiction (Cavallucci, 2007) and (Savransky, 2000). The knowledge search holds therefore the purpose, analogously to ARIZ step 3.1, to individuate the opportunities of introducing an X-element, capable of removing the negative effect and providing the jeopardized benefits at the maximum extent, such as figured out by the Ideal Final Result (Altshuller, 1984), which means a design strategy to satisfactorily address both the conflicting requirements

With reference to Figure 36, if any parameter is individuated, whose variation (increase or decrease) provides just benefits without any drawback, the procedure suggests performing such a modification and to reformulate the problem, thus restarting from the initial IS block (line 11). In case of the impossibility to identify a control parameter leading to the physical contradiction, the algorithm guides the user towards a set of suggestion and a meta-block that supports a further characterization of the undesired effect, addressing subsequently the user towards a deeper investigation, carried out in the RE (line 12) or PR (line 13) blocks.

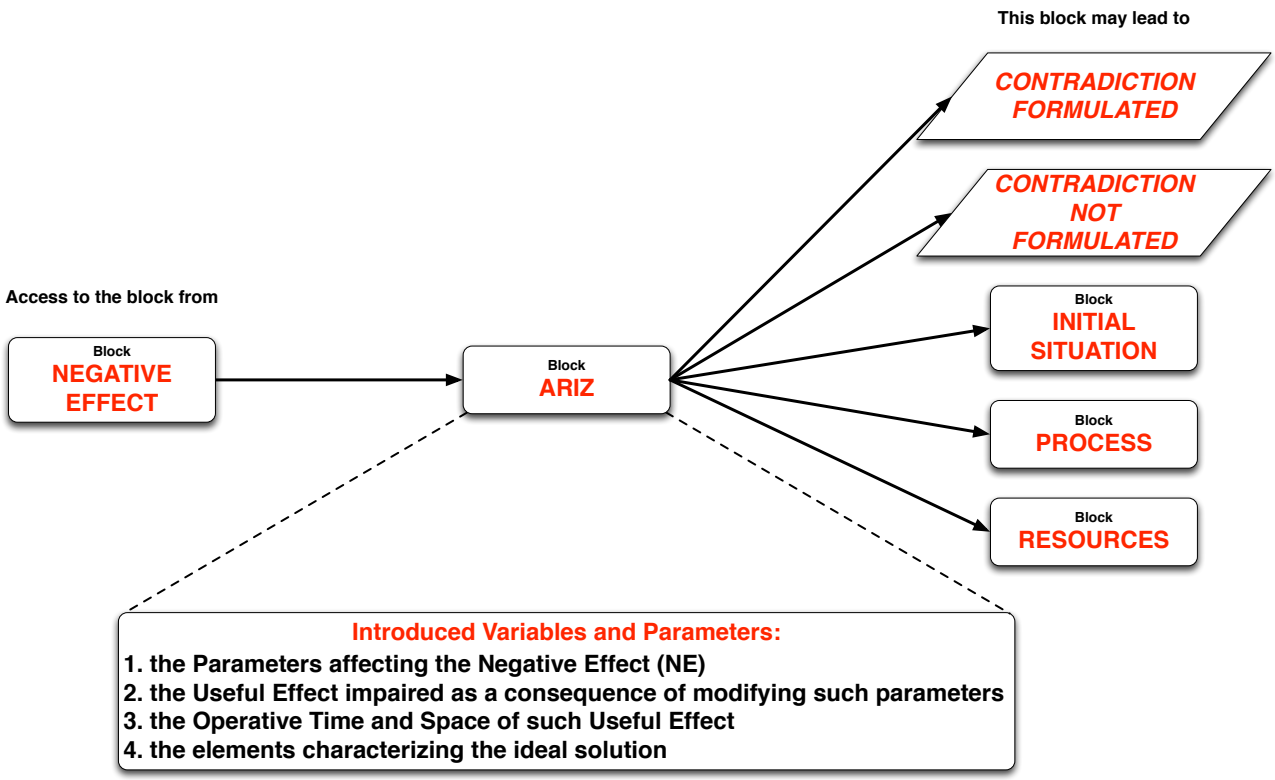


Figure 39: The logic underlying the block called ARIZ for identifying conflicts between couples of system requirements.

3.3.1.4 The logical block performance (PE block)

The block Performance (Table A-4, Appendix A) is addressed to reformulate the system under investigation or the undesired effect. It is accessed whenever the user recognizes any kind of underperformance of the system or the need for introducing a new function. At first it is required to define a performance to be enhanced or satisfied by the implementation of the new function and to explain the motivations for the increase of the performance itself. The user is then asked to individuate whom or what would perceive the benefits of the improvements, who or what does not allow the enhancements in the current technical system. With reference to Figure 36, if any of

the previously identified items is viable to be modified, the user is suggested to change the technical system under investigation, working on such object and consequently coming back to IS block (line 14). If the designer individuates that a modification of the production process should be carried out in order to perform the improvements, the algorithm directs the problem solving procedure towards the PR block (line 15). In the last option the designer is asked to formulate the negative effect of the system in terms of an unsatisfactory performance and consequently to follow the NE block (line 16).

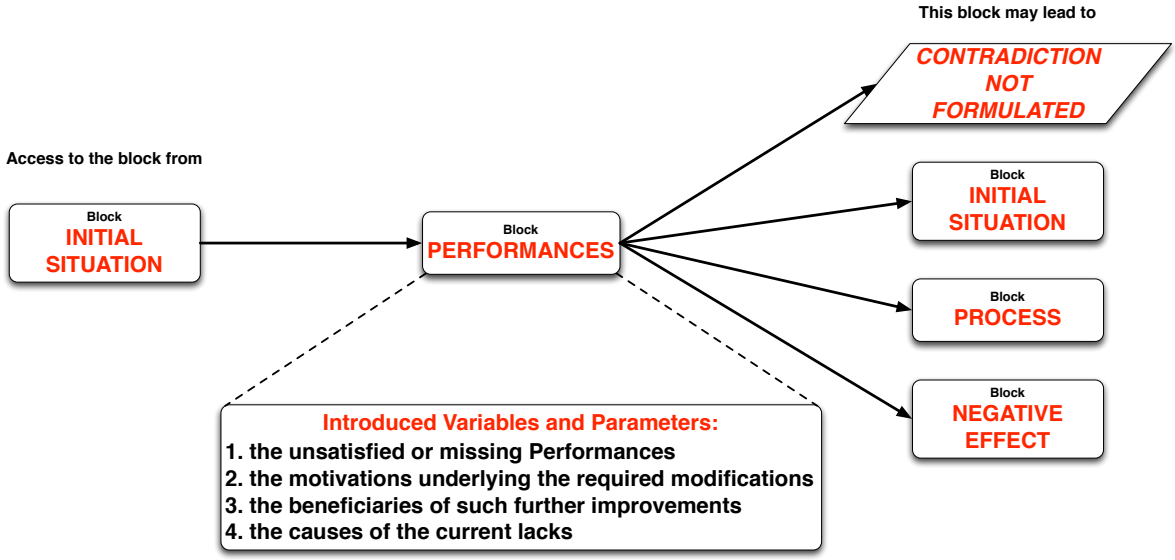


Figure 40: Graphical description of the logical block for the analysis of requirements concerning the delivery of Useful Functions at an unsatisfactory level.

3.3.1.5 The logical block resources (RE block)

In several cases, the excessive amount of resources spent by a technical system is considered just as an administrative drawback due to the fulfilment of certain product/service requirements. With reference to Figure 36, the block (Table A-5, Appendix A) is accessed when the user, failing to formulate the contradiction, assesses that relevant problems arise during the employment of the system. This logical block aims at investigating which resources the system needs for working correctly, classifying them in terms of space, time, information, material and energy, as a common framework of several researches within TRIZ (Vicent, 2006; Cascini, 2009).

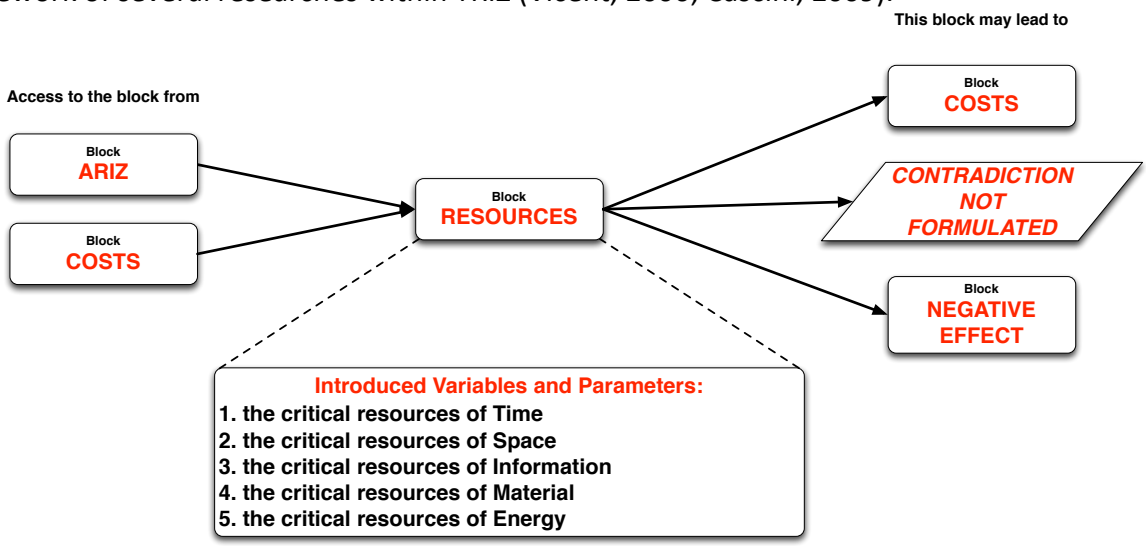


Figure 41: The logical block aims at determining the negative effects that potentially occurs because of an excessive use of resources.

In case the designer judges the direct costs as the most critical resources spent during the system's lifecycle, the algorithm guides him/her towards the CO block (line 17) for analysing the reasons for the high expenditures.

Among the amounts of resources spent the user is asked to determine which ones represent the most challenging criticalities and whether this issue can be assumed as the negative effect to be treated by the algorithm. In case of an affirmative answer, the user is redirected towards the NE block (line 18).

3.3.1.6 The logical block costs (CO block)

In TRIZ terms, costs are seen as quantities to be prevented having reference to the employment of resources or to inaccuracy of any product development stage (Domb, 2005). The logical block (Table A-6, Appendix A) is aimed at classifying what provokes high costs for the use, the production or the maintenance of the technical system. The resources provoking high costs, as a consequence of their excessive consumption, are clustered with the same criteria of the RE block. With reference to Figure 36, the questioning procedure directs the designer towards the RE block (line 19) if the costs concern the user of the system, whilst it guides towards the PR block (line 20) if the expenditures characterize the production process.

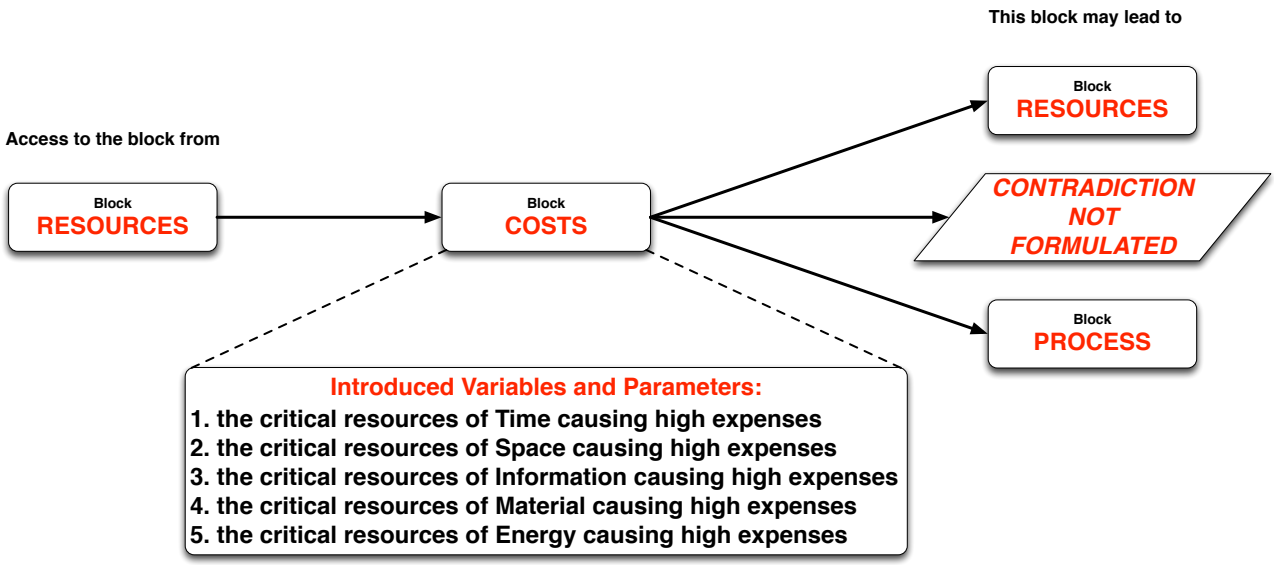


Figure 42: The block costs supports in defining the resources that determine excessive costs to be incurred.

3.3.1.7 The logical block process (PR block)

This logical block (Table A-7, Appendix X) concerns the investigation of further criticalities related to the manufacturing or delivering process.

The user is directed towards the block when the formulated undesired effect, which has not allowed the identification of a contra- diction, arises during the production process or characterizes the whole lifecycle of the system, as well as when unsatisfactory performances, flaws or high costs originate during the manufacturing stage. With reference to Figure 36, the scope of PR block is to reformulate the negative effect and the element that provokes it (line 21), downstream the individuation of the critical issues concerning the operations that are concerned with the production of the system. Since the focus of the investigation could be moved from the

product to the design, manufacturing and assembling phases, the questions let the user change even the system to be analysed (line 22).

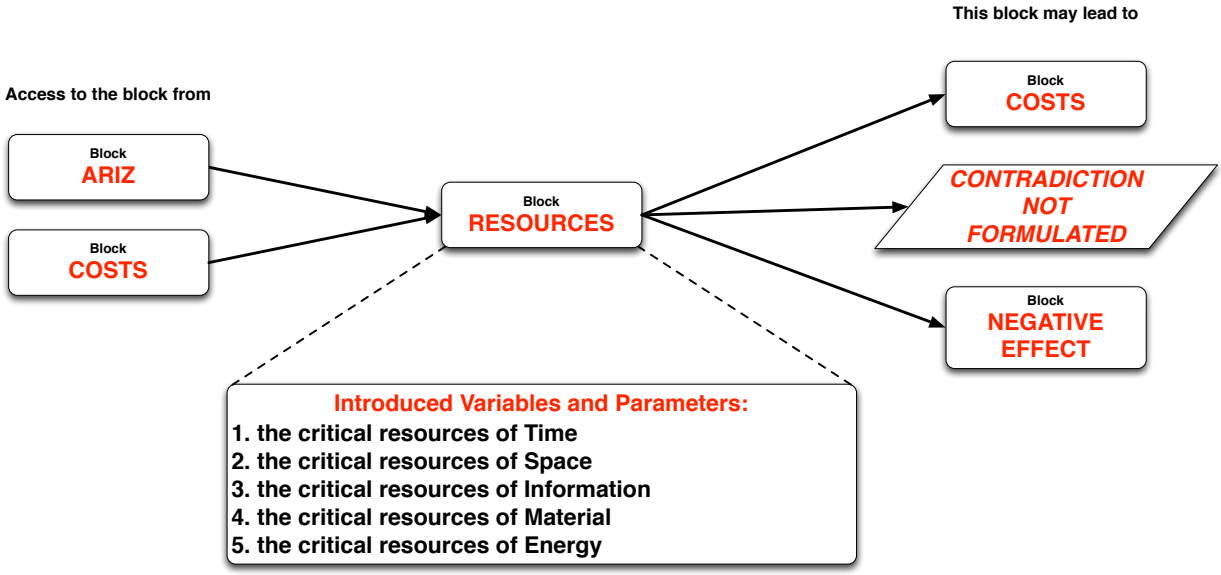


Figure 41: The logical block aims at determining the negative effects that potentially occurs because of an excessive use of resources.

3.3.1.8 Connection nodes

Table A-8 (Appendix A) summarizes a wide set of nodes, that do not belong to any logical block and that are mostly aimed at connecting them in a suitable way according to the user's answers. Several nodes attempt to guide the user towards the reformulation of the problem situation; others are addressed to investigate possible ways to modify the system under analysis. The described bundle of nodes includes the steps 144 and 145, labelled as ''Final'', that are addressed to connect the algorithm with different modules having different purposes.

3.3.2. Second release of the algorithm

After a first session of tests carried out to evaluate the effectiveness of the algorithm in supporting the analysis of inventive problems, several issue has emerged (Section 4.3.1). Indeed, the first version of the questioning procedure has showed considerable limitations in terms of the capability to widen the designer perspective, resulting in the overlooking of aspects relevant for the problem. The new version of the dialogue-based system integrates a further analysis module supporting at a greater extent the logic of the TRIZ System Operator. New tests discussed in Section 4.3.2 demonstrate that the modification allows improving the quality of the analyses, especially in terms of the identification of features to be advantageously redesigned in order to solve the problems.

The new block is aimed at widening the problem space representation in all the situations where successful analysis hasn't been performed. From a theoretical point of view, the System Operator can enhance this kind of investigation. The purpose of this thinking model is to replicate the way of reasoning of a creative personality. At the same time, if used as an instrument, it helps overcoming psychological inertia, since personal aptitude, background and environmental conditions make people focus just on a limited range of directions, rather than on an overall representation of the situation.

The System Operator is conventionally represented in 9 screens (a 3x3 matrix) ordered according to two axes: vertical and horizontal dimensions represent, respectively, the detail level according to a spatial perspective and the dynamics according to time evolution.

In details, a talented problem solver approaches a problem by considering the system and the object receiving its Main useful function, but also the relations among system parts (sub-systems), as well as its interactions with the external environment (super-system). Furthermore, each of these detail levels is considered according to a time perspective, meaning that they are examined in the time lapse in which the issue appears, but also in their past and future as well. It is worth noting that super-system/sub-system relationships and the past/future relationships are just relative concepts; in other terms, the representation of the System Operator as a nine-screen schema is just conventional, but its dimension should be arbitrarily considered extendible in any direction, as depicted in Figure 44.

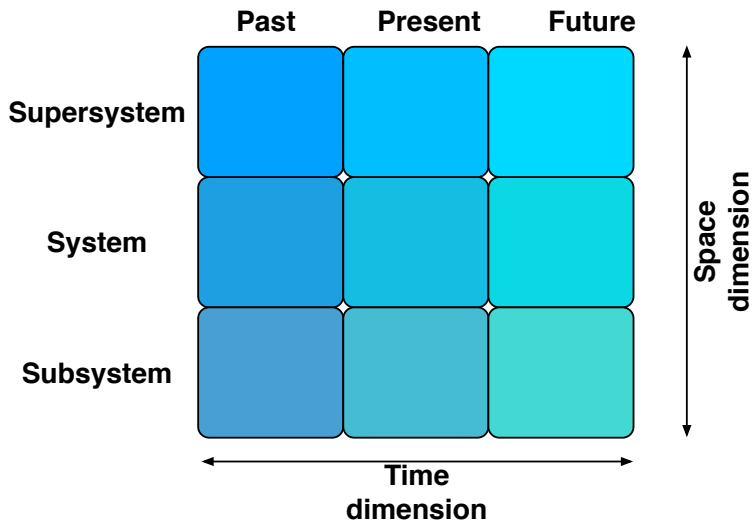


Figure 44: The System Operator or Multi-screen Schema

The new framework of the algorithm allows the user to deepen the analysis whenever the problem definition seems to be far from completeness, or even not correct. Therefore, its structure is slightly changed according to what is depicted in Figure 45 (The block ARIZ has been conveniently renamed into block "Contradiction", even if nodes in Table A-3 (Appendix A) are still characterized by the prefix AR).

The novel block embeds the logic of the System Operator: the essence of its logic is to bring the designer's thought in front of all the windows of the multi-screen schema:

- first to define available resources, characteristics or features available in the system, as well as in its parts or in its surroundings;
- second to identify, if possible, one of the above-mentioned characteristics as a means to solve the problem or to by-pass it.

The System Operator embedded into the procedure has a 3x3 matrix structure, since potential extensions in space and time dimensions can be considered as subsets of the main columns "Past"/"Future", as well as the main rows "Super-system"/"Sub-System".

The space dimension is examined starting from the System, then the sub-system and, at last, the super-system. The time perspective is taken into account by starting from the "Present" column in order to proficiently exploit all the answers the designer already provided during the former analysis. The boundaries of such time lapse are the beginning and the end of the main useful function delivered by the technical system under investigation.

Then, the Past column is examined before the Future column in order to favour preventive directions of solution rather than ones that just mitigate the undesired effects. It is worth to notice that the time axis of the System Operator has, in principle, several complementary meanings: it can be conceived as the time flow of a process (in this case the past column refers to

previous phases, while future column points to the following phases). Time can be associated also to cause-effect chains, such that past represents the root cause of a problem, the present illustrates the failure mode and the future the consequent negative effect. Eventually, the horizontal axis can be interpreted as evolutionary time, thus with different generations of the same system in adjacent columns. In this context, the first definition is chosen as the reference interpretation of the System Operator.

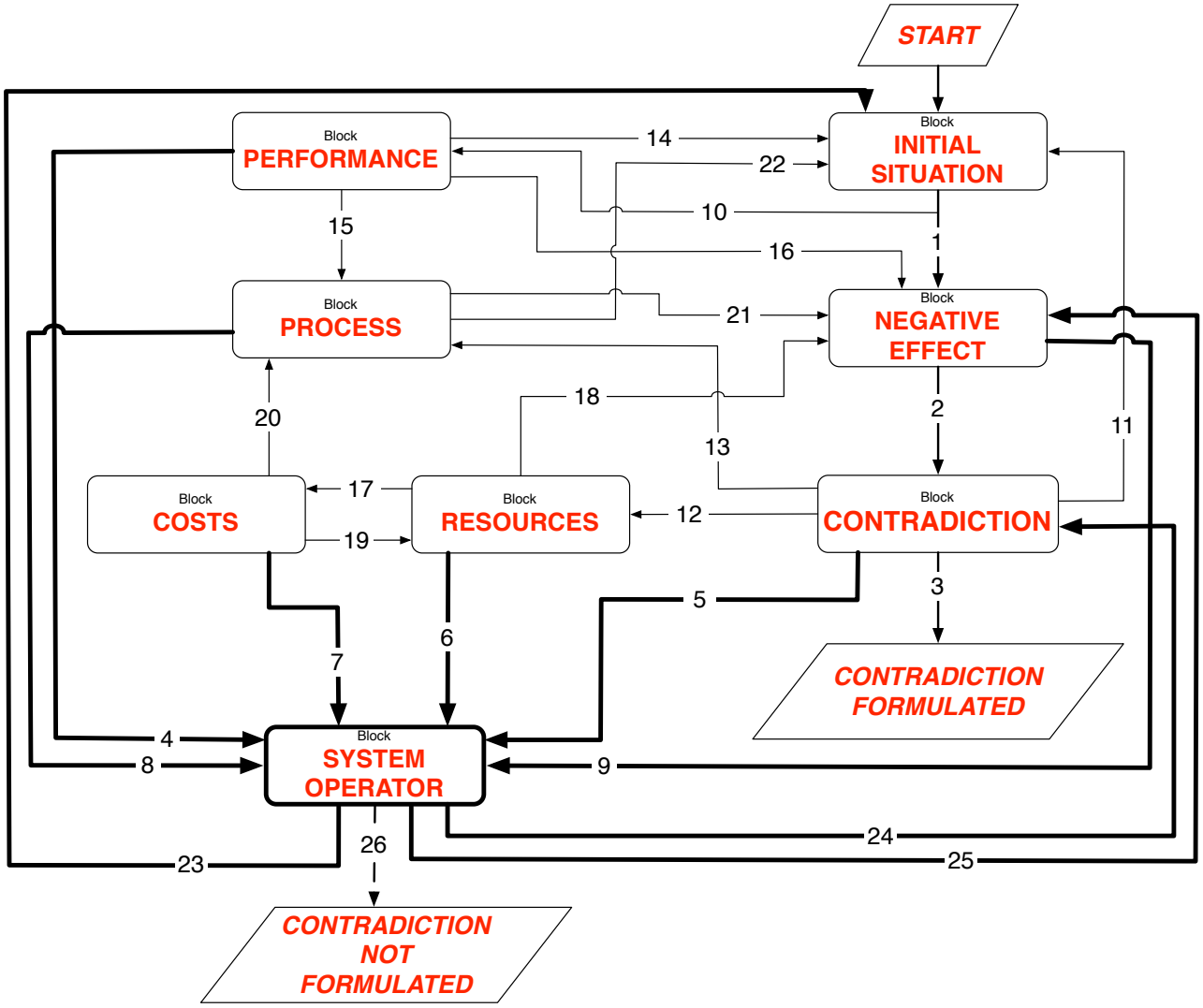


Figure 45: The new structure of the algorithm for inventive technical problem analysis, including the logical block based on the structure of the System Operator. Thicker lines represent new elements of the algorithm (paths and logical block)

In order to improve the efficiency of the problem analysis process, after the examination of each screen, the user has the faculty to skip the remaining part of System Operator investigation.

Indeed, when the designer perceives that one resource can be exploited to reformulate a problem or even solve it, it is possible to directly model the problematic situation according to OTSM-TRIZ by entering the Contradiction block (line 24) or to formulate a new problem from scratch (line 23) starting over with the analysis of the initial situation. However, at the end of System Operator exploration, some users may exit the block without a successful outcome (line 26), or continue the analysis by exploring the undesired effect; the algorithm suggests this option when such an investigation has not been previously carried out (line 25).

The new sequence of questions proposed by the algorithm is summarized in Table A-9, available in the Appendix A.

Also the new version of the algorithm has been tested and the results of such activity are presented in Section 4.3.2.

4. Application of the proposed methodological concepts and instruments.

This Section collects and discusses all the results obtained by both the application of the criteria for eliciting requirements and the algorithm for inventive problem analysis, as carried out by experts in both industrial and educational contexts.

It is organized into three sub-sections collecting testing activities according to both the instruments that have been used and the different contexts of the analysis, being they related to the definition of requirements for technologies concerning manufacturing processes or products. Each of the application here reported has a different extension, depending on the nature of the experiments at hand (qualitative and exploratory, or quantitative), the number of tester involved and the number of tests carried out by each of the tester. It follows that the tests carried out with a quantitative perspective and evaluated through statistical tools have a better reliability.

The first subsection collects three different testing activities. It starts presenting the adoption of criteria for requirement elicitation for the entire process aimed at manufacturing cabinets for domestic refrigerators. Such activity has been conducted together with the members of the from the Process Technology R&D team of Whirlpool Europe with an exploratory perspective aimed at understanding strengths and weaknesses of the proposed approach.

Moreover, a second testing activity carried out in industrial context is presented along this part. It aims at determining if the introduction of interviews carried out by a methodological facilitator allow system requirements to be retrieved with comparable outcomes in terms of largeness of the design specification and with better efficiency in terms of time required for the analysis. Such analysis has been carried out within the field of fluid-bed technologies with a spin-off of the Università of Tor Vergata (Rome, Italy). The last activity of this kind concerns, again, the analysis of a manufacturing process of interest for the Process Technology R&D team of Whirlpool Europe. In details, it concerns an ex-post definition of system requirements concerning the process for curing painting powders by means of photocatalytic IR panel, as an alternative to substitute conventional convection ovens.

The second subsection, indeed, concerns two different activities carried out to evaluate the capability of the criteria presented in Section 3.2 to support the definition of requirements for products. The first activity has been carried out with volunteers from the BS in Mechanical Engineering at the Politecnico di Milano and is aimed at evaluating the effects of the adoption of criteria on the design specification. The second one, on the contrary, is aimed at understanding the capability of the criteria to support the definition of new customer requirements. Such an activity has been conducted on the basis of data and information available from literature.

The third part, at last, describes the very intensive activity of testing the algorithm for supporting the analysis of inventive problems in technical contexts. Such part is further subdivided into two parts, each one concerning a specific release of the algorithm. In both cases tests have been carried out with volunteering students from the Università di Firenze and the Politecnico di Milano, being the algorithm also addressed to support designers with poor experience.

For each experimental activity, at the beginning, the objectives pointed out in Section 3.1 are introduced in order to clarify which is the purpose of testing and in which relation it is with the above mentioned objectives. Each section concerning the experimental activities, therefore, concludes with a brief discussion about the actual fulfilment of the objectives.

4.1 Description and evaluation of manufacturing technologies with criteria for eliciting technical requirements

This part of the Section aims at describing the experiments carried out on manufacturing technologies on real industrial test cases that seized the interests of Research and Development departments for innovation purposes. This part of the tests aims at evaluating the capabilities of the criteria described along Section 3.2 to be suitable for describing requirements about manufacturing Processes.

Moreover, according to the objectives set in Section 3.1, these tests also provide further insights about the capability of the criteria in easing the definition of the design specification with measurable characteristics (at least qualitative judgement by experts) and collecting a wide number of requirements, regardless of the specific technology under investigation.

4.1.1 Exploratory and qualitative analysis of the general capabilities of the criteria in the elicitation of knowledge from experts

The first application of the criteria, for what concerns manufacturing processes, has been carried out with the support of the expert of Whirlpool Europe on a test case concerning the production of insulated cabinets for domestic refrigerators.

This is the first test that has been ever conducted by exploiting the support of the criteria; therefore it focuses on a preliminary general and qualitative assessment about their capabilities to really describe the various facets concerning the requirements of a technological manufacturing technology.

Such an exploration devotes particularly attention to the capabilities of the criteria to obtain widely populated design specifications regardless of the technology at hand. To this purpose this kind of preliminary test has been conducted on a manufacturing process involving a large number of different technologies aiming at carrying out radically different functions.

Moreover it is interesting to also measure the efforts required by experts in identifying appropriate requirements in a measurable and non-redundant way.

4.1.1.1 Description of the test

To the purpose of exploring the capabilities of the criteria and to also produce industrial benefits for the company that participated the test, such a preliminary estimation has been carried out by means of a two-step evaluation.

First, it is necessary to define the set of requirements according to the description of the criteria. The interpretation of their meaning is not assisted by a methodological facilitator, except for what concerns the first application among the different technologies involved in the project. For this analysis an appropriate decomposition of the process in elementary phases is necessary.

Second, the assignment of qualitative judgements enables the degree of satisfaction of requirements to be determined according to an ordinal scale. The assessment of the degree of satisfaction or dissatisfaction related to each technology involved in the manufacturing process under analysis has been carried out by assuming a reference scale compatible with the accuracy and the completeness of the available information.

A panel of experts, variably composed by two or three people, has carried out the test as a roundtable discussion.

Nevertheless, since the Process Technology R&D department of Whirlpool Europe intended to run the same kind of investigation also on competing technologies that they do not yet

implement within their manufacturing process, so as to compare their potential with the ones currently adopted, it has been proposed to carry out an analysis at qualitative and exploratory level. This is mainly due to the practical impossibility to determine the appropriate and quantitative level of satisfaction for new technologies that have not been already examined by experimental data. Therefore, it is suggested to adopt the following criteria.

The degree of satisfaction/fulfilment for the requirements concerning the delivery of Useful Functions has been assessed through a range of values from 0 to 3 where:

- 0 means that the requirement is not satisfied at all;
- 1 means that the requirement is poorly satisfied;
- 2 means that the requirement is quite well satisfied;
- 3 means that the requirement is completely satisfied.

The seriousness of the requirements pertaining to the effects of a Harmful Function can be assessed using a range of values from 0 to 3, where:

- 3 means that the Harmful Function or its effects are not critical;
- 2 means that the Harmful Function or its effects are poorly critical;
- 1 means that the Harmful Function or its effects are critical;
- 0 means that the Harmful Function or its effects are heavily critical for the product/phase/process.

The amount of resources that the process phase under analysis requires in order to deliver the Main Useful Function and all the related auxiliary functions, can be assessed using a range of values from 0 to 3, where:

- 3 means that the resource is not consumed during the process phase;
- 2 means that the process phase requires small resources of that type;
- 1 means that the process phase requires a significant amount of that type of resource;
- 0 means that the resource is heavily used during that process phase.

Through these uniform scale of judgement it is possible to run this assessment on different technologies and provide useful elements of knowledge to decision makers for highlighting the need to start searching candidates for technology substitution.

Moreover, in those cases where the Process Technology R&D department of Whirlpool Europe has the chance to suggest directions of improvement to technology suppliers, such evaluation allow to point out which are the main criticalities within the domain of a single technology for a specific function. Indeed, such assessments collect the most relevant information about single technologies, but technicians and experts may easily compare their outcomes by means of homogeneous requirements, as clearly described in Section 2.4.3.

4.1.1.2 Application of the criteria to the technologies involved in the process of foaming for domestic refrigerators

Foaming of domestic refrigerators is a manufacturing process that requires several steps in order to produce a cabinet with the desired characteristics of thermal insulation. According to the modelling procedure described in Appendix D, the industrial process is composed by the following functional phases:

- Corona Treatment on a polystyrene sheet to improve the surface tension/energy of the sheet itself.
- Moulding of the refrigerator cellar by means of a device that changes the shape of the polystyrene sheet.
- Cutting of some parts of the cellar in order to refine its shape and make it suitable for the assembly.

- Workers assemble refrigerator outer sides together with the rear wall in Coroplast. This assembly gets joined together with the polystyrene cellar in order to produce the cabinet of the refrigerator.
- Pre-heating of the cabinet of the refrigerator;
- Placement into a metal structure that provides mechanical resistance to deformation due to polyurethane expansion.
- Mixing of the diisocyanate (MDI: Methylene diphenyl diisocyanate) and the pre-mixed blend of the polyol with the blowing agent
- Injection of the mixture, not yet expanded, inside the cavity of the cabinet
- Expansion of the mixture inside the cabinet by means of the evaporation of the blowing agent Polyurethane polymerization with small closed cells having the desired characteristics in terms of density and dimensions in order to provide the desired thermal insulation.

The overall EMS model describing the result of the whole manufacturing process is shown in Figure 46. Energy flows are not represented since the EMS model, according to the rules discussed in (Cascini, 2008) and presented in Appendix D, should just embed desired flows, considering real flows just at the behavioural level.

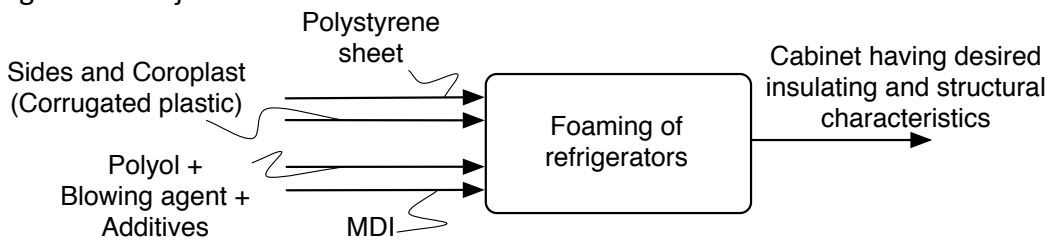


Figure 46: The EMS model describing the ideal transformation required to produce the cabinet of a refrigerator with thermal insulation properties

All the abovementioned phases (Figure 47) have been examined and assessed according to the criteria proposed in Section 3.2, by defining a proper set of requirements.

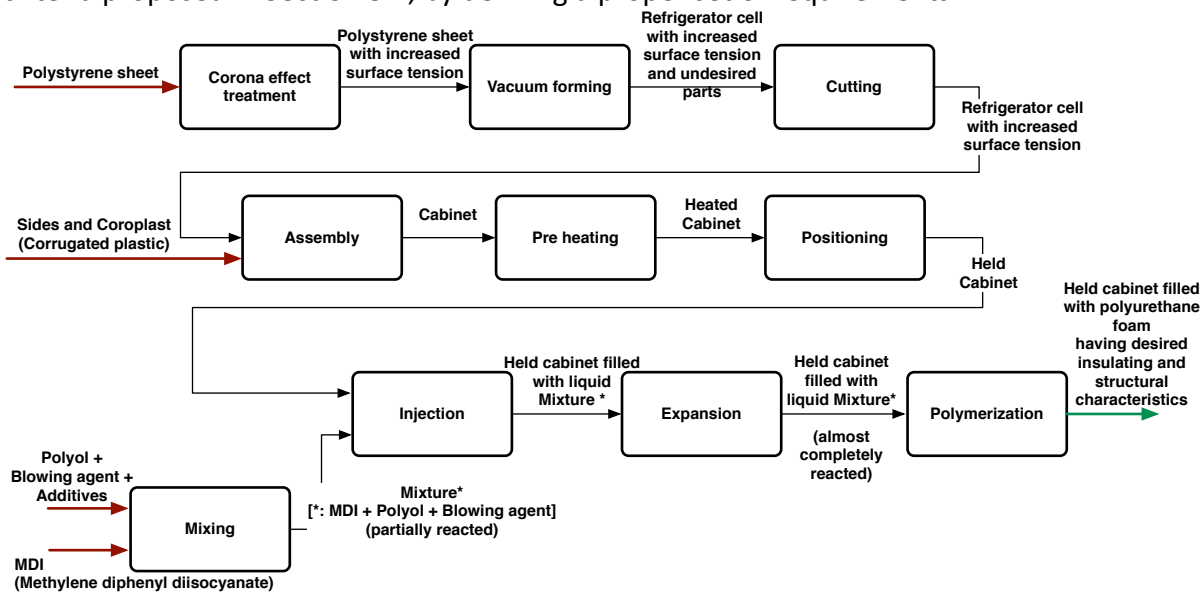


Figure 47: EMS model for the whole manufacturing process. Red arrows - incoming flows describing the objects to be transformed during the process. Green arrow - outgoing flow representing the product obtained at the end of the process.

Due to confidentiality issues, it is possible to just describe the assessment of the pre-heating phase by adding brief examples of specific requirements for each criterion.

This technology is aimed at increasing the temperature of the cabinet and it is delivered by means of convection ovens. Whirlpool Europe uses ohmic heater in order to convert electrical energy into heat. Such heat is diffused more efficiently inside the oven cavity by means of a forced airflow in order to increase heat transfer, thus reducing the time required to deliver this phase. Figure 47 collects all the models required by the steps of the procedure described in Appendix D.

Figure 47 also clarifies the required transformation from Object/Input flow (assembled cabinet) to Product/Output flow (Heated assembled cabinet). To this end, it is worth to mention that the requirements concerning the delivery of the Useful Function have been examined considering how the function "Heating" carried out in this way is capable to achieve the desired characteristics. Requirements concerning the presence of Harmful Functions and the Consumptions of Resources have been identified and assessed by taking into account the specific Behaviour of the Function, then considering the two Minimal Technical System models presented in Figure 48.

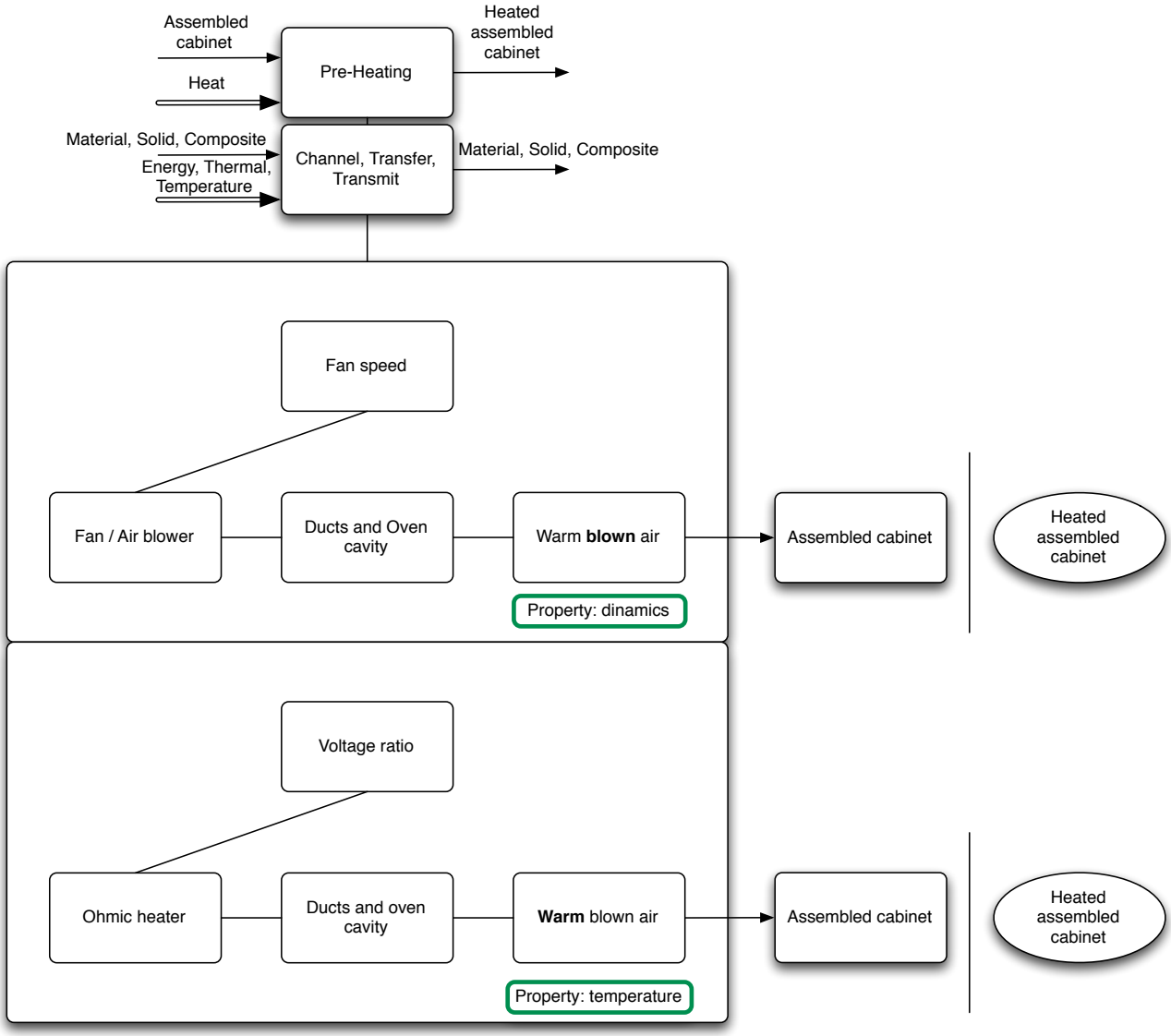


Figure 47: The Minimal Technical Systems models concerning the description of the Behaviour through which the Function of Heating is carried out by Convection Ovens.

The following list summarizes the set of EPs together with their degree of satisfaction according to the metrics of judgment proposed above. In the cases where the satisfaction assessment was not relevant to this case study, it is explicitly reported in the list.

Requirements concerning the delivery of Useful Functions

- Threshold achievement
  - *Quantity of flow*: - Number of cabinet per hour (2);
  - *Quality of flow:* - Temperature of the heated cabinet (2);
- Adaptability
  - *Versatility:* - Capability to treat different cabinet models (2);
  - *Robustness:* - Capability to produce uniform results (2);
- Sensitivity to external perturbations
  - *Quantity of flow:* - Outer temperature effects on the number of cabinet treated in a hour (2);
  - *Quality of flow:* - Capability to keep the value of temperature one achieved (2);
- Controllability
  - *Quantity of flow:* - Capability to treat more than a cabinet at a time (0);
  - *Quality of flow:* - Capability to set different temperature for heating (1).

Requirements concerning the presence of Harmful Functions

- Technical System against the Object/Product
  - *Object integrity*: - Capability to keep the cabinet shape without deformations (3);
  - *Product Wastes*: - *not applicable ➔ (3);*
- Environment against the Object/Product
  - *Sensitivity to critical external conditions: - not applicable ➔ (3);*
- Object against the Technical System
  - *Mechanical Resistance: - not applicable ➔(3);*
  - *Wear resistance:* - Wear of joints in inlet/outlet ports (3);
- Technical System against itself
  - *Reliability:* - Capability to keep warm blown air inside the oven cavity without losses (3);
  - *Expected life of the system:* - As is (3);
- Environment against the Technical System
  - *Corrosion resistance: - not applicable ➔ (3);*
  - *Resistance to critical external conditions: - not applicable ➔ (3);*
- Technical System against the environment
  - *Noise production:* - Noise produced by hair blowers (2)
  - *Environment pollution: - not applicable* ➔ (3)
  - *Heat discharged towards the environment:* - Heat discharged in the production site (2);
  - *Comfort and ergonomics:* - Degree of automation/user involvement (3);
  - *User safety:* - Safety of the workers that follow the cabinet on the production line (3);
- Object/Product against the Environment
  - *Pollution of product wastes: not applicable* ➔ (3).

Requirements concerning the Consumption of Resources

- Space resources
  - *Accessibility for workers (3);*
  - *Room required by the whole heating device (1);*
  - *Storability (not applicable ➔ 3);*
  - *Room required for the installation of the heating device (2);*
  - *Room required for the dismantling of the heating device (2);*
- Time resources
  - *Time required to heat a single cabinet (0);*
  - *Time for maintenance/failure fixing (2)*
  - *Number of heating processes required to achieve the desired temperature (2);*
  - *Time for assembly of the heating device (3);*
  - *Time for dismantling of the heating device (3);*
  - *Availability of the heating device including warm-up time (2);*
- Information resources
  - *User awareness to make the device work (3);*
  - *Competence of the maintainers for fixing the device, when necessary (2);*
  - *Ease of use of he heating device (2);*
  - *Ease of installation of the heating device (2);*
  - *Ease of disassembly of the heating device (2);*
  - *Ease of upgradability of the heating device (2);*
  - *Variety of parts composing the heating device (2);*
- Material Resources
  - *Capability to move the device in different zones of the production site (1)*;
  - *Required consumable/disposable material (not applicable➔3);*
  - *Reusability of items of the heating device (0);*
  - *Independence from other products: not applicable ➔ (3);*
  - *Recyclability/Reusability of the heating device (1);*
- Energy Resources
  - *Number of workers involved in the heating phase (3);*
  - *Energy/power required for working of the heating device (0);*
  - *Dependency on electric energy by the heating device (0);*
  - *Number of energy transformation carried out by the heating device in order to produce a heated cabinet (2);*
  - *Ratio between the energy transferred to the cabinet and the whole amount of the energy required for heating (1).*

4.1.1.3 Discussion of the results

This first testing activity has been led so as to elicit the knowledge of experts employed by Whirlpool Europe and working in the field of manufacturing cabinets for domestic refrigerator.
The elicitation method has included a facilitator just for one out of the ten diverse technologies included in the whole manufacturing process. Experts have carried out the remaining part of the elicitation autonomously, including the examination of the “Pre heating” phase, just through the interpretation of the written criteria.

For the process phase illustrated as an example in this paragraph, it appears evident that the criteria allow a certain number of system requirements to be identified, having different relevance (non relevant ones have been neglected) within the process:

- 8 requirements concern the performances of the technical systems in terms of capability to carry out the main Useful Function;
- 8 requirements for the potential presence of Harmful Functions and their effects; and
- 25 requirements about the needed Resources within the lifecycle of the device for carrying out the process phase.

All these system requirements were identified as relevant (or potentially relevant) for the objectives of process innovation undertaken by Whirlpool Europe, thus demonstrating a certain capability in carrying out at least qualitative measures based on judgements, thus addressing the objective concerning *validity* of the design specification. For what concerns *conciseness,* it is important noticing that such judgements enable the selection of relevant requirements so as to correctly populate the design specification with everything but the unuseful.

For what concerns the issue of *completeness*, interpreted as the capability to populate at the maximum extent the design specification, experts' opinion has been investigated. The discussion held with Whirlpool's experts about the efficiency end the effectiveness of the criteria highlighted that about 30% of the elicited requirements emerged exclusively by means of the explicit questions associated to the proposed list of reference criteria, while the company's experts were not typically considering them in technological analysis or evaluation.

Extending the consideration to the ten different phases involved in the manufacturing process for cabinet foaming, it is possible to note that an average number of about 40 requirements have been identified for each of the investigated technologies, thus demonstrating a good *repeatability* of outcomes.

For what concerns *non-redundancy,* experts identified requirements without producing overlapping concepts such as the ones that potentially originates from the different perspectives on functions, demonstrating that such criteria allow the different facets involved in the innovation process to be distinguished with no ambiguity. Moreover, in none of the above cases a requirement that have been taken into account by the experts before the elicitation couldn't be classified according to the proposed classification, thus demonstrating a complete capability of covering the range of requirements that may emerge as the result of the elicitation.

From the viewpoint of the *ease of use*, the application conducted in Whirlpool Europe showed that a mean of three to four working hours are necessary to carry out a complete analysis pertaining to each phase included in the process, both because of difficulty in the interpretation of the criteria and of the need of searching knowledge from external sources to introduce meaningful values for judgement. According to this last consideration new approaches for the elicitation should be introduced in order to reduce the time required for the analysis and improve the usability of the criteria. Such issue have been investigated during the next testing activity.

4.1.2 Investigation about the potential of interviews for easing the elicitation of requirements from experts

This activity has been carried out with the collaboration of technical experts from the Università di Roma Tor Vergata, in the context of a project into which the PhD candidate was not directly involved. Nevertheless, the definition of system requirements represented a necessary starting point for that project and therefore it has been taken as a good chance to verify if interviews carried out by a methodological facilitator could improve the contextualization of the criteria and reduce the time required for completing the analysis. The activity of elicitation, differently from the one described in Section 4.1.1, concerns one technology having three different applications, each one characterized by different transformations between the Object and Product. In details the fluid bed technology represent the core of the investigation. The domain of application ranges

from the curing/coating of surfaces, through the polishing of metallic surfaces, to the cleaning of components presenting some oily residuals.

4.1.2.1 Description of the test

This activity aims at determining to which extent the introduction of face-to-face interviews can help the effectiveness and the efficiency in using the criteria described in Section 3.2.

The former has to be evaluated in terms of capabilities of the criteria to enlarge the set of requirements considered as relevant for the development of new technical solutions in the field of fluid-bed technologies. The latter, indeed, has to be estimated in terms of the ratio between the obtained results and the efforts necessary to achieve such a goal.

It is worth mentioning that the estimation concerning the efforts also depends on the individual knowledge about a specific topic; however, this issue has been disregarded by considering all the experts involved in the diverse analysis of Section 4.1 as people holding a very good experience in the field they wanted to investigate with greater details.

A panel of two experts has carried out the test in a roundtable conversation including, as said, the facilitator. To verify the abovementioned objective, the test has been organized according to a two-step method:

- Autonomous description of the requirements for a specific application by the experts without any kind of support (no interview)
- Interview carried out by the methodological facilitator with the purpose of investigating the requirements that have not been previously considered by the experts so as to verify their potential relevance.

At the end of the activity it is planned to make a comparison between the results obtained by the experts by themselves and the ones obtained through the use of criteria. In details, it is planned to compare the number of requirements elicited in both the steps, in order to verify if some residual knowledge not verbalized by the experts can be still elicited and also the time spent in carrying out the two different steps.

Moreover, it is also planned to compare the time required by this kind of analysis to the one carried out in Section 4.1.1, in order to better understand if the presence of a methodological facilitator can improve the efficiency of the whole process.

4.1.2.2 Application of the criteria to the Fluid Bed Technologies

As mentioned above, the test has been carried out in the domain of fluid bed technology. In details, three different applications (functions) have been considered according to the current potential of these devices (neglecting, because of expertise issues, the adoption of fluid bed technologies in the field of pyrolysis and other method for energy production).

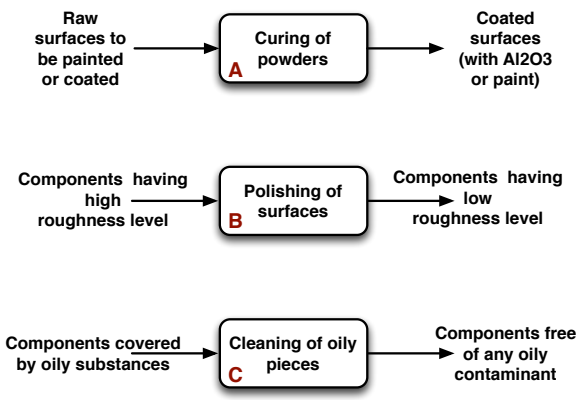


Figure 48: The Energy-Material-Signal models characterizing the three different functions addressed with the fluid bed technology.

The three EMS models characterizing the functions are presented in Figure 48.

Interviews could not be recorded and also the information here presented is collected without accurate descriptions, because of confidentiality issues. Nevertheless brief description of the way the tree applications carry out the functions ins provided in order to better understand the meaning of the elicited requirements.

With reference to Figure 48, the three technologies have been analysed one by one, starting from Technology A: Curing of powders in a fluidized bed. Such application is carried out to both paint metallic surfaces and to coat them with Alumina (Al_2O_3). It follows that different powders are necessary to paint or coat. Such process is carried out also by electrically charging the components to be treated as well as air and powders composing the fluid bed.

The expert presented the technology by specifying the requirements that they consider for developing devices capable to obtain significant technological advantages in comparison to less evolved products using the same technology. This description took about 15 minutes during which they also have described the general principles that drive this kind of application, however such a description were substantially integrated with the identification of main drivers for technological development. The requirements elicited during this step are collected in Table 1 and classified according to the relevant classes (UF = Useful Functions, HF = Harmful Functions, RES = Resources consumptions).

Table 1: Requirements for Technology A described by experts without any support for elicitation

ID	***System Requirements***	***Main class***	***Sub-class***
1	Thickness of paint	UF	Threshold Achievement - Quality
2	Uniform distribution of paint	UF	Controllability (Quality)
3	Integrity of material to be painted	HF	System vs. Object
4	Recovery of non-used paint	HF	System vs. System
5	Use of solvents	HF	System vs. Environment
6	Amount of energy to heat metal	RES	Energy
7	Amount of painting powder	RES	Material
8	Amount of air	RES	Material
9	Amount of energy to move air and powder	RES	Energy
10	Voltage level of air	RES	Energy
11	Amount of energy to electrically charge air	RES	Energy
12	Material required for air electrification	RES	Material
13	Electric charge of the material to be painted	RES	Energy

After their description, the criteria for eliciting requirements have been reviewed systematically by the methodological facilitator that skipped already treated arguments and asked contextualized questions in order to understand if some other requirement could have played a relevant role in the development of new technological solutions for this application. It is worth noticing that the questions somehow stimulated the interviewed experts that started taking into account new requirements, without following necessarily the sequential logic presented in Section 3.2. The interview lasted about 30 minutes during which requirements have been also systematically classified. After the interview, the list of requirements has been updated according to the new requirements collected in Table 2.

Table 2: Requirements for Technology A elicited through the support of criteria.

ID	***System Requirements***	***Main class***	***Sub-class***
14	Productivity	UF	Thres. Achiev. - Quantity
15	Selective distribution of paint	UF	Controllability (Quality)
16	Sensitivity to humidity level (powder packing)	UF	Sensitivity
17	Capability to obtain uniform results with different shapes of the object to be painted	UF	Versatility (Quality)
18	Roughness of the painted layer	UF	Thres. Achiev. - Quality
19	Porosity of the alumina coating layer	UF	Thres. Achiev. - Quality
20	Range of available colours	UF	Controllability (Quality)
21	Thickness of the alumina coating layer	UF	Thres. Achiev. - Quality
22	Dirtiness of the painting tub with powders	HF	System vs. System
23	Filters dirtiness	HF	System vs. System
24	Environmental pollution	HF	System vs. Environment
25	Capability to view inside the painting tub	HF	System vs. Environment
26	Dirtiness of the element holding the piece to be painted	HF	System vs. System
27	Ratio of coverage by the holder on the piece to be painted	HF	System vs. Object
28	Noise produced	HF	System vs. Environment
29	Separation of painting from the painted component	HF	Object vs. Environment
30	Wear of the tub for fluid bed (in alumina coating)	HF	System vs. System
31	Electrical conductivity of the holding component	RES	Energy
32	Physical contact between the piece to be painted and the holding element	RES	Material
33	Thermal capacity of the object to be painted	RES	Energy
34	Time required to heat up powders in hot dipping context	RES	Time
35	Characteristic of compressed air (pre-compressed or on-the-fly)	RES	Energy
36	Chemical (electrical) affinity between painting powder and object to be painted	RES	Material
37	Time for coating with powders	RES	Time
38	Time for cleaning	RES	Time
39	Amount of info needed to start-up the fluid bed	RES	Information
40	Amount of info to drive an already booted system	RES	Information
41	Curing time of painting powders	RES	Time
42	Amount of energy required by the heater	RES	Energy
43	Need of a oven heater for curing	RES	Material/Space
44	Position of the blower within the tub	RES	Space
45	Energy transformation to electrically charge powders	RES	Energy

Summarizing the results for Technology A, 13 requirements have been determined by the experts without any support in about 15 minutes. After interviewing the experts for about 30 minutes, 32 new requirements have been highlighted as relevant at various extents.

The same logic has been also followed to capture requirements for what concerns technology B. Such an application uses the impacts of fluidized particles having particular mechanical characteristics. The impact of such particles reduces the roughness of metallic surfaces that get polished that way. It is worth noticing that this kind of technology is not suitable for all the different kind of metallic material and produces good results with relatively hard materials.

The first part of the discussion was conducted by experts without any kind of support for eliciting requirements. At the end of the presentation, which lasted about 45 minutes, the requirements have been collected as for what present Table 3.

Table 3: Requirements for Technology B described by experts without any support for elicitation

ID	***Evaluation Parameter***	***Main class***	***Sub-class***
1	Adaptability according to the shape of the object to be treated	UF	Adaptability - Versatility
2	Adaptability according to the roughness of the object to be treated	UF	Adaptability - Versatility
3	Target value of roughness	UF	Thresh. Achiev. - Quality
4	Controllability of superficial roughness	UF	Controllability - Quality
5	Integrity of surfaces to be treated (colour deposition)	HF	System vs. Object
6	Room required by the rotating drum	RES	Space
7	Amount of material required to polish objects	RES	Material
8	Abrasiveness capability of the polishing material	RES	Material
9	Time required for roughing	RES	Time
10	Time required for polishing	RES	Time
11	Energy amount to fluidize polishing particles	RES	Energy
12	Energy required to move the rotating drum	RES	Energy
13	Energy required to move objects with axial symmetry	RES	Energy

The interview by the facilitator lasted about 15 minutes, during which some more requirements have been elicited, as presented in Table 4.

Table 4: Requirements for Technology B elicited through the support of criteria.

ID	***Evaluation Parameter***	***Main class***	***Sub-class***
14	Polishing quality dependence on temperature level	UF	Sensitivity - Quality
15	Unwanted removal of material	UF	Controllability - Quality
16	Range of treatable material (according to their elasticity response)	UF	Adaptability - Quality
17	Capability to treat objects of radically different sizes	UF	Adaptability - Quantity
18	Noise produced by the blower	HF	System vs. Environment

19	Noise produced by the drum	HF	System vs. Environment
20	Polishing materials residuals on the treated object	HF	System vs. Object
21	Need of filters to prevent environmental pollution	HF	System vs. Environment
22	Abrasion of inner surface of the tub	HF	System vs. System
23	Behaviour of powders in distributing according layers having different coarseness	HF	System vs. System
24	Time required for cleaning the object at the end of the polishing procedure	RES	Time
25	Room required by the devices	RES	Space
26	Amount of information to start-up the device	RES	Information

Summarizing the results for Technology B, 13 requirements have been determined by the experts without any support in about 45 minutes. After interviewing the experts for about 15 minutes, 13 new requirements have been highlighted as relevant at various extents.

At last, it has been carried out the examination of the application to clean objects covered by oily substances, as a results, for instance, of previous manufacturing processes. This cleaning process occurs by means of a preliminary spinning carried out with no fluid bed and thus overlooked for the analysis. Then, objects covered by a smaller amount of oily substances get immersed into the tub for the fluid bed and the impact with fluidized particles allow to detach oil from the surface of the object to be cleaned. The list of requirements mentioned by experts, during their 45-minutes long description of the technology, is organized in Table 5.

Table 5: Requirements for Technology C described by experts without any support for elicitation

ID	***Evaluation Parameter***	***Main class***	***Sub-class***
1	Amount of dirt removed	UF	Thres. Achiev. - Quality
2	Different kind of dirt particles to be removed	UF	Adaptability - Versatility
3	Uniform cleanliness of the surfaces according to the shape of the object	UF	Adaptability - Versatility
4	Uniform cleanliness level according to the roughness of the treated object	UF	Adaptability- Versatility
5	Sensitivity to temperature level in the environment	UF	Sensitivity - Quality
6	Oil recovery after cleaning	HF	Object vs. Environment
7	Presence of cleaning particles stuck on the surface to be cleaned	HF	System vs. Object
8	Capability to view inside the cleaning tub	HF	System vs. Environment
9	Time required for cleaning	RES	Time
10	Energy required to fluidize the cleaning particles	RES	Energy
11	Required collision force between cleaning particles and the object to be cleaned	RES	Energy
12	Mechanical resistance to collision by a fluidized particles	RES	Material
13	Shape of the fluidized particles	RES	Material
14	Chemical Affinity between the cleaning	RES	Material

	particles and the object to be cleaned		
15	Amount of information needed to start the device	RES	Information
16	Amount of information to let the system properly work	RES	Information

The interview with the methodological facilitator took about 15 minutes and, in turn, produced the results reported in Table 6.

Table 6: Requirements for Technology C elicited through the support of criteria.

ID	***Evaluation Parameter***	***Main class***	***Sub-class***
17	Capability to adapt the device according to the object to be cleaned	UF	Adaptability - Versatility
18	Capability to be used with different materials	UF	Adaptability - Robustness
19	Cleaning medium stuck on the object to be clean	HF	System vs. Object
20	Components integrity (as spoiled by the particles)	HF	System vs. Object
21	Need of filtering system to prevent oil leakages	HF	System vs. Environment
22	Dirt removal from cleaning particles at the end of the treatment	HF	Object vs. System
23	Noise by the blower	HF	System vs. Environment
24	Noise by the fluid bed from inside the tub	HF	Object vs. Environment
25	Components integrity (as compromised in cleanliness by other components immersed in the same tub)	HF	Object vs. Product
26	Room required to put the object to be clean inside the tub	RES	Space
27	Number of treatments on the same object before obtaining satisfactory cleaning	RES	Energy
28	Characteristics of the cleaning material	RES	Material
29	Need of object pre-treatment by spinning	RES	Energy
30	Room required by the tub	RES	Space
31	Material needed to carry out the cleaning cycle	RES	Material

Summarizing the results for Technology C, 16 requirements have been determined by the experts without any support in about 45 minutes. After interviewing the experts for about 15 minutes, 15 new requirements have been highlighted as relevant at various extents.

4.1.2.3 Discussion of the results

The main outcomes, as measured according to the objectives of this activity, are presented in the following Table 7.

Table 7: Summary of the results of the activity about the investigation of requirements for three different applications using the fluid-bed technology.

	Technology A			***Technology B***			***Technology C***		
	# of Req.	*%*	*Time*	*# of Req.*	*%*	*Time*	*# of Req.*	*%*	*Time*
Requirements defined without any kind of support	13	28,9%	15’	13	50,0%	45’	16	51,6%	45’
Requirements defined with the support of criteria	32	71,1%	30’	13	50,0%	15’	15	48,4%	15’

According to the objectives stated at the beginning of Section 4.1.2, this test aims at determining the contribution of interviews by methodological facilitator in easing the adoption of the criteria for eliciting requirements from experts. The results obtained support this kind of assumption, indeed the mean time required for the analysis of a single technology drops from 3-4 hours to just one hour. From the one hand this represent an encouraging outcome about the increase *efficiency of the use* of criteria, on the other hand it also introduce the issue to support the investigation with someone skilled in knowledge elicitation, as witnessed and widely discussed along Section 2.3.4.

For what concerns the effectiveness, the criteria have also demonstrated to be capable of, at least, almost doubling the results of investigations carried out without any support, thus addressing the concept of *completeness*. Moreover, in terms of *repeatability* of results, it is possible to recognize a little decrease of the average number of requirements elicited along the phases. From the average of forty (40) in the previous situation to less than 35 in these three cases. This effect could be influenced both by the presence of the methodological facilitator coordinating the analysis and by the specific influence of individual knowledge in specific domains.

It is also worth noticing that a surprising outcome has been registered along this investigation: once the first interview has been carried out, the experts started to learn the logic of the questioning procedure. Indeed, when they had to describe new applications of the Technology, they reviewed, with increased autonomy, a wider set of facets that have not been taken into consideration before. This phenomenon as influenced the durations of the description and the elicitation in the last two cases, as reported in Table 7.

An accurate analysis of the requirements presented in Tables 1-6 allow to notice that there is no *redundancy* among the requirements generated for a specific technology. The effect could be referred to the presence of the facilitator and, indeed, the contextualization of questions allow to better understand their content and give precise answers. The analysis of the tables also allows noticing that all the requirements have their own *validity*. Indeed, all of them can be measured at least in terms of presence/absence and for many of them it is also possible to determine quantitative threshold values for inferring satisfaction about the outcomes. In terms of *conciseness,* non-relevant requirements have been highlighted during the discussion.

4.1.3 Ex-post analysis of requirements to map drivers for supporting decision making in choosing candidates for technology substitution.

The last activity, which directly addresses the need to map requirements in the sphere of manufacturing processes, is represented by an ex-post analysis of the requirements of a technical system in order to evaluate its features. Such an analysis is mostly concerned with the evaluation

of technology already involved in manufacturing processes. The evaluation, as described in Section 2.4.4, represents the strategy to understand both the level of satisfaction achieved with the currently employed technologies and the potential of emerging technologies that could be a candidate alternative in cases of technology substitution. Comparisons can be also made in order to understand the best choice among diverse alternatives. This experimental activity has been conducted with an exploratory approach, in order to understand if in case of technology evaluation all the requirements that drive the decision-making process have been taken into account or not.

This represented both a relevant goal for Whirlpool Europe, which has been the industrial partner of this test, and for the developer of the criteria. Indeed, the adoption of criteria for making comparisons among technologies, as well as for recognizing features that hinder technology transfer, could represent a strategic and effective support to the decision-making processes in both industrial contexts and design process.

Into the details such an analysis have considered the process for curing painting powders on the sheet metal surfaces to be employed for the structure of household appliances (e.g.: the oven cavity, the door of a domestic refrigerator, …).

4.1.3.1 Description of the test

According to the overall goal of this test, it is important to verify if the definition of requirements can effectively map the different facets involved in the evaluation of a technical system and, more specifically, a manufacturing technology. In this case, moreover, the decision-making process has been already concluded once such analysis has started. The logic of this "a-posteriori" analysis is to check if the decision process could have steered earlier to the adoption/rejection or if there are still several aspects to be considered and the decision for adoption/rejection has been made too much time in advance and on the basis of partial knowledge and information.

The structure of test, to this purpose, is relatively straightforward. According to the outcomes obtained with previous tests presented and discussed in Section 4.1.1.3 and Section 4.1.2.3, the best way to map the technical requirements of a technology consists in reviewing the whole set of criteria in order to populate a large set design specification. Such a review produces better results when carried out by the support of a methodological facilitator, which is in charge of asking questions and characterizing the elicited requirements. Nevertheless, it is also worth noticing that the effective mapping of requirement into the specific classes set by the criteria is not a specific issue to be addressed, in this context, for the purposes of such an investigation.

Therefore, this investigation have been carried out through an interview with Whirlpool's Experts in manufacturing processes that where in charge of providing data capable to support the decision making process. The whole set of requirements elicited during the interview has been subsequently discussed with the experts themselves in order to understand if all the requirements and the related capability to satisfy them by the candidate technology were taken into consideration or not.

A panel of two experts has carried out the evaluation as a round table discussion into which the facilitator just introduced questions, without suggesting any kind of judgement.

4.1.3.2 Application of the criteria to the technology for curing powders by means of photo-catalytic panels working with IR radiation.

The preliminary part of the interview was aimed at determining into which relationships are the currently employed technology (conventional heating by convection ovens) and its candidate for

substitution, so to understand what is the main driver that suggested this kind of technological shift, if applicable.

In order to clarify such a view, the competition between the two systems has been modelled according to a Network of Problems (as presented in Section 2.4.3). Such a model is depicted in Figure 49.

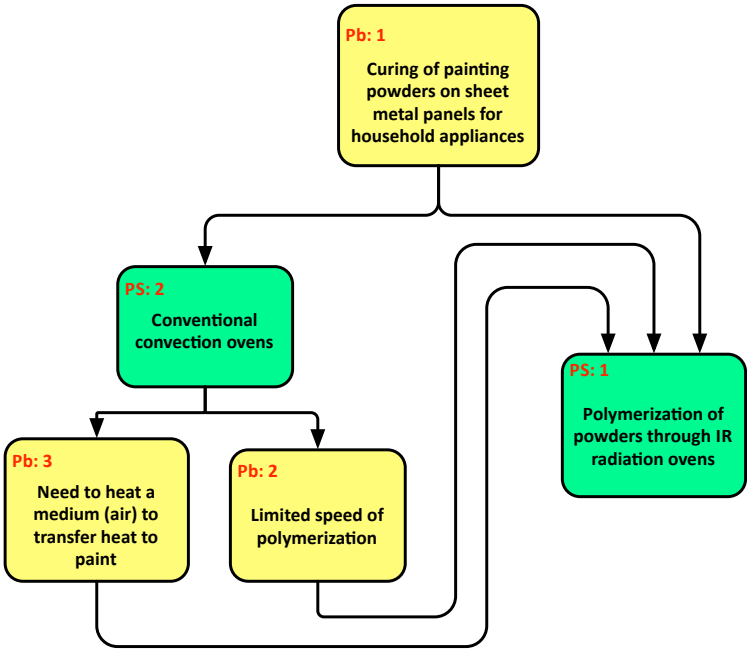


Figure 49: Representation of competitive advantages provided by the technology employing photo-catalytic IR panels against the current limitations of traditional convection ovens.

According to this perspective it has been clarified which function the two diverse technologies carry out in terms of EMS model, as presented in Figure 50.

Figure 50: Energy-Material-Signal Model for the Function transforming powders on a surface into a unique painting layer.

According to this perspective, consistently with the objectives of removing redundancies and being complete, once defined the reference level for the analysis with the above reported EMS model concerning the function the investigation has begun with the interview of the facilitator that scanned all the different criteria to elicit the greatest number of requirements from experts.

The analysis ranged from the definition of system performance (Useful Functions), through the recognition of potential Harmful Function determining undesired effects, to the required resources to let the system properly work. Such results are respectively collected into Figure 51, Figure 52 and Figure 53.

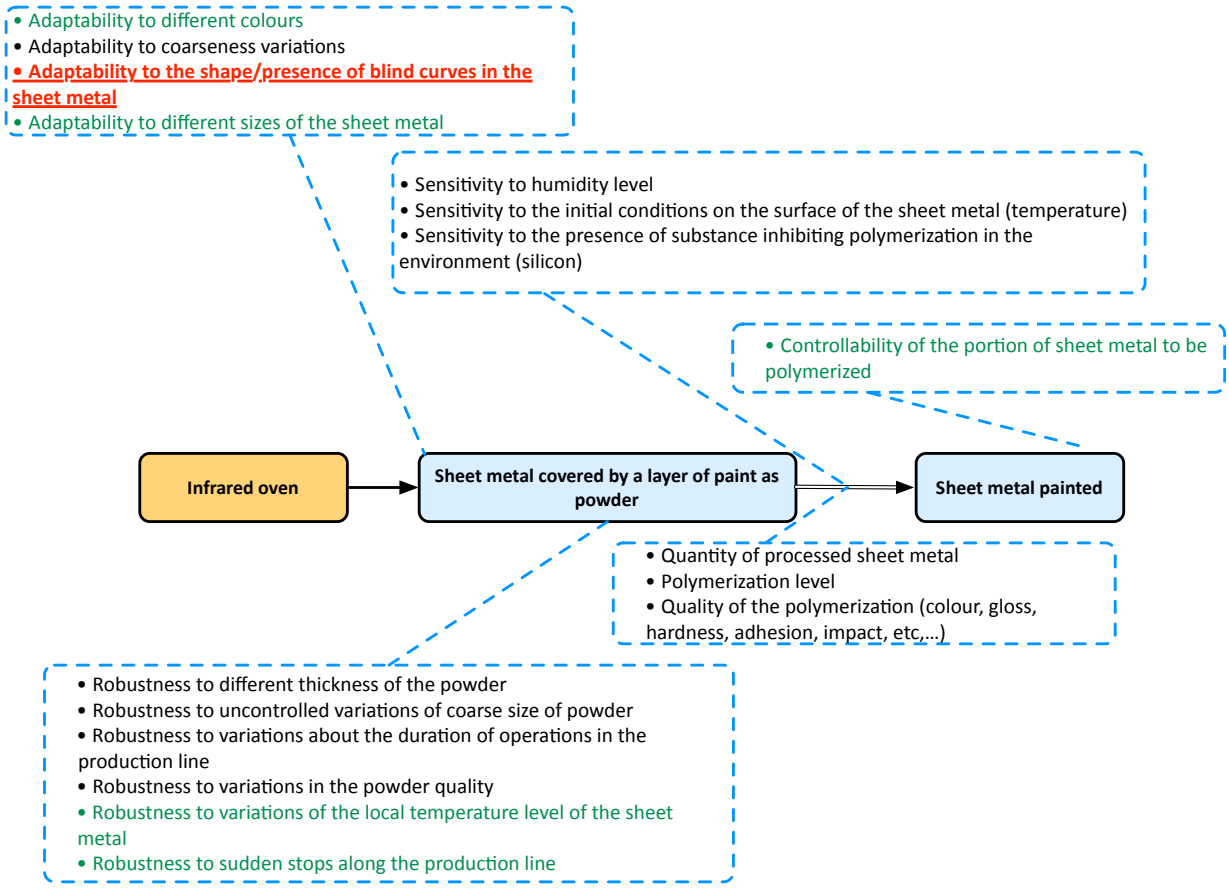


Figure 51: Technical requirements of the technology for curing powders by means of Photo-catalytic IR Panels

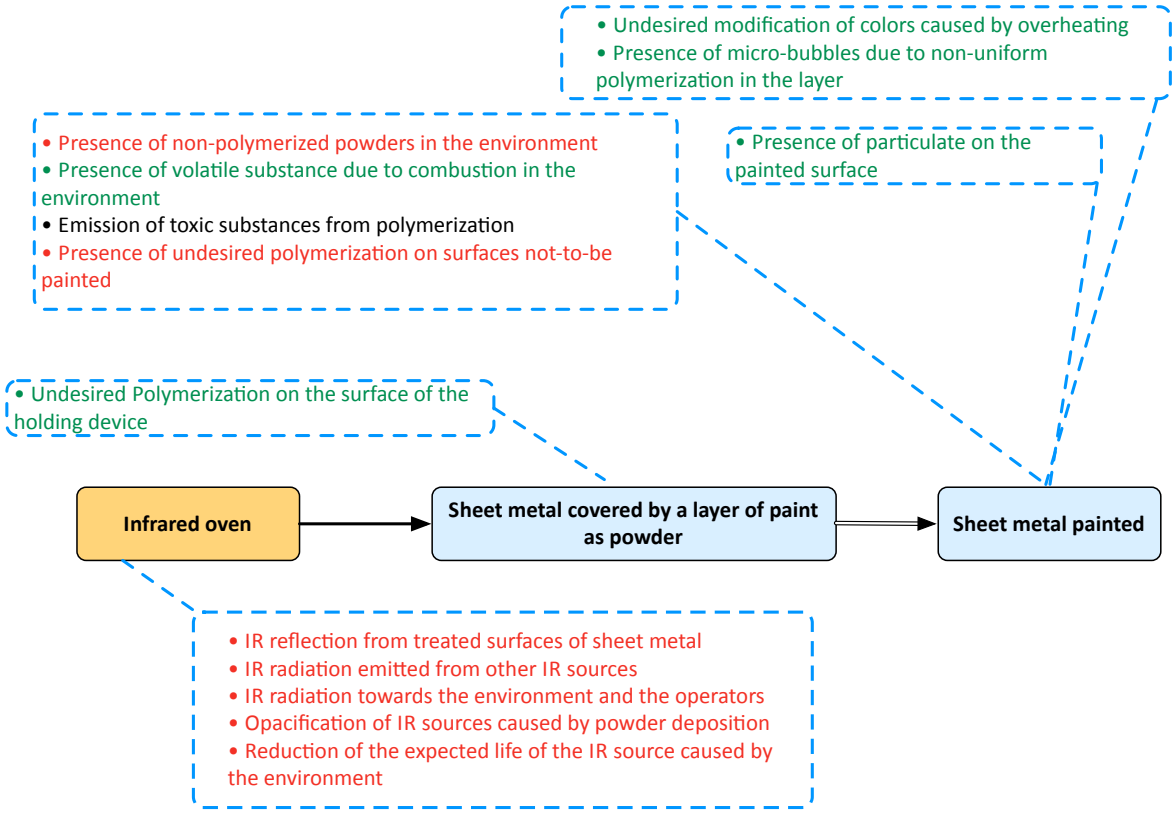


Figure 52: Requirements concerning the potential presence of undesired effects due to Harmful Functions

	Set-Up	Preparation of sheet metal and powder	Polymerization	Removal from handling devices	Routine maintenance	Dismission
Space	Handling device for movement and orientation of the IR panels		Room occupied by the plant	Room required for sheet metal cooling after polymerization		
Time	Setup time for the IR panels caused by configuration changes	**Warm-up time**	Polymerization time	Cooling time of the sheet metal	Time required for routine maintenance	
Information	Information about the definition of setup rules for IR panels caused by configuration changes		Real-time monitoring of working parameters Real-time monitoring of IR proper working			
Material	Handling device Thermal insulation IR screening towards the environment		Powder consumption for undesired polymerization on surfaces not-to-be painted Waste		Change of IR sources (expected life) Filters	Dismission of special materials (IR panel)
Energy			**Electric energy required for working** **Thermal energy required for working**			
€ (various)	Installation cost		**Cost of IR-specific powders**		Other maintenance costs	

Figure 53: Table collecting the requirements concerning the resources (rows) consumed by the system in the different phases (columns) of its lifecycle. Costs (€) have been added to ease the analysis for experts, but such requirements can be practically placed, if further analysed into the appropriate category among Space, Time, Information, Material and Signal.

4.1.3.3 Discussion of the results

As for the objective of this activity, it is important to understand if all the requirements potentially impacting the decision-making process in technology substitution problems have been considered before the adoption or the rejection of the concept during the decision making process.

This kind of analysis has been carried out through the application of criteria for the identification and the classification of requirements. The presence of the facilitator has been, once again, crucial to ask contextualized questions so as to ease the formulation of answers (*ease of use*).

Form a different perspective, the classification issue can be overlooked because the comparisons are driven by homogeneous sets of requirements among different technologies, regardless their artificial classification.

The Figures 51, 52 and 53 collect all the requirement generated within this test by means of the criteria. For what concerns the specific definition of requirements, the ones depicted with the green colour are those who are satisfied by the photo-catalytic IR panels under investigation. Red ones, on the contrary, stand for the requirements that are currently better satisfied by conventional convection ovens. Requirements depicted in black are the most interesting for this discussion, since they are those ones that have not been considered before the decision making process conclude with the approval or the rejection for the technology change. From a quantitative point of view it is possible to remark that within an overall amount of 54 measurable requirements (*completeness* and *validity*), distributed as it follows:

- 20 requirements better satisfied by the technology using photo-catalytic IR panels for curing powders inside appropriate ovens (coloured in green);
- 17 requirements better satisfied by the conventional technology using warm blown air inside convection ovens (coloured in red);
- 17 requirements that are completely new to the experts and that, therefore, have not been considered before to feed the decision-making process with a complete set of data.

From the perspective of the importance of the retrieved data, however, it is still doubtful if the whole analysis carried out in advance would have had an influence in steering the decision process. To this purpose, it is important to mention that requirements represented in bold are the ones that have played a major role in choosing to adopt or reject the new technology.

Being it a single test, it is not possible to measure the *repeatability* in terms of diffused efficacy for these purposes. Nevertheless, it is remarkable that the investigation through question-and-answer techniques has provided higher benefits (in terms of number of elicited requirements) than the ones experienced with the test of Section 4.1.2, even if this specific aspect may depend also on the domain of application and, for sure as highly discussed in Section 2.3.4.2, the knowledge owned by experts.

In terms of *non-redundancy*, the requirements presented in Figures 51-53 demonstrate that there is no overlapping among them. As for *conciseness*, "costs (€)" represents a class that needs to be discussed. They could be properly considered in appropriate categories (e.g.: the *cost of powders* depends on powder properties, which is a matter concerning the resources of material) or organized into more detailed requirements so that it is possible to position them in appropriate categories (e.g.: the requirement "*installation costs"* depends on manpower for installation, which is a resource of energy; on the materials required to build the required technology, which should be considered among the related resources, …). Nevertheless, being this experiment mostly focused on the capability of requirements to support the processes of decision-making, it is important to notice that the dimension of costs has somehow to be mapped, because it represents one of the main collectors of information to decrease the complexity of decisions.

4.2 Application of the criteria for eliciting product requirements

As briefly mentioned at the beginning of Section 4, this part of the document aims at describing two experimental applications of the criteria for eliciting requirements about technical systems in the sphere of products. Therefore, this part of the document contributes to demonstrate that the criteria proposed in Section 3.2 are suitable also for the identification and the classification of product requirements, thus addressing the objective concerning the *flexibility* of use for both product and process issues. To this purpose, it is also worth remarking that, from the perspective of the delivery of functions, specific technologies implemented in the phases of a more complex process are neither more nor less than products. Vice versa, specific products can exactly represent what in the Section 4.1 has been referred as "technology". Therefore, along these tests the criteria are expected to continue contributing the enrichment of the design specification consistently with the objectives determined in Section 3.1. In addition, a different kind of interaction for eliciting the knowledge will be experienced during the first test, in order to determine to which extent the goodness of results is affected by the presence of a facilitator.

Differently from what has been proposed in Section 4.1, these tests have been conducted in an educational context (the first one) and according to the data available from literature (the second one).

4.2.1 Application of the criteria to products having different complexity

This test aims at addressing all the objectives recalled in the abovementioned paragraph. The choice of conducting the test in an educational context depends on the need to establish to what extent the individual knowledge may affect the *repeatability* of the results, in terms of a diffused *completeness* (number of elicited requirements) among different testers. Moreover, a test with a wider number of participants, such as the one that is available in an educational context, represents a good chance to quantitatively evaluate the efficacy of the criteria in enlarging the individual perspective on requirements, as qualitatively witnessed by the three experiments carried out in industries.

More than 20 students of the Bachelor of Science (MS-propaedeutic curriculum) in Mechanical Engineering at Politecnico di Milano participated to the tests. In details the test has been carried out, so as to have results for comparisons, into two different rounds within the same group. Indeed, due to reasons of availability, it has not been possible to carry out the test also with the support of a control group. Moreover, the intrinsic variability of the presence of people at classes occurring in different days determines variation in the both the composition and the size of the sample, thus excluding the chance to carry out a paired t-test of Hypothesis. Unfortunately these limitations cannot be overcome, even if such a paired t-test would have provided the best insights for what concerns the impact of criteria in teaching people to follow a systematic logic to elicit requirements, so as to estimate the triggered effect in learning-by-doing.

Such limitations impose to make some assumptions during the test planning, in order to partially restrain the abovementioned limitation and balance them with the need of obtaining insightful results with reliable quantitative values.

Without the constraint of testing the learning-by-doing effect, it is proposed to carry out the test according to two different steps, with a time lapse of a week. The first test does not include the support of means for eliciting knowledge about requirements. The second one, on the contrary, has to be carried out by introducing the support of the criteria presented in Section 3.2.

Moreover submitting a test on the same subject do not allow to map anything really significant, because students, after a week, could have already shared impressions and opinions as a consequence of the first testing session, thus improving their knowledge on the field.

It is thus proposed to submit two test cases of different complexity to the students' attention: a laser printer and an iron to remove creases from clothes. In order to reject the null hypothesis that the criteria do not provide a significant support in the identification of requirements, it is proposed to drive the elicitation of requirements for the laser printer during the first testing session and the iron during the second one. The assumption underlying this choice is consistent with the idea that higher is the number of parts and higher is the inherent complexity of a technical system (Simon, 1981). Moreover, the higher complexity should imply that there are more requirements to be satisfied as a consequence, for example, of the mutual interactions between system components and the resources each one of them may need within the technical system.

Hence, the first session of the test has asked people to determine the largest list of requirements about a laser printer without any support for their identification.

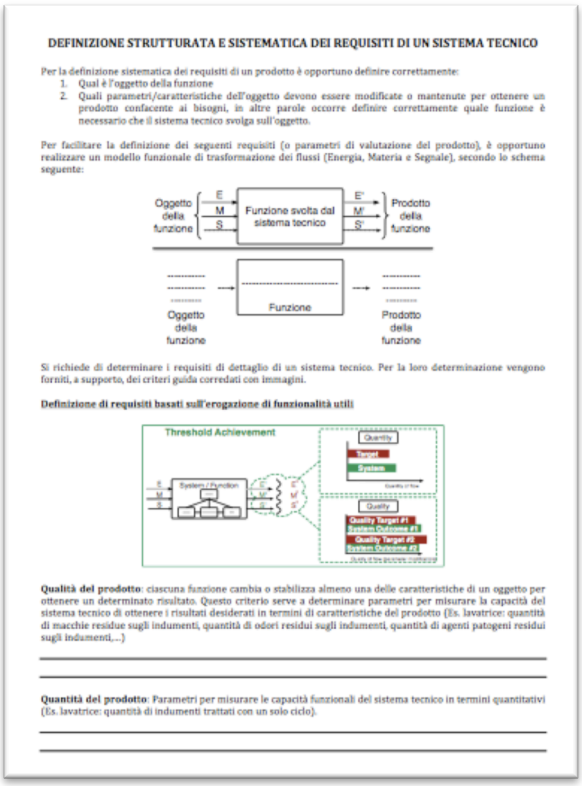
The test about the iron, on the contrary, has been carried out by the support of criteria. On the basis of the good results obtained by interviews, this test represented a chance to start exploring the possibility to release the methodological facilitator to drive the analysis by the introduction of a tailored questionnaire. Being the group of testers composed exclusively by Italian students, the questionnaire has been delivered in their mother tongue, as a reasonable strategy to limit the perturbations due to language misunderstanding, which could have altered the collected results. A set of detailed requests has been prepared to support the elicitation of requirements

and the logic of the questionnaire systematically follows the sequence of the criteria as proposed in Section 3.2. To ease the comprehension of the questionnaire content and the meaning of the criteria, each question has been matched with the same examples presented in the section concerning the original proposal of this research work. Moreover, in order to set a common background for the analysis, the questionnaire begins by this statement (translation from Italian):

> *To systematically define the requirements of a product it is suggested to properly define:*
>
> - *The object of the function*
> - *Which characteristics or parameters of such object should be modified or kept to obtain a product that meets the needs; in other words it is necessary to define which function the technical system carries out on the object.*

This statement is followed by the generic EMS model, as presented in Figure 28, suggesting to determine the changes and the characteristic parameters in a second one to be filled according to the situation at hand (in this case it is required to model the function carried out by an iron). Once such reference concepts have been defined, the background is set and the analysis for the elicitation of requirements can start. The first page of the questionnaire is presented in Figure 54.

The time limits to fill the questionnaire have been fixed in 45 minutes.



DEFINIZIONE STRUTTURATA E SISTEMATICA DEI REQUISITI DI UN SISTEMA TECNICO

Per la definizione sistematica dei requisiti di un prodotto è opportuno definire correttamente:

1. Qual è l'oggetto della funzione
2. Quali parametri/caratteristiche dell'oggetto devono essere modificate o mantenute per ottenere un prodotto confacente ai bisogni, in altre parole occorre definire correttamente quale funzione è necessario che il sistema tecnico svolga sull'oggetto.

Per facilitare la definizione dei seguenti requisiti (o parametri di valutazione del prodotto), è opportuno realizzare un modello funzionale di trasformazione dei flussi (Energia, Materia e Segnale), secondo lo schema seguente:

Si richiede di determinare i requisiti di dettaglio di un sistema tecnico. Per la loro determinazione vengono forniti, a supporto, dei criteri guida corredati con immagini.

Definizione di requisiti basati sull'erogazione di funzionalità utili

Qualità del prodotto: ciascuna funzione cambia o stabilizza almeno una delle caratteristiche di un oggetto per ottenere un determinato risultato. Questo criterio serve a determinare parametri per misurare la capacità del sistema tecnico di ottenere i risultati desiderati in termini di caratteristiche del prodotto (Es. lavatrice: quantità di macchie residue sugli indumenti, quantità di odori residui sugli indumenti, quantità di agenti patogeni residui sugli indumenti,...)

Quantità del prodotto: Parametri per misurare le capacità funzionali del sistema tecnico in termini quantitativi (Es. lavatrice: quantità di indumenti trattati con un solo ciclo).

Figure 54: The first page of the questionnaire submitted to student for the elicitation of requirements concerning an iron. Note that also figures proposed along Section 3.2 have been introduced to ease the understanding of the content of the questionnaire.

4.2.1.1 Description and discussion of the results of the survey

The entire set of the results is too extended to present it here entirely, nevertheless for the sake of clarity and completeness they are presented in the following by means of descriptive statistics data.

To this purpose, Table 8 collects data pertaining to both the experiments.

Table 8: Summary of the results of the testing activity carried out on products at different levels of complexity. The first test has been carried out without any support for requirements identification. The second one has been supported by the criteria of Section 3.2

	Laser Printer (First test - 1 -)	***Iron (Second test - 2 -)***
Average	17	40,83333333
Standard Deviation	6,008765527	9,115999631
Max value	27	60
min value	10	26
Sample Size	21	25

The preliminary examination of these results show that the average number of requirements (first row) defined by the support of the criteria is more than the double of the average of requirements identified without the support of criteria for the product having, according to the assumption, a higher level of complexity and, therefore a higher number of requirements to be elicited.

One remarkable result comes from the cross comparison between Max and min values (3rd and 4th rows): the higher number of requirements elicited without the requirements differs of just one unit from the minimum number of requirements elicited through the support of criteria.

It intuitively appears evident that the criteria also provide a significant contribution to the definition of product requirements (*flexibility* between products and processes). The large number of requirements identified by means of criteria brings further evidences in favour of the achievement of the *completeness* objective. Moreover, large descriptions of the design specification have occurred in many different cases and without particular exceptions, thus also fulfilling the objective of *repeatability*. To determine if the abovementioned objectives have been satisfied also in terms of statistics significance, it is proposed to test the effectiveness of the contribution by means of these two distributions, under the Hypothesis of equality between the average values. The most suitable statistics to test this hypothesis is the t-stat by Student because of the poor knowledge about the population. The two mutually exclusive hypotheses are:

- *H_0: the difference in the average values depends on chance and the criteria do not provide any statistically significant contribution to the definition of requirements (H_0: $\mu_1 = \mu_2$)*
- *H_a: the difference in the average values depends on the treatment and therefore the criteria support the definition of new requirements (H_a: $\mu_2 > \mu_1$)*

The value of the test statistics have been calculated according to the following formulas, suggested in cases where Hypothesis testing has to be carried out between two samples pooled together, with a cumulative number of participants higher than 30 and under the assumption that the two standard deviations of the related populations are equal (as it is, being them part of the same group of people)

$$t = \frac{(\overline{x}_1 - \overline{x}_2) - d_0}{s_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}, \qquad (1)$$

where S_p^2 (pooled variance) is calculated as follows:

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}, \quad (2)$$

The degrees of freedom, in this case, are 44 as indicated by the denominator of the pooled variance.

The value of test statistics is 10,2471668 that corresponds to a *p-value*= 1,56E-13, calculated for a one-tail distribution. This result goes beyond the highest expectations because of the very low value assumed by p-value, meaning that the possibility that the criteria do not provide any effect on the result has a probability of being true is lower than one in six thousands billions. It is quite reasonable to accept the idea that the criteria provide some kind of support, even if, according to the abovementioned limitations such value could be affected also by the complexity of products that makes the laser printer more hard to understand. To obtain further insights on this facet, more experiments are necessary.

For what concerns completeness, however, it is worth to consider this parameter also in terms of an appropriate exploration of all the alternatives suggested by the criteria. To this purpose it is worth mentioning that, subdividing the results according to the three main categories (Useful Functions, Harmful Functions and Consumption of Resources) the distribution changes according to what is presented in Table 9

Table 9: Summary of the results as proposed in Table 8. Details about the different categories under which the requirement can be classified.

	Max	***Min***	***Average***	***Standard Deviation***	
Useful Functions	8	1	4,1	2,049390153	***Laser Printer***
Harmful Functions	5	0	1,8	1,151657844	
Resources Consumption	19	6	11,1	4,216508908	
Useful Functions	14	4	8,333333333	2,3343683	***Iron***
Harmful Functions	24	9	13,54166667	3,671028368	
Resources consumption	28	8	18,95833333	5,204339048	

Even according to these results, it appears as evident that the criteria improve the exploration of the different facets concerning innovation, as pointed out by the Law of Ideality Increase by TRIZ (Section 3.2 and Appendix C).

For what concerns the other objectives it is worth mentioning that the objective concerning *ease of use* is greatly achieved also through this kind of written interaction that includes figures, means for setting the reference level of analysis and examples to improve the comprehension of the meaning of the criteria. This conclusion can be drawn from the analysis of the time required by matching the result in terms of time required for carrying out the analysis (45 minutes) and the number of elicited requirements (40 as the average value).

For what concerns *validity* and *non-redundancy,* it is possible to affirm that this kind of interaction presents some drawbacks that did not appear during the interaction mediated by the facilitator. Indeed some requirements, despite they are defined in a measurable manner (at least by dichotomous values, satisfying the objective of *validity*) are addressed to the wrong class for a possible misinterpretation of specific questions. However, this phenomenon appears just at the beginning of the analysis, when the testers still don't have a clear overview of the whole set of criteria. Moreover, in most cases switches between concepts appear because of different perspectives about dissatisfaction: some useful functions poorly controllable or scarcely adaptive to different situations get considered as effects of Harmul Functions.

4.2.2 Application of the criteria to new characteristics of products

As widely mentioned in the above pages, this section exploits some contributions from literature in order to understand to which extent the current criteria can map the new emerging characteristics, attribute and requirements of innovative products. This investigation is carried out with an a-posteriori analysis having an analogous logic, but different purpose, to the one proposed in Section 4.1.3. Since this activity did not required to plan and design any specific test, this subsection is organized into a unique block that briefly describes the theoretical framework into which this experience has been developed and the approach adopted for the evaluation.

Recognizing the capability to map the new attributes of renewed or radically changed products can give preliminary indications about the potential role of the criteria in supporting the definition of new values for products (here the concept of "value" blends with the one proposed along Section 2.4.4 for what concerns creativity, thus also "closing the circle" around the concept that values can be evaluated by means of the satisfaction of requirements).

Indeed, the definition of guidelines for new value proposition is an interesting team that is vivid and debated in the scientific community as reviewed by Borgianni (2011).

This specific test has been planned on the basis of the concepts expressed by Kim and Mauborgne (2005) in the book where they present their strategy to skip the market competition by creating a so-called "Blue Ocean", as opposed to red ones where sharks kill small fish, where there is a certain room in the market to propose successful businesses and obtain great incomes.

Regardless of the real adoption of the Blue Ocean Strategy in real industrial context and its efficacy in driving the development of corporate business, it is worth noticing that their "Four Action Framework" has a general validity as a model to map the changes in product values. The framework is intended to remove the trade-off between product differentiation and the need of containing costs. According to such a perspective, to build a new value curve for a corporate business it is necessary to investigate which factors should be completely *eliminate* from the current business, which ones should be *reduced* and, on the contrary which, among the existing, *raised* in value. Moreover, and most important, it is also important to understand which factors that have never appeared in the market should be *created* (Figure 55 and Figure 56).

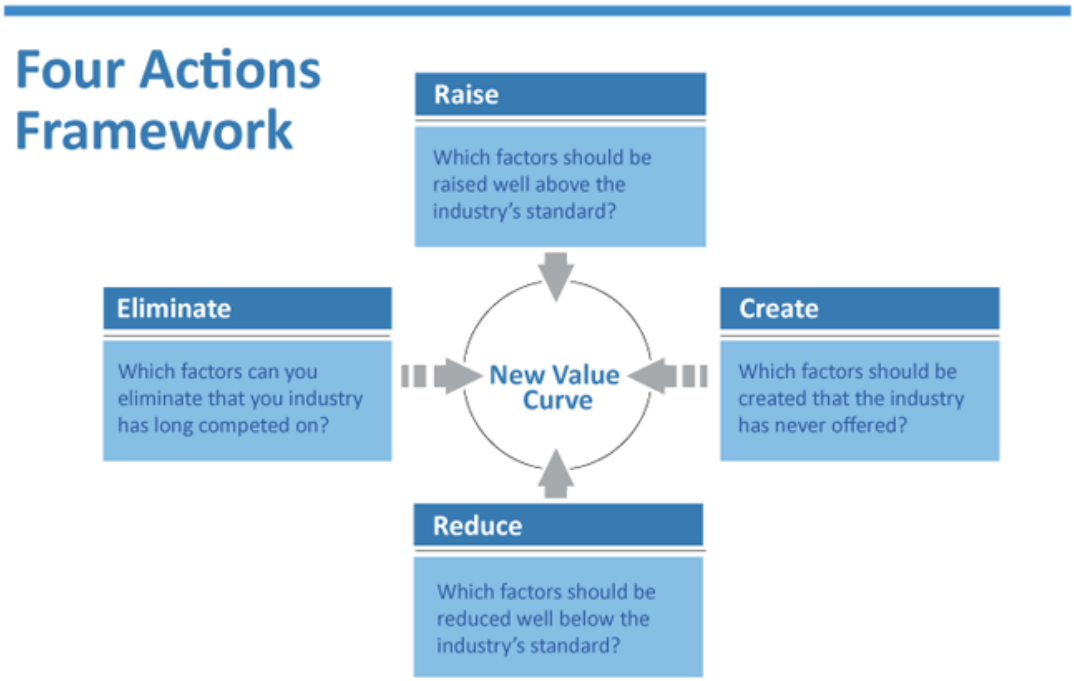


Figure 55: The four-action framework (from http://www.blueoceanstrategy.com)

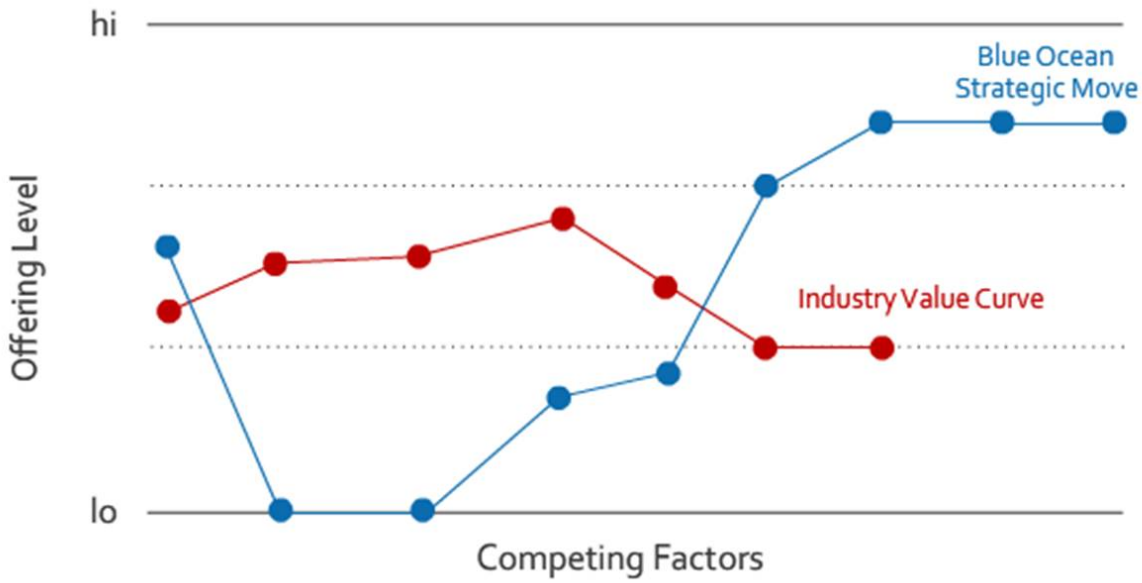


Figure 56: example of value curve (also known as Strategy Canvas) where it is possible to recognize the "Create - Raise - Reduce - Eliminate" pattern of value change (from the website by Kim and Mauborgne, http://www.blueoceanstrategy.com).

In order to clarify the meaning of the different actions, Figure 56 provide interesting examples to discuss before going into the details of the analysis of this test. The blue line represents the new value curve developed through the various BOS actions for a successful business strategy; the red one concerns the standard offer of values by the industry. Each dot is placed in correspondence with competing factors, as referenced in the x-axis, namely the customer requirements that drive people's choices for purchasing goods and services.

The blue dots on the x-axis represent the action of eliminating a customer attribute from product as a means to differentiate from the others. The most left blue dot, indeed, represents the action of raising the current value offered by industry. On the contrary, the fourth blue dot from left represent the opposite action concerning the Reduction of values offered by Industry. The most important for this purposes, however, is recognizable at the extreme right of Figure 56: blue dots have no correspondences with the competitor, they have created new element to satisfy different need on the market. An example of this kind of innovation is the videogame console Wii by Nintendo that refuses the run for improved graphical performance by introducing a completely new concept of interactive game that involves the whole body.

A said, such "factors", by definition dramatically influence customer satisfaction and it is therefore interesting to understand to which extent the criteria are capable to map the "create" attributes.

To this purpose, "create" attribute concerning 92 different products and service have been taken into account by exploring the reviews carried out by Borgianni et al. (2011 and 2012). Such collection of create attributes includes 172 occurrences unevenly distributed among products. The whole classification of these criteria is omitted in this Section and it is proposed in Appendix G.

Nevertheless, for the sake of clarity and to ease the comprehension of the logic under which these "create" attributes have been considered and classified, Table 10 presents an excerpt of the entire list.

Table 10: Excerpt of the table included in Appendix G, containing the *"Create"* Attributes of 92 cases of new products launched in the market with different commercial feedbacks.

Case study	Requirement definition	Classification	Sub classification
[Yellow Tail] wines	Fun and adventure	UF	Threshold Achievement
[Yellow Tail] wines	Ease of drinking (i.e. because of sweetness)	HF	System against the object
[Yellow Tail] wines	Ease of selection	RES	Information

Before going into the detail of the investigation, it is worth mentioning that the perspective of this analysis has to switch from the technical side to a more customer oriented view of satisfaction. This is the reason why, for this analysis, the reference EMS model cannot take into account a single function, since each product or service perform different actions. On the contrary, what does not change, in this perspective, is the object of each single function, which is directly the customer.

The evaluation, therefore, has been carried out by considering the diverse parameters directly addressable to the customer and that the product or the service tries to modify to trigger satisfaction. The three examples presented in Table 10 have been considered from this viewpoint and are presented in the following text in italic with the purpose of clarifying the logic of the analysis and ease the readability of Appendix G.

> *[Yellow Tail] wine is a new kind of wine characterized by a captivating and distinguishing label in different colours for different kind of wines (Ease of Selection). The kangaroo depicted on the label has the aim of recalling the wild atmospheres of Australia and its Outback so as to trigger in the customer the will to travel and experience the Walkabout experience made famous by the movie "'Crocodile' Dundee" (Fun and adventure). Regardless its zone of origin is not well renowned for producing wines of good quality, it has been assembled with vine variety characterized by a sweet and smooth taste of poor complexity that places it as an alcoholic alternative to soft-drinks (Ease of Drinking).*

In the first case of Table 10, the capability of the label to trigger of new emotions goes in the direction of producing new sensations when purchasing wine (not drinking, in this case). It represents an attractive feature, but whose effects can be recognizable just at an emotional level.

In this perspective the function concerns triggering emotions at the moment of purchase, then represent a parameter concerning the achievement of threshold value. Those who are stimulated maybe buy the bottle, the others, probably, prefer a good wine. On the other hand, those who are not used to buy wine can feel some discomfort because of its strong taste and its intrinsic acidity. The choice of producing a sweet wine goes in the direction of removing a harmful function for those who do not appreciate the f differences between bottles of different years by the same producer or the strong character of those wine that needs long ageing in big or very small oak barrels. The label, again, at last, aims at making the product recognizable, thus releasing the buyer from unfruitful searches among market shelves.

Such an analysis has been carried out on the diverse customer requirement with good outcomes. In just 2 cases out of 172 the definition of the appropriate classification has not succeed. These two cases concerns:

1. The Ford Edsel, a car for which people where asked to contribute in definition of its name through TV shows.
2. And the supposed "Swedish Identity" that IKEA can somehow trigger into the individuals.

This mapping constituted a challenging activity since it is quite difficult to determine which is the good perspective to look at new customer requirements with a repeatable approach. In several cases more than a classification appeared as correct to the author's eyes. This multiplicity of interpretation somehow limits the adoption of this kind of criteria for supporting the definition of guidelines for the development of clearly oriented innovations. To define such a guidelines it would be necessary to rely on a structure method for distinguishing the various situations in which new "create" attribute has to appear and the way it has to be univocally interpreted.

Nevertheless, such characterization of attributes has demonstrated that these criteria can map the requirements in almost the 99% of cases and therefore their use as triggers and stimuli to generate new ideas and concept deserves further investigation in the future.

4.3 Identification of conflicting technical requirements in inventive design problems

After an overall evaluation from both qualitative and quantitative perspective for the criteria described in Section 3.2, which is further discussed in the Conclusions of this text, this section presents the two testing activity carried out with students from both the Politecnico di Milano and the Università di Firenze with the algorithm for the analysis of inventive problems. This algorithm represents an ideal continuation of the development of the criteria, since its paths for analysis directly address the various facets pointed out in the three different classes in terms of requirement satisfaction for the performance level achieved by a Useful Function as well as the need to deal with products that reduce at the maximum extent the presence of side effects (Harmful Functions) and the consumption of Resources.

Moreover the same algorithm embeds in its structure the exploration of different dimensions of the problem, for what concerns both the spatial and temporal hierarchies. This improves the capabilities of depicting the design space so that Ill-Structured Problems (situations) turn into Well Structured Problems to which it is possible to apply standard and known strategies for their solutions. In other words, this part of the testing activity aims at evaluating the actual contribution of this algorithm in supporting the technical examination of the situations in which an existing concept of product needs to be redesigned because of the emergence of some discontentment.

These two tests have been conducted on different releases. The first one concerns the first framework of the algorithm, as presented in Section 3.3.1. The second testing activity, indeed, has focused on a subsequent release, whose advancements have been presented in Section 3.3.2, containing a new block so as to better meet the objectives of supporting the designers in finding conflicts among requirements, in order to prioritize the definition of solution concepts. The logic is to design by refusing compromises in favour of the overcoming of contradictions, which is the engine of the evolution of technical systems according to the second postulate of TRIZ.

4.3.1. Tests of the first release of the algorithm for identifying conflicting requirement during the analysis phase of the design process.

The present section describes at first the organization of the testing campaign set up to validate the proposed algorithm. Then, the results of the experimental activity are discussed, estimating

the effectiveness of the system through a comparison of the outputs with analogous experiences, as well as its robustness, by evaluating the repeatability of the outcomes.

4.3.1.1 Organization of the testing activity

The preliminary validation activity of the proposed dialogue based system and web implementation has been carried out by the means of a controlled method suitable for verifying the efficiency of novel techniques within computer science. More precisely, according to the clustering criteria introduced by Zelkowitz and Wallace (1998), the conducted testing activity fulfils the requirements of synthetic environment experiments, whereas a large group of subjects (commonly up to 30) replicate software tests in order to investigate the main features related to systems design and usability.

With reference to the mentioned kind of experiment, the resulting outcomes are subsequently evaluated by the means of statistical models. At the same time the performed test and its reported description take into account relevant issues about experimentation tasks, as suggested in (Kitchenham, 1996) and briefly recalled and expanded in (Zelkowitz, 1997), such as:

- possibility for other researchers to replicate the test;
- local control, due to the possibility of modifying aspects of the dialogue-based system according to further desired evaluations;
- the possibility to generalize the results, thanks to the randomization of the subjects performing the tests.

The proposed dialogue-based algorithm for problem solving has been tested by 30 Master Degree students in Mechanical Engineering at Università di Firenze (Florence, Italy) and at Politecnico di Milano (Milan, Italy). This group of students, because of their ready availability, represents a sample of convenience, whose employment, also regarding recent projects, is widespread for testing activities within design (Lemons, 2010; Johnson, 2010) and computer science (Ernst, 2008; Mendicini, 2009).

All these students had already received 20 lecture hours about TRIZ fundamentals. Most of the companies proficiently adopting TRIZ within their product cycle, believe that an introductory training for a beginner lasts at least 36 hours, while an advanced vocational course (including ARIZ) should involve about 200 hours (Adunka, 2007; Lee, 2010). Therefore those students cannot be considered as TRIZ practitioners, whose experience may consistently impact in their problem solving capabilities.

Before the algorithm test, all of them had carried out manual exercises concerning the application of problem solving tools for industrial problems, with extremely different proficiency results. The students' evaluation for both the manual and the computer-supported proofs allow a within-subject test to be performed. Within-subject approaches are largely diffused in the reference field of the current research, as witnessed by recent contributions concerning design (Nam, 2009; Trabelsi, 2010; Youmans, 2010; Zadeh, 2010) and computer science (Zhang, 2008; Aquino, 2010). The computer test involving the described algorithm has been carried out assigning different problems to individuals than in the manual exercise, in order to obtain unbiased results, thus avoiding the crossover effects representing the main limitation of within-subject designs. The problems that were used for testing the computer-based algorithm are reported in Section 4.3.1.2

The quality of the problem analysis processes in both the situations allows highlighting whether the students get benefits from the software employment. In detail, the double test to which all the individuals were subjected, lets the examiners remark which subjects perceive the greatest advantages from the software, according to their estimated problem solving skills.

Further tests of the proposed computer supported procedure have been carried out by a group of 4 PhD students and a postdoctoral research fellow in Mechanical Engineering with no TRIZ background, in order to appreciate differences and similarities according to the level of competences.

Given the encouraging results of the mentioned tests, as reported in Sections 4.3.1.3 and 4.3.1.4, a further verification activity has been designed in order to best appreciate the role of the algorithm in supporting the problem analysis skills. The new test has involved manual exercises about the same problems, by introducing a control group represented by a different set of Master Degree students in Mechanical Engineering, with matching competences and education with respect to the previous group; a convenience sampling was newly carried out, thanks to the availability of 22 subjects. The employment of control groups is widely recalled in recent literature with the aim of evaluating the effects of design practices (Collado-Ruiz, 2010; Vargas Hernandez, 2010) and software supports (Hassard, 2010; Scheuer, 2010). Such experiment and its outcomes are described in 4.3.1.5.

4.3.1.2 Test problems

The testing activity of the web-based procedure has been carried out in computer laboratories where each person, in at most 90 minutes, had to analyse one of three real industrial problems described in the following. These problems have been chosen for their different characteristics, in order to evaluate the different capabilities of the algorithm in driving the user towards the logical blocks of the dialogue-based system related with the task (removal of a negative effect, implementation of a new function, enhancement of a given performance), which was considered the most proper for each of them.

Although each problem structure depends on the user interpretation (Simon, 1973), it is expected that people model the case A as a typical TRIZ contradiction or as a situation where a given performance is required. The problem B clearly points to a negative effect, but should be preferentially modelled as a contradiction, i.e. with two conflicting requirements to be satisfied, while the problem C should address the tester towards the implementation of a new performance or the improvement of an existing one.

Finally, the three problems have been assigned to the students and to the fellows as it follows:

- Problem A: 11 students (5 from Milan and 6 from Florence) and 2 PhD students (both from Milan);
- Problem B: 13 students (6 from Milan and 7 from Florence) and 1 PhD student (from Florence);
- Problem C: 6 students (all from Florence), 1 PhD Student and 1 postdoctoral research fellow (both from Florence).

The description of the problems is enriched with viable solution concepts. Although no problem solving process was required, the proposed concepts help in evaluating the correctness of the abstraction process.

Problem A: Anodizing tank

The aluminium is subjected to the anodizing process in order to increase:

- *resistance against corrosion, wear and abrasion;*
- *surface hardness.*

The workshop of a company that produces aluminium beams comprises an array of anodizing tanks. The average dimensions of the tanks are 3 m in height, 4m in length, 1m in depth. The tanks contain cleaning acids and

other chemical substances meant to work as fixing agents. Some tanks must be kept at the temperature 96°C.

A suspended tray conveyor catches the holders on which the beams are hanged and moves them from one tank to another with the variable pace of 5-20 minutes. The problem concerns the conservation of the higher temperatures of the pools, minimizing energy waste, avoiding the usage of lids that would provide complications for the movement of the conveyor.

A possible solution, described in (Hagen, 1968), is the employment of floating balls or different objects, viable to create an insulating blanket covering the pool and allowing, at the same time, the introduction of the holder and the beams.

Problem B: X-ray inspection system

An X-ray inspection system checks the presence of foreign bodies inside foodstuff, in order to select and remove non-compliant items. In order to protect the workers and onlookers from X-rays, lead layers internally line the device. Obviously the input and outputs for the items to be inspected cannot be screened in the same way.

Such inputs and outputs are configured as rectangular windows that allow the flow of the conveyor belt and consequently of the foodstuff. Curtains with fringes, which embed the lead layers viable to absorb the X-rays, perform the protection of the windows. The external shell of the fringes is usually made of a polymer. The needed flexibility of the fringes doesn't represent any problem, due to the extreme ductility of the lead; once the item to be examined has crossed the passage, the curtain elements come back by themselves to their position.

However, each object impacting the curtain produces wear. The fringes are normally replaced once a year, but in some cases the substitutions are necessary within few days. The items causing the greatest wear are the lollipops. Arrays of 3 lollipops are carried inside the inspection system, with the sticks being fitted in a support moved by the conveyor.

Several solutions can be found by applying the TRIZ inventive principles determining separation in space, e.g. by creating a waved path for the transportation belt or by substituting the fringed curtain with a rotating inlet such that the items under inspection do not touch the partition surface.

Problem C: Gas transfer among cylinders

It is necessary to transfer all of the gas from a transport cylinder to two empty (working) cylinders (e.g. oxygen tanks for deep-diving). The capacity of each of the working cylinders is equal to one half of the capacity of the transport cylinders.

If the transport cylinder connects directly with the working cylinders, an equal pressure is fixed in all the cylinders and, as a consequence, half of the gas stays in the transport cylinder. An alternative is the use of a compressor, but it is more complicated and expensive: the gas is pumped from the large cylinder into two others. In this manner it is possible to transfer all the gas, but it is necessary to employ special equipment, such as

a high-pressure compressor, which is not convenient, for example, on a boat.
The aim is to find a method to fully transfer the gas from the transport cylinder to the working cylinder without the use of any additional equipment.
A possible solution (Petrov, 2004) consists in positioning the small cylinders, filled with water, at a higher quote and to open the circuit connecting them with the big one. The difference of pressure pushes the water in the transport cylinder, forcing the gas to move in the opposite direction.

4.3.1.3 General overview of the results of the computer aided system

The results of the problem situation analysis have been evaluated according to the following metrics:

- a good result is characterized by a precise description of the problem by means of requirements, without particular mistakes or misinterpretations, as well as by a large set of features and elements required by the dialogue based system, viable to lead towards an appropriate information retrieval;
- a satisfactory result is characterized by a global comprehension of the problem under investigation with an almost complete description of its main characteristics also in terms of identified requirements; the available information about the problem gives just preliminary direction of research for information gathering;
- an unsatisfactory result relates to a poor description of the problem, rich of misinterpretations and with no useful information capable to enlarge the potential solution space.

Table 11 provides an overall outlook of the results gathered by the Master Degree Students from both the Universities, while PhD students were considered separately. In the assigned time, more than 60% of the Master Degree Students were driven towards one of the final nodes of the algorithm (144 or 145, depicted in Table 8), as well as 23 of 30 (76,6 %) gave at least a satisfactory description of the problem situation. However, just a small part of them (13,3% of the grand total) properly formulated a contradiction.

Table 11 :Outcomes obtained by students of both the Academic Institutions involved in the testing activities and organized according to the metrics adopted for the evaluation

		Institution		
		Università di Firenze	***Politecnico di Milano***	***Both***
Outcome	***Completed procedure***	63,2%	63,6%	63,3%
	Formulated contradiction	10,5%	18,2%	13,3%
	Good result	36,8%	54,5%	43,3%
	Satisfactory result	42,1%	18,2%	33,3%
	Unsatisfactory result	21,1%	27,3%	23,3%

The latter students achieved the best results in terms of abstraction as depicted in the Hill Model (Appendix E): they got to the description of a physical contradiction and also identified the main characteristics that the solution should have in order to positively solve the problem. An example of formalized contradiction is reported in Table 12, which highlights the original text of the main nodes that contribute to its formulation resulting as a consequence of the filled fields, previously

in square brackets. The shown example (referred to problem A) illustrates how the contradiction is completely formulated; regardless the user-system interface doesn't explicitly recall the TRIZ concepts. The consequent contradiction model is reported in Figure 57.

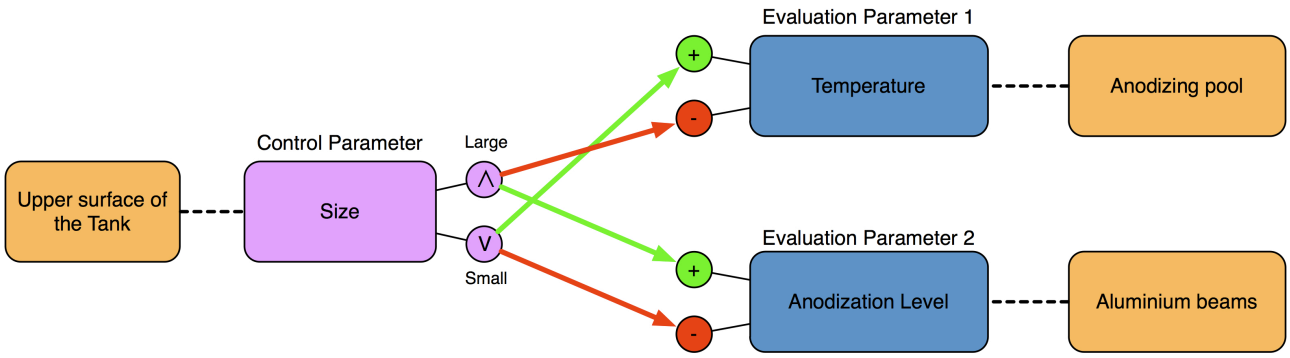


Figure 57: The contradiction model generated through the dialogue reported in Table 12.

Table 12: Right - an excerpt of the dialogue-based interaction occurring between the computer and the human. The column "Formulation" contains the generic question to be enriched through the variable introduced in a step-by-step fashion by the user of the platform.

Node	***Formulation***	***Main steps to achieve the formalized contradiction***
79	Q.: Which is the undesired effect that arises in the system as a consequence of getting the satisfactory level of the [PERF]? *(use a substantive without the article, e.g.: high noise, overheating,...)*	Q.: Which is the undesired effect that arises in the system as a consequence of getting the satisfactory level of the capability of isolation? *(use a substantive without the article, e.g.: high noise, overheating,...)* A.: decrease of temperature of the pool
34	Q.: Are you aware of any parameter, influencing the [OE], and belonging to one of the following: [SYS] [OBJ] [BEN] [SSYS]	Q.: Are you aware of any parameter, influencing the decrease of temperature of the pool, and belonging to one of the following: • tank • acids • aluminium beams • industry • open space • worker • other anodizing tank A.: Yes
38	Q.: Type a list of parameters (one per row) concerning the [VOE] and capable to impact/influence [OE] *Use substantives without the article (e.g. length, roughness of the external surface, pressure, thermal capacity...).*	Q.: Type a list of parameters (one per row) concerning the tank and capable to impact/influence decrease of temperature of the pool. *Use substantives without the article (e.g. length, roughness of the external surface, pressure, thermal capacity...).* A.: size of the upper surface of the tank

39	Q.: Choose one of the parameters belonging to the following list, focusing on what mostly, if any, influence the [OE]: [LPVOE]	Q.: Choose one of the parameters belonging to the following list, focusing on what mostly, if any, influence the decrease of temperature of the pool: • size of the upper surface of the tank A.: dimension of the upper surface
40	Q.: In order to weaken the [OE], should I increase or decrease the [PVOE] of the [VOE]? Type "increase" or "decrease"	Q.: In order to weaken the decrease of temperature of the pool, should I increase or decrease the size of the upper surface of the tank? Type "increase" or "decrease" A.: decrease
41	Q.: In order to enforce the [OE], should I increase or decrease the [PVOE]? Type "increase" or "decrease"	Q.: In order to enforce the decrease of temperature of the pool, should I increase or decrease the size of the upper surface? Type "increase" or "decrease" A.: increase
42	Q.: Do any bad consequences come out if you [NOOE] the [VOE]'s [PVOE]?	Q.: Do any bad consequences come out if you decrease the tank 's size of the upper surface? A.: Yes
43	Q.: When we [NOOE] the [VOE]'s [PVOE], does this result in the weakening or in the disappearing of any positive effect or useful function concerning any of the following items? [SYS] [OBJ] [BEN] [SSYS] [COMP]	Q.: When we decrease the tank 's size of the upper surface, does this result in the weakening or in the disappearing of any positive effect or useful function concerning any of the following items? • tank • acids • aluminium beams • industry • open space • worker • other anodizing tank A.: Yes
44	Q.: Type such positive effect *Use a substantive, without the article, or a verb in the -ing form (i.e. heating the gas, linking the components, control, deposition of salts...)*	Q.: Type such positive effect *Use a substantive, without the article, or a verb in the -ing form (i.e. heating the gas, linking the components, control, deposition of salts...)* A.: anodization of the aluminium beams
50	Q.: If you [NOOE] the [PVOE] of the [VOE], the [OE] is weakened, but this results in the diminishment of the [PE] too. Is it right?	Q.: If you decrease the size of the upper surface of the tank, the decrease of temperature is weakened, but this results in the diminishment of the anodization of the aluminium beams too. Is it right? A.: Yes
51	Q.: If you [NUOE] the [PVOE] of the [VOE], the [PE] increases, but the [OE] is enforced too. Is it right?	Q.: If you increase the size of the upper surface of the tank, the anodization of the aluminium beams increases, but the decrease of temperature is enforced too. Is it right? A.: Yes

Consistent with the OTSM-TRIZ problem solving models mentioned in Section 3.3 and presented in Appendix E, the algorithm has proved to be successful in stimulating the user in refining the problem under investigation, by asking him/her whether the detail level of the analysis is correct or not, allowing consequently to focus on different hierarchical levels of the system, thus moving upwards or downwards in the central column of the System Operator depicted in Figure 44 (more than 50% of the students have modified their initial definition of "system").

The convergent process described by the Funnel Model (Appendix E) emerges by analysing the body of results produced within this testing activity: the students, by following similar paths of investigation, frequently converged towards the same problem model, answering the questionnaire with similar definitions for the needed variables, even if, in many cases, this hasn't resulted sufficient for formulating an appropriate contradiction. Coherently with the objective of this research, the structure of this step-by-step procedure allows to obtain convergent results even when the users start the analysis from different perspectives. It could be interesting to make useful comparisons among design methods in order to assess which ones, as well as TRIZ, and most specifically the ARIZ procedure (Appendix F), produces good results in terms of repeatability and similar outcomes.

For what concerns the potential differences in the solving path followed by more specialized people, the group formed by the PhD students and the postdoctoral research fellow produced only good or satisfactory results. In three cases they got to a good formulation of a contradiction, thus abstracting the problem and identifying the main features of the solution. In the remaining two cases the description of the problem is just satisfactory, but useful to perform a preliminary information search through the available sources (patents, scientific and technical literature) through which it is possible to enhance and refine the analysis itself or to find proper solutions.

4.3.1.4 Evidences from the within-subject test

The manual test that was previously carried out led to the following shares of proficiency results:

- good: about 46%
- satisfactory: about 19%
- unsatisfactory: about 35%.

By comparing the overall outcomes of the manual tests conducted by the MS students and those obtained through the proposed dialogue based system, the share of students showing negative results drops therefore from roughly 35% to about 23%. Moreover, it is worth noticing that the percentages of good results are pretty similar regardless of the support of the computer-aided procedure.

However, an in-depth analysis of the results highlights that students that had showed good problem solving skills (approximately 46% of the grand total) didn't obtain particular benefits in approaching the situation by means of the dialogue-based system (Table 13). One third of them described the topic to be analysed by modelling it correctly, while the remaining two thirds produced a worse analysis than the one they could arrange without guided support (although with different problems). Nevertheless, it is worth to mention that just 15% of them produced a complete unsatisfactory model of the problem, while the others depicted it at least at a satisfactory level.

On the contrary, the greatest benefits of the procedure (Table 13) emerge with those students that had previously showed more limited (just satisfactory or even poor) problem solving skills (respectively the 19% and the 35% of the grand total). Indeed, 80% of the first ones and 56% of the second ones described the problem in a more appropriate way than they had been capable

without exploiting any support. The carried out analysis helped them in both correctly identifying spaces of solution that hadn't previously emerged because of psychological inertia or lack of knowledge and narrowing down the direction of research for useful information aimed at problem solving purposes.

Table 13: correlations between the results obtained through the adoption of the algorithm and the tests on problems carried out without the support of the algorithm

	General amount of students [%]	***Positive outcomes with the questioning procedure [%]***	***Negative outcomes with the questioning procedure [%]***
Students having used PS methods with good results	46,2%	83,3%	16,7%
Students having used PS methods with satisfactory results	19,2%	80,0%	20,0%
Students having used PS methods with unsatisfactory results	34,6%	55,6%	44,4%

As depicted in Table 11 and recalled at the beginning of this subsection, the outcomes of the procedure can be considered good in the 43,3% of the cases, while the others are satisfactory for the 33,3% and non-satisfactory for the 23,3%.

Moreover a comparison between the Master Degree students from both the academic institutions, does not highlight particular differences, since positive results have been obtained by about 75% of the sample (approximately 80% in Florence and 70% in Milan); however it is important to mention that students from Politecnico di Milano totally got better quality results (good, roughly 54%; satisfactory, 18%) than their mates from Università di Firenze (good, about 37%; satisfactory 42%).

By thoroughly investigating the procedures carried out by the students that obtained good results, it is important to highlight that many of them achieved great benefits by changing the definition of the "technical system": they progressively changed the scope of the problem by identifying an appropriate detail level and the critical requirements to be improved or the causes that prevent their satisfaction. It is noticeable that all these students, regardless of the industrial case under analysis, considered the problem related to unsatisfactory or even missing performances of the technical system. The iteration of the procedure gave them a different perspective of the whole problem and, by means of problem reformulation, one third of them identified a critical contradiction for the solution of the problem. The students of this group that didn't get to the definition of the couple of conflicting requirements, anyway leveraged their knowledge in order to give a description that made sense and however viable for a profitable information retrieval. The greatest part of these students (about 85%) came indeed to one of the final nodes of the procedure with positive conclusions.

On the other hand, the students that didn't succeed in obtaining valuable results often followed an odd logic, since they experienced some difficulties in distinguishing between elements/components of the system and their related parameters. Some of them (about 50%) tried to force the procedure towards the direction of a solution they had intuitively elaborated, rather than using the dialogue based system as a guiding tool to gradually explore the

characteristics of the problem under investigation. Differently from their colleagues that obtained positive result, the greatest part (around 57%) of these students didn't get to the end of the procedure, without taking therefore advantages from the refinement of the definition of the system.

It is equally important to verify whether the goal of approaching the problem with the right branch of the procedure has been met. By considering the sequence of steps that all the students went through, the analysis of Pearson's correlation has been carried out, remarking that the students, regardless their success in exploiting the procedure, followed very similar paths of the problem investigation. Indeed, the lowest value of correlation between pairs of exercises is approximately 0,72; such evidence can be considered from two different points of view. First, the individual cognitive processes are sensitive to similar education programs; second, the procedure doesn't have the expected capability of driving the user in the distinction of different issues. In order to remove this ambiguity, it is worth to carry out further tests with different people from various expertise fields and with different vocational experiences.

4.3.1.5 Control group test: description and outcomes

A control group test has been designed in order to produce statistical data capable to determine if the computer support may significantly help the user in the analysis of the initial situation of a technical problem. The computer-based procedure represents the treatment to which a different set of experimental units (students/problem solvers) was submitted.

Moreover, the control group that has performed such test on the same problems described in Section 4.3.1.2, allows to better pinpoint the benefits and drawbacks arising from the employment of the algorithm. More precisely the test with the control group was set up to estimate the proposed procedure in terms of:

- capability to entail a systematic abstraction process (Hill Model, Appendix E), in which a large set of features are taken into account;
- the capability to guide the user in reformulating variables and concepts;
- the effect of using terms previously introduced by the user;
- the effect of following suitable alternative paths with the objective of identifying the couple of conflicting requirements.

Advantages and disadvantages are therefore estimated according to the declared objectives of the algorithm, thus evaluating:

- the richness of features and variables of the problem under investigation that have been introduced, as well as their correctness and utility within subsequent patent search and problem solving tasks;
- the problem analysis and abstraction paths that have been followed;
- the capability to describe the problem situation through the individuation of conflicting requirements.

The students were asked to answer a set of six questions, provided in a random order, regarding the main issues for the problem description. It was additionally asked to specify the order followed during the situation analysis, with the objective of evaluating their reasoning process. This aspect is critical since a predetermined order for such questions would allow making comparisons between two different algorithms (computer-based vs. paper), while the declared objective is to determine whether the dialogue-based procedure brings benefits if compared to individual capabilities. In order to allow the repeatability of this experimental activity, the abovementioned set of questions is hereby reported:

- Synthetically describe the core problem of the technical system under investigation (maximum 30 words).
- What technical function should be carried out in order to satisfy the needs of the end users employing the device under study?
- Remark who or what undergoes the modifications carried out by the technical system that is described.
- Describe the most impacting undesired/harmful effect/condition (including performances that achieve an unsatisfactory level and further missing functions) that emerges in the described situation.
- With reference to the undesired phenomenon or unsatisfactory aspect of the case study, clarify who or what mostly perceives the bad consequences that arise.
- Which element(s) cause(s) the problem described in the case study? Clarify if such component performs any positive function.

It is worth noting that giving the students a set of predefined questions constitutes by itself a support to the problem analysis, since many students, as well as many designers, tend to analyse technical problems by intuitively skipping most of the relevant questions, thus omitting not negligible portions of the analysis. Nevertheless, it has been decided to propose a set of standard questions, in order to have more comparison elements between the two tests.

As briefly described above, the students supported by the dialogue-based procedure had to follow a predetermined path that, according to author's experience, supports the abstraction process of the problem. On the other hand, the students of the control group were free to answer the questions using the order they preferred. Therefore, the capability of carrying out a comprehensive analysis of the problematic situation has been evaluated by considering all the above-mentioned features.

The analysis of the sequences of answers specified by the 22 students involved in the control test, reveals that they have followed 16 different reasoning paths, thus resulting in a great variability of the logical procedure followed by the individuals; moreover, approximately two thirds of them almost had no meaning, nor solid structure.

Nevertheless, the order selected by the students for answering the proposed questions has not been considered as an evaluation criterion for the correctness of the analysis. Besides, the evaluation in terms of good, satisfactory and unsatisfactory outcomes has been conducted in analogy with the metrics adopted for the former computer-aided test (Section 4.3.1.3). Then, the overall set of information contained in the answers has been evaluated in terms of completeness of the problem description by remarking its key elements, individuation of evaluation parameters and impacting design variables, width of the solution space etc.

The control test has been conducted with the same time constraints of the computer-based experiment. The author had preliminary estimated that the complete analysis delivered by means of the above mentioned set of questions would require less time than the one performed with the support of the computer. However, this assumption has not been confirmed, since the quickest students concluded the test in about 75 minutes and the greatest part of them required all the available time (90 minutes).

Among the 22 students that carried out the test:

- 12 obtained an unsatisfactory result (54,5%);
- 6 obtained a satisfactory result (27,3%) and
- 4 obtained a good result (18,2%).

Table 14: Summary of the results carried out by the test group (Computer-Aided row) and the Control group that worked without the support of the algorithm under test (Individual row). Contingency table of Observed results.

		Outcomes of the procedures			
		Good	***Satisfactory***	***Unsatisfactory***	***Total***
Analysis approach	***Computer-Aided***	13 (43,3%)	10 (33,3%)	7 (23,3%)	30
	Individual	4 (18,2%)	6 (27,3%)	12 (54,5%)	22
	TOTAL	**17**	**16**	**19**	***52***

Table 14 summarizes the results of this test, together with the ones obtained by means of the computer-based algorithm. These data clearly shows that the overall outcomes obtained by means of the dialogue based procedure are significantly better than the results of a non-supported analysis.

Indeed, the algorithm allows to get good descriptions of the problem in approximately 43% of cases while just 18% of the individual investigations produces good results. On the other hand, the ratio of unsatisfactory results grows from 23% to 55% when the initial situation analysis of a technical problem is performed just relying on individual capabilities.

In details, in many cases these students did not produce any valuable analysis since they just tried to replicate with their own words what they read in the text concerning the described problems and, whenever they tried to deepen the investigation, they took into account negligible issues related to aspects of marginal relevance.

Somehow, the task of answering to a random sequence of questions related to a problematic situation, revealed to bring worse results even compared with those achieved by the initial group of students without any computer support.

In order to strengthen the reliability of the conclusions, a Pearson's Chi-square test has been carried out in order to verify if there is an association between the two categorical variables related to the followed procedure for problem analysis. In detail, this statistical test aims at discussing if the results obtained are dependent to each other or if the treatment, i.e. the computer-aided procedure, plays some influence on the outputs.

People randomly picked from the same population (MS students in Mechanical Engineering) compose the two statistical samples. The 30 students that analysed the problem by the dialogue-based algorithm constitute the sample of people to whom the treatment has been applied. The above described control group (22 students) form the sample that described the initial situation of the technical problem just by means of individual capabilities. Furthermore, the descriptions of the experiment conducted on both groups and the adopted evaluation metrics are sufficiently detailed to show that this statistical test may verify if the treatment affects the results of the problem analysis. According to a rule of thumb, a proper value for the significance level of the test is 0,05, which means that the probability of an incorrect rejection of the null hypothesis is 5%.

Then, considering the limitations due to all the effects related to unknown causes that may affect the test, the null and the alternative hypotheses are, respectively:

- H_0: there is an association between the results obtained by means of the computer-aided procedure and the ones produced with the individual analysis;
- H_a: there is not an association between the results obtained by means of the computer-aided procedure and the ones produced with the individual analysis.

Table 15 summarizes the expected "theoretical" results, obtained and calculated under the hypothesis of statistical independence as mentioned in the null hypothesis. Such values are required in order to verify if the null hypothesis has to be rejected. The expected values contained in each cell are greater than 5 and the two samples are composed by more than 20 elements each, then the Chi-square test can be performed without applying the Yates' correction.

Table 15: Contingency table of Expected values. The Testing and the Control group are organized in rows; the obtained outcomes are organized in columns.

	Good	***Satisfactory***	***Unsatisfactory***	***TOTALS***
Computer-Aided Analysis	9,81	9,23	10,96	**30**
Individual Analysis	7,19	6,77	8,04	**22**
TOTALS	**17**	**16**	**19**	***52***

The number of degrees of freedom to be considered is 2, since it is calculated by multiplying the number of rows, reduced by one, by the number of columns, still reduced by one. The value of the Chi-square test-statistic is 5,99 meaning that the p-value is 0,05, i.e. the probability that the null hypothesis is true is 5%. This means that the null hypothesis can be rejected and it is possible to assess that the treatment (the support given by the computer-aided procedure) plays a relevant role in affecting the quality of the initial analysis of technical problems.

4.3.1.6 Discussion of the results of the first testing activity

The first testing campaign performed with the prototype system for inventive problem analysis demonstrates that it is possible to support the thinking process of an inexpert designer by means of a dialogue-based human-computer interaction. In fact, MS students in Mechanical Engineering clearly benefit of the computer support, both in terms of completeness of the analysis and correctness of the problem formulation.

The proposed TRIZ-based algorithm is capable to guide the largest majority of users with very limited TRIZ competences towards a precise description of a given technical problem by means of an appropriate set of design variables and evaluation criteria; a noticeable percentage of them reaches the identification of the couple of conflicting requirements (the contradiction) behind the problem and the related operational space and time. Indeed, the latter achievement should be considered the main objective of a TRIZ-based procedure, thus highlighting the need to further investigate why two thirds of the students who obtained good results in the problem analysis with the computer support, still failed to complete the task of describing the problem itself as an OTSM-TRIZ contradiction.

The tests performed so far have confirmed also that the computer guide is very effective at producing a convergent problem solving process as prescribed by the Funnel model (Appendix E), which appears to be a necessary feature since the 22 students of the control group followed 16 different paths, most of them apparently without a proper logical meaning.

Besides, the investigation must be deepened in order to properly interpret the behaviour of the users with respect to the other OTSM-TRIZ models of problem solving mentioned in Section 3.3 and presented more extensively in Appendix E.

For example, despite the analysis of the tests made with the support of the computer clearly revealed that the algorithm stimulates also the reformulation of the problem, by changing the perspective of the analysis according to the logic of the central column of the System Operator (Figure 44), appropriate measures still have not been identified to measure the efficiency of such

process. More specifically, the next studies (presented in Section 4.3.2) aims at measuring the capability of the algorithm to break the user's psychological inertia and to identify useful resources for problem solving at different detail levels (super-systems, sub-systems) and in different time intervals (past-future).

Another aspect to be further investigated is the combined effect of basic TRIZ education and computer support. In fact, the efficiency of the tool might be enhanced by the introduction of the key concepts of TRIZ, even without a detailed training about system modelling and contradiction analysis. From this perspective the human-computer interaction might be more effective through the integration of graphical information in the output dialogues, in order to clarify with a visual representation the meaning of the algorithm questions and the results of the user's answers.

Finally, the study still has not considered the correlation between the individual profiles of the students (e.g. mark received in previous courses, English language skills etc.) and the outcomes of the computer-supported test. This correlation might provide relevant insights about the strengths and the weaknesses of the algorithm, since the results achieved by the PhD students involved in the preliminary tests were definitely better than those of their younger/less qualified colleagues. Besides, students with higher intuitive problem solving skills got fewer benefits than their less talented mates.

4.3.2 Tests of the second release of the algorithm for identifying conflicting requirement during the analysis phase of the design process.

The second testing activity is presented in a more agile fashion, since the greatest efforts to obtain highly reliable quantitative results have been devoted in the previous testing phase.

In this case, the testing activity has been carried out with the second release of the algorithm, by exploiting the availability of a group of Italian students attending Master Degree courses pertaining to the class of Industrial Engineering and coming from Politecnico di Milano (9) and the University of Florence (6). This group of students, as the ones participating the first testing activity, attended about 20 hours of TRIZ lectures. Then, even in this case, it follows the consideration that they cannot be considered TRIZ or, at least, skilled problem solvers since the most relevant industries using TRIZ in R&D department train their fellows with 40-hours long (basic) to 200-hours long courses (experts) (Adunka, 2007; Lee, 2010).

Furthermore, so as to explain the opportunity to present these results more straightforwardly, this experiment is aimed at comparing the capabilities of the new module in enhancing the problem modelling activity with reference to the previous version of the algorithm. To this purpose, the activity has been willingly carried out without a control group.

Indeed, the contribution of the new module can be assessed considering what results could be reached with the two different versions of the algorithm, taking into account that the new one allows the users that end without a successful outcome to go on with the analysis by means of the System Operator block.

The problems to be analysed (two, in this case) by means of the algorithm have been described and proposed in English language, as follows:

> ***Problem A***: *A system for applying a piece of a thin film on the surface of a glass includes a driving roller, a support roller and a vacuum system which is integrated in the device supporting the film. A non-sticking separator protects the adhesive side of the film; an appropriate device (separator mechanism) removes the protection before the film is applied on the glass. At the end of the process of application, the adhesive film cannot be*

supported by the vacuum system; as a result the film is free to move from its supporter and traps air bubbles when it joins the glass. These air bubbles are considered a defect. The implementation of a vacuum system within the support roller has to be rejected since its surface must have no holes for a good quality of application of the film. Furthermore, an attempt to reduce the distance between the free end of the film and the support roller has not solved the air bubble problem.

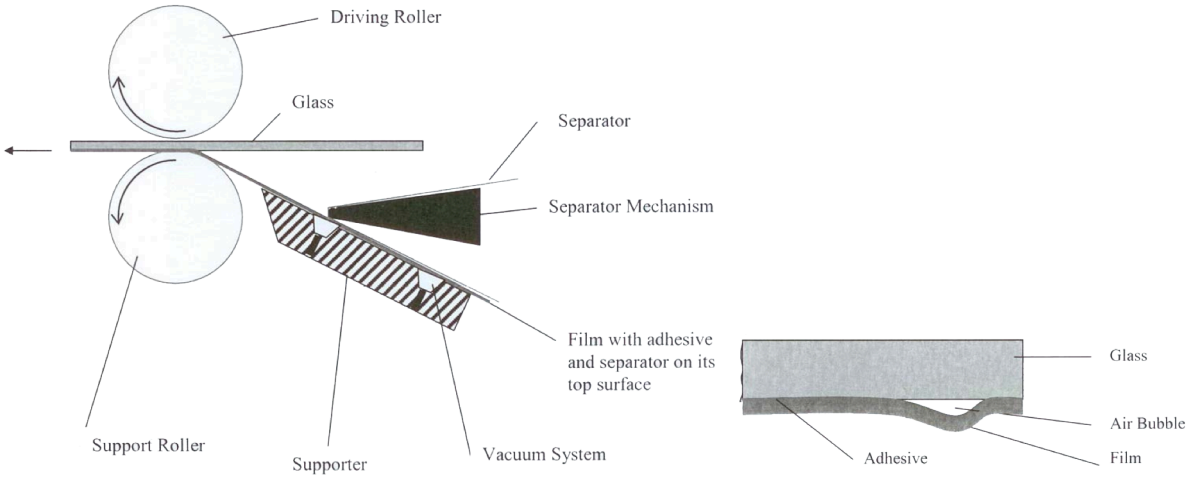


Figure 58: Images describing how the system for glass coating works and how the problem appears

Problem B: *It is required to fasten the panhandle to the main body of a frying pan. Rivets are conventionally used in order to fix the mutual position between the panhandle and the main body. However, this structure worsens the cleanliness of the main body, since food residuals usually get stuck in the joining place. Consequently, in order to enhance the cleanliness of the frying pan, the main body is fastened to the panhandle through a welding joint and a threaded joint. The main body, the panhandle, a dowel, a ring nut and a bolt compose the assembly. The main body and the dowel are made in aluminium while the panhandle is in Bakelite. The dowel gets externally welded to the main body, while internally has an internal screw thread. The ring nut covers the dowel and gets locked in a fixed position by means of reference ribs. The ring nut delivers two functions on the panhandle: protects it from heat and stabilize its position when the assembly is complete. The panhandle is locked from its lower part to the remaining parts by means of a bolt that is joined to the internal thread of the dowel. The threaded joint produces a small deformation in the main body when the bolt is fastened to the dowel. As time goes by, this deformation increases and the whole assembly starts to lose stability. When the frying pan is in use it also bears the load of the food contained in the main body. This further induced deformation increases the instability and after a while the frying pan gets unusable because of the loosening of the panhandle.*

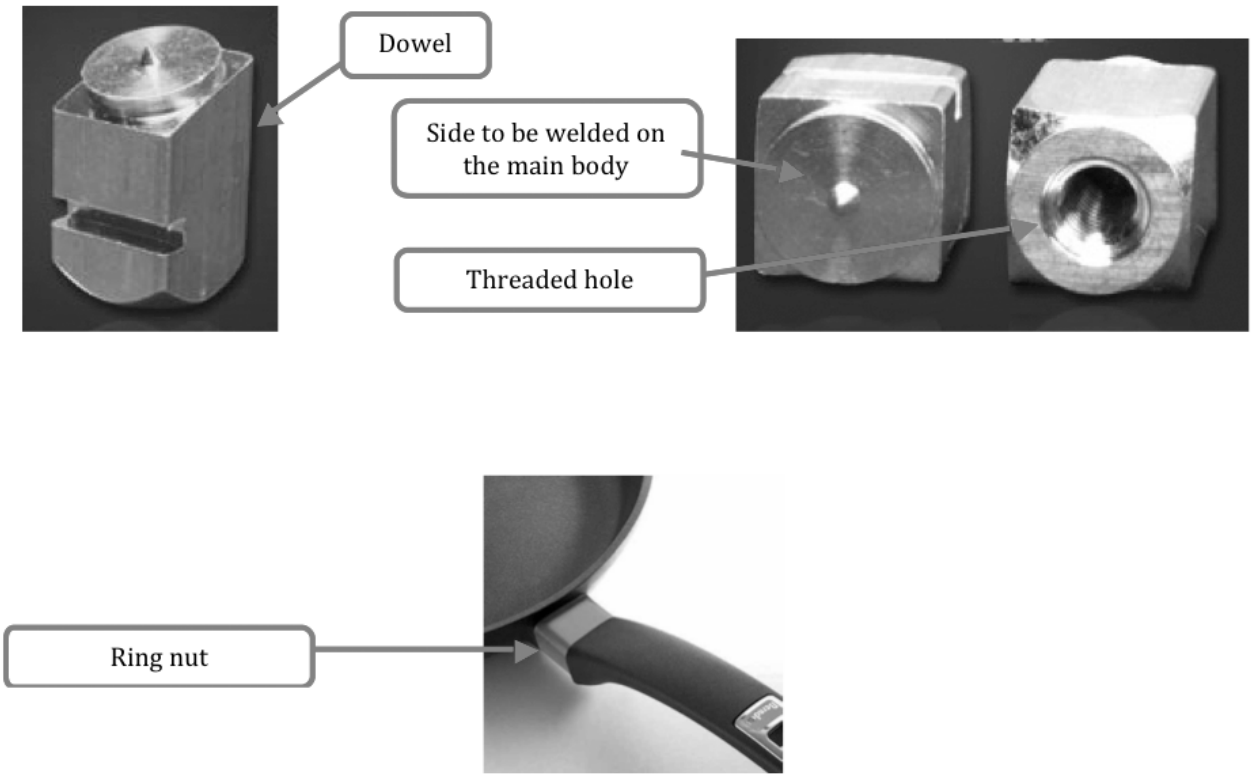


Figure 59: Some elements of the joint composing the junction between the panhandle and the panbody

Each student has a free personal access to a website where the algorithm has been implemented (http://www.smeinnovation.org) and no specific time limit for carrying out the analysis, even if they were advised that an analysis should not require more than a hour and a half, as a whole.

Among the 30 analysis tests that were carried out:

- just 3 of them (10%) didn't conclude the analysis and stopped before the conclusion;
- 10 of them (33,3%) identified a contradiction according to the OTSM-TRIZ contradiction model (an example is represented in Figure 6);
- 12 (40%) of them solved the problem by identifying a characteristic of the system or of its surroundings without formalizing a contradiction;
- 5 (16,7%) of them stopped the analysis without deepening the investigation by means of the new System Operator block.

Then, it is possible to claim that about three quarters of the proofs resulted in a successful analysis of the problems by means of the procedure and just one quarter didn't come to a proper model of the problematic situation. Furthermore, it is worth noting that in 12 exercises out of 30 (40%) the students analysed the problematic situation by means of the System Operator block and none of their analysis produced unsatisfactory results. This result, if compared to what would happen with the previous version of the algorithm, highlights that the System Operator block improves the capability of the system in producing valuable problem analyses. Indeed, without the help of this new logical block, 20 out of 30 (66,7%) students wouldn't carry out a correct problem analysis.

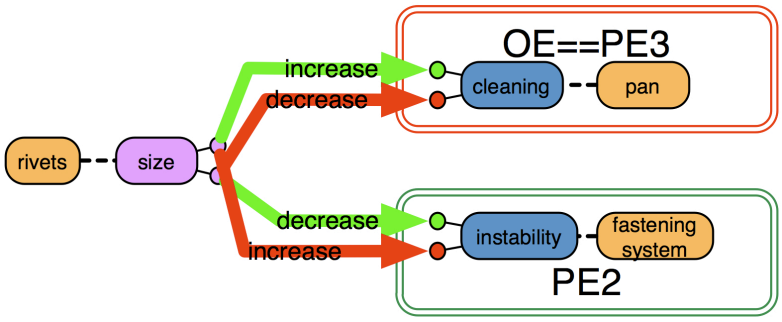


Figure 60: problem of the frying pan: example of OTSM-TRIZ model of contradiction

More in detail, in the 12 experiments that have involved the System Operator block, the students modelled the problem with a contradiction (again, the two conflicting requirements to identify in order to efficiently address the problem solving process) in just two cases, while in the remaining 10 cases they just identified a useful resource that can help in solving the problem without implying any further drawback for the technical system. At last, it is important to point out that none of these students chose to reformulate the problem from scratch.

With the aim of better pointing out the advantages arisen with the second version of the dialogue-based system, it is worth to mention that the previous testing activity had different purposes than these experiments, as reported in Table 16. Nevertheless, the wide body of results emerging from the first testing campaign, if examined according to a different metrics, can be compared to this second experimental activity. This allows highlighting the benefits arising by the introduction of the module for broadening the analysis of problems, which are illustrated in the following section.

Table 16: Comparison of the tests performed with the previous and the current version of the algorithm.

	Previous version of the algorithm	***Current version of the algorithm***
Objective	Demonstrate that the algorithm improves the results of non-supported analysis of inventive problems	Demonstrate that the introduction of a module for broadening the analysis of inventive problems improves the results of computerized analyses
Metrics	• Correctness of the answers; • Amount of identified problem features; • Reusability of variables for patent searches.	• Number of identified couples of conflicting requirements; • Type of problem formulation; • Quantity of concluded analyses.

4.3.2.1. Discussions

The results of the test point out the relevance of broad-spectrum problem investigation and, in the specific case, the contribution provided by thinking through System Operator when designing with the support of a TRIZ-based CAI system.

With reference to the test performed with the previous version of the algorithm, the rate of completed analyses, formulated contradictions and quality outcomes is significantly enhanced, although the new block is not addressed to play an equivalent role according to each single issue, as summarized in Table 17. Additionally, if compared with the outcomes mentioned in Sections 4.3.1.4-6, the topic of the analysis seems to play a significantly lower impact in determining the ratio of good results. Indeed the two exemplary case studies show the same percentages of formalized contradictions and non-inventive problem formulations; unsuccessful cases differ for the percentages of interrupted questioning procedures (13,3% for the air-bubble formation, 6,7% for the frying pan) and stopped analyses neglecting the System Operator blocks (13,3% vs. 20%).

Table 17: Comparison of the tests performed with the previous and the current version of the algorithm.

	Test with the previous version	***Test with the current version***
Formalized contradictions	13%	33%
Non-inventive formulation of the problem	13%	40%
Concluded analyses	63%	73%

It has to be highlighted that the further employment of the new logical block occurs in those cases that no section of the dialogue-based system is capable to guide the user in performing a proper formulation, typically after some elements of the problem have been investigated. Consequently the exploitation of the System Operator branch should not imply a consistent time burden when performing the analysis with the dialogue-based system, being it preferentially accounted at the beginning of the problem analysis process. The average number of answered procedure nodes confirms the hypothesis: the survey of the results indicates how, on the average, 48 nodes have been tackled when the new block is involved, 64 when the user is not directed in such investigation area. The 30 analysis tests required a different time amount without significant differences between the two problems; the overall range spans from about 45 to about 90 minutes.

Further insights regard the quality of the results, not just in terms of the formal correctness of the problem schematization, but also from the viewpoint of the usability of the outcomes within real problem solving tasks. The formalized contradictions, i.e the couple of conflicting requirements characterizing the problem, were qualitatively evaluated in terms of the explicitness of the typed parameters and elements in effectively representing conflicting issues to be overcome in order to reach an inventive solution. Students that individuated non-inventive formulations of the problems (regardless the involvement of the System Operator block) were asked to motivate why the measures they would undertake would lead to improve the system without particular negative consequences. Whereas relatively few relationships among the parameters constituting the contradictions resulted vague, a greater ratio of ideas provided according to non-inventive formulations were evaluated as partial, poorly creative, hardly feasible or however unclear solutions. An example follows of doubtful non-inventive formulations regarding both the case studies (Table 18).

Table 18: Examples of unclear non-inventive problem formulations

	Modification of certain features assessed by the tester as feasible and without negative consequences
Frying pan problem	decrease the dowel's deformation (in order to weaken the instability of the system)
Air bubble problem	increase the power of the vacuum pump (in order to weaken the inadequate expulsion of air)

The motivations provided by the students remark how, in several cases, such inaccurate problem descriptions result as a consequence of separately elaborated solutions, thus trying to force the procedure towards the embodiment of previously conceived ideas. The tendency of concentrating on solution embodiments and justifying their effectiveness results as a common behaviour of novice designers, such as those involved in the testing campaign of the dialogue-based system. The crucial stage of problem analysis typically results incomplete due to their consideration of an insufficient number of relevant issues within the design problem (Ahmed, 2005). Kokotovich argues that inexperienced designers lack appropriate thinking tools for accurately mapping the complex interrelations among the concepts and the issues involved in the design (Kokotovich, 2005).

On the basis of these considerations, it can be assessed that the developed logical block for broad-spectrum thinking has resulted very useful in identifying resources or features capable to impact on the core problem of the investigated topics, but it has just marginally influenced the solution-oriented aptitude of novice designers. From this point of view further developments of the dialogue-based Compuer-Aided Innovation system should be performed aiming at customizing the procedure according to the user experience in design tasks. Such measure should allow the questioning algorithm to consistently comply with the individual behaviour of designers with regards to their preferred orientation towards the careful analysis of the problem or rather the focus on thought solutions and their further flaws. Of course, in the second case (to be discouraged), the procedure should be capable to address in each case a comprehensive system analysis and to show alternatives and advantages with respect to previously determined ideas. In order to ease the mapping of relevant issues of technical problems, additional human-computer interactions should be experienced than the unique text communication form currently supported by the dialogue-based system (e.g. by exploiting visual representation tools). Moreover, the capability to map the complexity of the relationships of the systems should be supported through performing multi-contradiction analyses (according to the Network of Contradicitons) rather than highlighting single conflicts.

5 Conclusions

This last section aims at recalling and reorganizing the main elements that characterize this work so that some main conclusions can be drawn about the overall goal of this work and the specific objectives that have been pointed out during the development of the activities, also in terms of strengths and weaknesses of the proposed approach.

Moreover some considerations about the potential future developments of this work are depicted with reference to potential fields of application.

5.1 Summary of the activity

In the introduction, the overall goal of this activity has been expressed as the need to identify new instruments that are capable to support the engineering design processes by pointing out which are the objectives and the requirements to be satisfied by a design proposal that has to address the emergence of needs from both the industry and the market.

The formulation of such a goal comes from the consideration that industries have to face the challenge of competition by innovating their products, processes or services that represent their business. In this context, Systematic methods are the best alternative among design methods in order to steer the design process with effectiveness and efficiency (Gero, 2012), thus stopping to miss opportunities that, without the appropriate definition of objectives, won't be not just taken, but also even recognized. In other words, pointing out the right directions for the development of innovative solutions, therefore, is the key to drive the engineering design processes with effectiveness and efficiency, avoiding the risks due to wrong choices, which, in turn, dramatically impact on investments and revenues and compromise the aim of keeping industrial competitiveness. Knowledge plays the paramount role in the definitions of such objectives, instruments and means to externalize it from the individual sphere (tacit), where it gets generated, to the external world where it has to be discussed and used and also shared for future reuse (explicit), have a strategic relevance in supporting the design processes. Existing means to support the definition of objectives and requirements during the engineering design process (e.g. Pahl, 2007) are effective in a wide range of cases. However, they are characterized by an apparent contradiction: the ones that support the definition of a wide number of requirements are mostly suited for specific fields of technology (e.g.: standards and checklists) and show lacks in terms of their flexible use in different industrial contexts. On the other hand, methods capable to answer to the exigencies of different domains of technique are mostly tailored to address the satisfaction of an overall objective at a time (e.g.: Design for X guidelines).

It is according to this perspective that the overall goal of the whole research activity has been set, with the objective of overcoming the abovementioned dichotomous situation. The proposal of a new set of criteria, at a higher level of abstraction, for the definition of requirements and objectives, that can be contextualized according to the specific situation at hand, thus allow addressing multiple objectives in a wide range of different applications. Moreover, to ease the adoption of such instruments and means in industry, computers are recognized as partners for supporting the whole design process (Lubart, 2004) and, more in detail, for the elicitation of tacit knowledge so that it is possible to easily use it within innovation development cycles.

Along the second section, the analysis has been carried out with reference to the issues emerged in scientific literature about the relevant topics for this research work. To this purpose a

definition of innovation has been provided in order to share a common vision on the purpose of this work. Together, the main scenarios for characterizing innovations have been presented in order to discuss that both technology and market have a paramount role in, respectively, pushing or pulling innovation and that common dynamics link them together in the emergence of new needs. According to this perspective, the emergence of new needs is directly connected with situations where things must be changed in order to attain a certain degree of satisfaction that gets lost because of the modified conditions in the environment or in the inner side of individuals.

Within this context, requirements are discusses as important drivers to understand which are the objectives to be addressed with higher priorities in order to attain desired goals. Moreover, they are also examined according to the role they play in the different cognitive processes leveraged by systematic design methods. According to this perspective, the role of knowledge have been widely explored and discussed by distinguishing it into what can be expressed and verbalized (explicit knowledge) and what, in turn, strictly pertains to the inner sphere of the individual and that can be hardly formalized (tacit knowledge). Consistently with what presented in the introduction, among the issues that have emerged at a greater extent, it is worth mentioning the need of turning tacit knowledge into explicit knowledge in a process of externalization, since once the personal knowledge gets externalized it is possible to purposefully share and reuse it. The author, from the dual viewpoint of tacit and explicit, has carried out an analysis of the relevant sources of knowledge capable to feed the design processes with meaningful content. The objective of this analysis is to define where this knowledge is available and which are the means currently available for its exploitation. The role of requirements has been, therefore, focused within the scope of the development processes, since these processes are in charge of delivering technical solutions in the contexts where needs emerge as market or technology exigency. More specifically, the role of requirements has been investigated in the domain of methods for systematic design. The author has reviewed the most acknowledged perspectives for systematic design by different authors addressing this topic.

The discussion tries to distinguish design methods between the ones that support the design process by pointing out critical tasks in different stages of the development and the others, which mainly focus their attention to the cognitive processes involved in the design activities. This discussion allows the author to identify points in common and organize the research within the borders of a framework that pools models describing both design-related cognition and the practical sequence of stages characterizing a systematic product development process. Indeed, the role of requirements in the development process have been analysed by taking into account the three main cognitive process occurring in design: Analysis, Synthesis and Evaluation. This choice has been driven by the necessity of identifying the role of requirements in design in the most general way, so as to provide meaningful support in the definition of objectives and criteria for driving all the early phases/stages of systematic processes and not just a few of them. The role of computers in supporting both the generation of ideas and the management of requirements has been finally explored and discussed into this section.

The third section of the document presents the goal of the research activity with greater details and more specific objectives, consistently with the ones emerged from the literature analysis. The new proposal of criteria for supporting the definition and the characterization of requirements to populate the design specification has, therefore, to achieve the objective to be *flexibly* used in different context concerning the development of both products and processes. Moreover, the criteria should address the need of producing a design specification capable of exploring the range of potential alternatives at the maximum extent (*completeness*) without neglecting relevant aspects and noting unuseful ones (*conciseness*), considering the collected requirements just once, without introducing ambiguities that could be misleading for driving the

design process (*non-redundancy*) and in a way that it is possible to link the capability of the different design proposal to generate satisfaction or dissatisfaction according to the objectives (*validity*). Moreover, the criteria should satisfy the double goal of producing the above results with good *repeatability*, thus releasing from the individual capabilities in externalizing the owned knowledge, and pronounced *ease of use*, both in terms of interpretation of the abstract concepts and in terms of time to carry out the analysis.

In the context of improving the ease of use, section three concludes with the development of an algorithm to be embedded into a dialogue-based computer interface for supporting the analysis of inventive problems. Such an algorithm has been developed in two steps in order to introduce the concepts highlighted by the criteria in the diverse paths through which the analysis can be carried out. The first step of development has defined the overall structure of the algorithm (7 logical blocks and about 150 questioning nodes), also in terms of variables to be investigated and elicited from experts' knowledge, opportunities for their reuse as well as connections among nodes and concepts. The second release of the algorithm, in turn, addresses the limitations emerged within the first testing session. It includes a new block aimed at widening the boundaries of exploration and providing shortcuts for the investigation of trivial solutions that were not immediately evident at the beginning of the analysis. From the one hand, these two different tests allowed to understand which is the potential of questions-and-answer techniques for the elicitation of knowledge from experts and, on the other hand, to directly address a specific need along the design process, which concerns the definition of conflicting requirements to be faced with higher priority among the set included into the design specification.

Section four presents the different applications where both the criteria for the elicitation of requirements and the algorithm for the analysis of inventive problems have been tested, so as to catch insights about their effectiveness. The first two parts of this section aim at describing the potential of the criteria in supporting the definition of design specification from both the sides of products and processes, while the third parte of this section concentrates on the algorithm for the analysis of inventive problems and provides details and statistical data to demonstrate the feasibility of the proposed approach. Into the details the criteria have been tested in three different manufacturing contexts:

- the foaming of cabinets for the insulation of domestic refrigerators (10 different process phases) currently implemented by Whirlpool Europe;
- the novel applications (for three different purposes) developed and investigated by a spin-off of the Università of Roma Tor Vergata in the field of fluids bed technologies;
- the ex-post analysis of a technology for curing painting powders on the sheet metal surfaces of domestic appliances as a potential candidate for substituting the current technology, employed within one of the manufacturing process of Whirlpool Europe.

Moreover, the investigation about the capability of the criteria has been also carried out in an educational context, whit an experiment on the definition of requirements for products of different complexity, with the purpose of having sufficient data to make statistically significant consideration based on a wider set of data.

Then, an ex-post characterization of a set of newly appeared product/service requirements has been carried out by means of data and information retrieved from scientific and business literature. The overall purpose of this investigation is to obtain a preliminary evaluation about the capability of the criteria to describe also functions concerning the direct satisfaction of customers. This switch in the perspective has been referenced by considering the customer as the object of the function carried out through the new attributes and not just as the user of the analysed product.

At last, the effectiveness in driving the design processes of people with not so much experience in the field of engineering design is discussed on the basis of two experiments using different releases of the algorithm for inventive problem analysis. These tests aims at pointing out the capability of the developed algorithm in supporting the identification of conflicting requirements as well as in defining the design space so as to support the retrieval of information and knowledge from explicit sources, such as patents, books and whatever codified and retrievable through the world wide web.

All the three subsections into which section four is divided present experiments tailored to verify specific objectives both in a qualitative and quantitative way. Results of each experiment are also discussed at the end of each test with the double goal of tracking progresses and improving the comprehension about the specific researched issues.

The achievement of the goal set in the introduction of this text is discussed in the next subsections, by taking into account the results presented and discussed after each testing activity in the Section 4.

5.2 Achievement of the objectives and strengths

As briefly mentioned above, this research activity aimed at the definition of criteria for driving the elicitation of knowledge from experts in order to point out the objectives and the requirements for driving the design processes with improved effectiveness and efficacy.

The achievement of such a goal has been subdivided into different objectives, according to the shared visions about the characteristics that requirements should hold in order to proficiently use them as drivers for the design process.

For what concerns the *flexibility* of use of the criteria in different contexts, the obtained results are satisfactory. The general framework into which the requirements have been structured for characterizing the different facets involved in innovation (Useful Function, Harmful Function, Consumption of Resources) demonstrated to be widely applicable to situations concerning both products and processes. During all the three activities concerning manufacturing technologies, experts have explored the three different categories without encountering difficulties (except for ease of use, as discussed below). Moreover, the testing activity on the criteria with students produced good results in terms of average number of product requirements elicited, witnessing a critical support in the definition of the design specification. Such efficacy of the criteria has been subjected to Hypothesis test with the data retrieved by the analysis of product requirements. The results have demonstrated that there is a statistically significant relationship between the use of criteria and the number of requirements that populate the design specification.

As for the *completeness*, the criteria have provided evidences that they properly drive the exploration of the different facets concerning the evolution (and therefore the innovation) of technical systems. In both the applications to products and processes, the testers have considered the three different drivers of innovation as stated in the Law of Engineering System Evolution #4 from the TRIZ body of knowledge (Appendix C). Moreover, in the first two industrial tests (foaming and fluid-bed technologies), the experts have witnessed that, without the criteria, the exploration of the range of potentially relevant requirements would have stop in advance, thus neglecting relevant facets to be considered. The third of such tests, in turn, has shown that through the criteria 16 requirements more than the ones previously investigated by experts have been elicited, which could be used as criteria for decision making in such a technlogy substitution problem.

All these three tests have also evidenced how the criteria support both the definition of relevant and non-relevant requirements. Such cautelative approach target the objective of completeness, as just said, but the decision of conveniently neglecting some requirements in

order to keep the design specification as neat as possible is still possible and practically demonstrated by expert judgements. These three tests, therefore qualitatively concur to demonstrate that the criteria also allow to meet the objective of *conciseness,* even if by human decisions.

In terms of *validity*, the criteria demonstrated to generate good results form the very first tests. Indeed all the generated requirements have been identified and formulated in order to allow their evaluation at least with dichotomous values, so as to characterize the satisfaction or dissatisfaction. During the first test, an assessment of the satisfaction about the elicited requirements has been performed with an ordinal scale of judgment. On the contrary the validity of requirements in the other tests on manufacturing technologies can be evaluated by the direct analysis of the produced outcomes. Many of them are quantitatively measurable with appropriate units; the others are at least matter of evaluation by means of dichotomous values, exactly as it has happened for the requirements elicited by and from students, for what concerns the example of the iron.

The issue of producing a *non-redundant* design specification has required an analysis within each set of requirements generated by means of the criteria. Generally speaking, this objective has been almost completely achieved, since some issues have emerged just whenever some criteria have been wrongly interpreted, thus leading to ambiguous definition of requirements. However, in such cases, it is sufficient to further detail the concept behind the already elicited requirement in order to correctly address it to one and just one of the specific facets that allow the characterization to be carried out. Moreover it is necessary noticing that, up to now, such operation of disambiguation can be just effectively carried out through the presence of a facilitator.

The *repeatability* has to be intended as the capability of the criteria to achieve the expected objectives in a diffused way, thus releasing from the individual ability to elicit individual knowledge. The experiments have witnessed that the criteria allow an average of forty requirements to be generated for the technologies or the products investigated. Such a result appear to not depend on the specific interaction used for the elicitation, since small variations are appreciable regardless the externalization of knowledge has been conducted by written description of criteria, surveys or face-to-face interviews.

The criteria for the elicitation of requirements, at the beginning of the activity, have demonstrated to be hardly understandable by experts without the support of a methodological facilitator that contextualizes them in the specific situation. Three to four hours of activity were required to completely examine the criteria and define related requirements. The introduction of interviews mediated by a facilitator (used in the investigation of fluid bed and curing technologies), as well as the examples for clarifying the meaning behind each criterion, drop this time to about an hour. Significant results in this sense have been obtained through a survey/questionnaire for the exploration of the criteria with students. In less than an hour an average of forty requirements have been elicited for a product, thus further slashing the time required for the analysis. Moreover, the interviews carried out with experts in the field of fluid bed technologies have presented some clues about the potential learning-by-doing effect that deserves to be further investigated.

The satisfactory results, obtained through the adoption of question-and-answer procedures for the elicitation, have also played a relevant role in the determination of the global architecture into which the algorithm for the analysis of inventive problems has been implemented.

The evaluation of the algorithm, which is currently available in his last release at the URL: http://www.smeinnovation.net, has been carried out in two different sessions of testing, one for each release of the algorithm generated so far.

During the first session of tests, it has been possible to point out that the support provided to the analysis of problems is statistically significant. Moreover, the greatest benefits from its use appear in those situations where the designer has poor problem solving capabilities. The first session of testing has also highlighted that the algorithm evidenced some limitations for what concerns the exploration of the design space in terms of broadening the perspective through time and space. According to this evidence, a new version of the algorithm has been developed by introducing a new logical block, which aims at widening problem exploration, without modifying the original architecture of the whole framework. The results obtained with this new release of the algorithm have witnessed a significant shift in the outcomes of the performed analysis. One third of the testers managed to identify a couple of conflicting requirements, and 2 testers out of 5 identify a trivial direction for solving the problem by simply reformulating it with a different perspective, which is probably sufficient to turn it form an Ill-Structured to a Well-Structured Problem.

5.3 Limits

The main limitations about the use and the capabilities of criteria have been highlighted in the test carried out with an ex-post analysis of the customer attributes. In details it has emerged that an incomplete definition of the model for contextualizing the analysis (EMS model) does not allow to carry out, in several cases, univocal characterizations for the attributes under investigation.

Nevertheless, this kind of analysis has also demonstrated that at least one meaningful characterization is possible in almost all the cases (≈99%), which suggests that this approach can be properly evaluated just in case the criteria get used in combination with a method for removing ambiguousness, e.g. by defining the perspective of the analysis in a repeatable manner.

From a different perspective, it is worth mentioning that some limitations also concern the statistical test that have been carried out to quantitatively establish the capability of the criteria in concretely supporting designers in defining an increasingly populated design specification, by comparing such results to what happens naturally, without the support of the criteria. The first shortcoming of this evaluation stands in the absence of a control group so as to infer the statistical significance of the benefits generated by the criteria with methodologically correct procedures. Moreover, the whole test swivels on the assumption that a laser printer, being a complex system composed by a large number of parts, can be characterized by a higher number of requirements than an iron, which is composed by a smaller number of components. Nonetheless, the very low value obtained through the t-test for the p-value (there is one probability in six thousand billions that the criteria do not affect the identification of requirements) allows remarking that, to some extent, the criteria support the identification of requirements.

For what concerns the algorithm for the analysis of inventive problems some limitations, which emerged in the first version, have been removed with the second release. Nevertheless more than a quarter of the testers still concludes the analysis with an unsatisfactory outcome or, worse, quits it before coming to a conclusion. This specific behaviour suggests that the dialogue-based interface triggers some frustrating feeling in those individuals experiencing some difficulties in the interpretation of questions, as it happened with just the description of criteria during the first test on manufacturing technologies (foaming). Among the hypothesis about the causes generating this kind of effect, it is possible that the written communication progressively limits the

attention of the individual that, in turn, get bored of that kind of dialogue, probably because it runs on a different plane than the one occurring in standard human-human interaction.

5.4 (Further) Potential applications

It has been widely discussed along all this work that the requirements and, more in general, the design specification generate benefits for the design process, because of the crucial role of requirements in defining the problem state, the goal state as well as the boundaries of the design state space into which the solution to a problem has to be searched. Most of the tests proposed in Section 4 pursue these objectives, in abstract terms. Moreover, it has mentioned that there is an increasing trend in evaluating creativity in products by means of three constructs: novelty, usefulness and surprise. In each of these cases it is possible to determine the differences among two generations of the same product by means of the design specification that characterizes them.

Differences in the achievements of different requirements could be used straightforwardly to improve the definition of the value of usefulness. On the contrary the emergence of new requirements (which neither more nor less can be considered as “create” attributes according to the Blue Ocean Strategy jargon) could be useful to better describe the character of novelty and being used as an index of the emergence of surprise in the assessor of creativity.

Nonetheless, the requirements generated through the use of the criteria can be used for populating the rows and the columns of the House of Quality (if the criteria gets interpreted, in both cases, with the proper detail level for the investigation). A potential contribution could be provided for populating a Network of Contradictions (Khomenko, 2007), being the generated requirements part of the characteristic nodes of the Network as well. In turn its use could be integrated in the definition of a Network of Problem as a means to double check the correctness of the analysis, based on the assumption that a problem populating the network identifies at least one requirement to be satisfied.

On the other hand, the algorithm for the analysis of inventive problems is currently working and available through a dialogue-based platform on the World Wide Web. People who is interested in its use can access the website and ask for credentials to test and exploit its capability. It is assumed that the highest benefits of its use can be obtained for the phases of Conceptual Design, even if it could be also capable to address problems that more often emerge during the embodiment stages of the design process.

5.5 Further developments

All the limits emerged in the discussion of part 5.3 represents good opportunities for further developing the criteria as well as the algorithm.

According to the current stage of development of these concepts, one of the most promising directions to generate further scientific and technological advancements could concern the implementation of a dialogue-based system for the direct elicitation of system requirements. Such an implementation should not be limited to the direct transformation of a paper-based questionnaire within a computer application. In order to exploit such a system at the maximum extent the challenge would be to replicate the capability of the facilitator to interpret criteria and asking expert contextualized questions.

With the viewpoint of the already developed algorithm for problem analysis, it would be interesting to extend the support of computers to the whole process of development of new solution, thus introducing modules capable to also support cognitive processes of Synthesis and

Evaluation in a unique environment in which the designer freely moves, also with reference to the recently studied process of co-evolution of problem and solution.

References

Ackoff R.L., (1989) From data to wisdom, Journal of Applied Systems Analysis 16 p.3–9.

Adunka R.; (2007); Lessons Learned in the Introduction of TRIZ at Siemens A&D. In: 7th TRIZ Future Conference.

Aha DW, Muñoz-Avila H.; (2001); Introduction: interactive case-based reasoning. Applied Intelligence;14:7–8.

Aha DW, Breslow LA, Muñoz-Avila H.; (2001); Conversational case-based reasoning. Applied Intelligence;14:9–32.

Ahmed S., (2005); Encouraging Reuse of Design Knowledge: A Method to Index Knowledge, *Design Studies*, 26(6), 2005, pp. 565-592.

Ahmed S.; (2006); An approach to assist designers with their queries and designs. *Proceedings of the ASME IDETC* 2006,359-66.

Akao Y.; (2004); Quality Function Deployment: Integrating Customer Requirements Into Product Design; Productivity Press.

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

Allen, T.J.; (1986); Organizational structure, information technology and R&D productivity; Working paper / Alfred P. Sloan School of Management -- 1666-86R; Cambridge, Mass: Massachusetts Institute of Technology

Allen, T.J.; (1997); Organizational structure for product development; Sloan School of Management, WP (International Center for Research on the Management of Technology) ; 166-97. Working paper; WP 3989-97; Massachusetts Institute of Technology

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).

Amabile, T. M. 1996. *Creativity in context.* Boulder, CO: Westview Press.

Ameri, F.; Dutta, D.; (2005); Product Lifecycle Management: Closing the Knowledge Loops, Computer- Aided Design & Applications, Vol. 2, No. 5, 577-590 . DOI: 10.3722/cadaps.2005.577-590.

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

Aquino N., Vanderdonckt J., Condori-Fernàndez N., Dieste Ò., Pastor Ò.; (2010); Usability evaluation of multi-device/platform user interfaces generated by model-driven engineering. In: Proceedings of the 2010 ACM-IEEE International Symposium on Empirical Software Engineering and Measurement.

Archer L.B.; (1984); Systematic method for designers. In: Development in Design Methodology. Cross N. (ed.); John Wiley & sons; Ltd; Chichester.

Aurisicchio M., Bracewell R., Wallace K., (2006); Characterising the information requests of engineering designers. *Proceedings of the 9th International Design Conference DESIGN* 2006;1057-64.

Becattini N., Cascini G., Rotini F.; (2009); "Correlation between the Evolution of Contradictions and the Law of Ideality Increase", Proceedings of the TRIZ Future Conference 2009, Timisoara, Romania, pp. 26-34.

Becattini N., Borgianni Y., Cascini G., Rotini F.; (2010) "Coaching the Cognitive Processes of Inventive Problem Solving with a Computer" - First International Conference on Design Creativity ICDC 2010 – Kobe – Japan (29 Nov-1 Dec)

Becattini N, Borgianni Y, Cascini G, Rotini F; (2011-a) "Computer-Aided Problem Solving - Part 1: Objectives, Approaches, Opportunities"- BUILDING INNOVATION PIPELINES THROUGH COMPUTER-AIDED INNOVATION - IFIP Advances in Information and Communication Technology, Volume 355/2011

Becattini N., Borgianni Y., Cascini G., Rotini F.; (2011-b); "Computer-Aided Problem Solving - Part 2: A Dialogue-Based System to Support the Analysis of Inventive Problems"- BUILDING INNOVATION PIPELINES THROUGH COMPUTER-AIDED INNOVATION - IFIP Advances in Information and Communication Technology, Volume 355/2011

Becattini N., Cascini G., Petrali P., Pucciarini A.; (2011-c); "Production processes modeling for identifying technology substitution opportunities"- Published on the proceedings of the 11th TRIZ Future Conference 2011 – Dublin– Ireland (2nd-4th Nov).

Becattini N., Borgianni Y., Cascini G., Rotini F.; (2012-a); "Model and Algorithm for Computer-Aided Inventive Problem Analysis" Volume 44, Issue 10, October 2012, Pages 961–986 Computer-Aided Design Journal – Elsevier

Becattini N., Borgianni Y., Cascini G., Rotini F.; (2012-b); ARIZ85-C and knowledge-driven patent support; Proceedings of the TRIZ Future Conference 2012, Lisboa, Portugal, 24-26 October 2012.

Becattini N., Borgianni Y., Cascini G., Rotini F.; (2013-a); "About the Introduction of a Dialogue-Based Interaction within a CAD System"; Computer-Aided Design & Applications, 10(3), 2013, 499-514.

Becattini N., Borgianni Y., Cascini G., Rotini F.; (2013-b) “A TRIZ-based CAI Framework to guide Engineering Students” Accepted for publication on the International Journal of Engineering Education

Ben-Aried A., Easton T., Product Design Compromise Using Consensus Models, in: Consensual Processes, Studies in Fuzziness and Soft Computing Volume 267, 2011, pp 405-423

Boden, M. A.; (2009); *Computer Models of Creativity*; AI Magazine; AAAI; 30(3), 23-34.

Bordegoni M., Ferrise F., Lizaranzu J.; (2011); Use of Interactive Virtual Prototypes to Define Product Design Specifications: a Pilot Study on Consumer Products, in: Proceedings of IEEE International Symposium on Virtual Reality Innovation 2011, 2011, pp. 11-18.

Borgianni Y., Cardillo A., Cascini G., Rotini F.; (2011); Systematizing new value proposition through a TRIZ-based classification of functional features; Procedia Engineering, Volume 9, 2011, Pages 103–118; Proceeding of the ETRIA World TRIZ Future Conference.

Borgianni Y., Cascini G., Rotini F.; (2012); Investigating the Patterns of Value-Oriented Innovations in Blue Ocean Strategy; International Journal of Innovation Science; Volume 4, Number 3 / September 2012; p. 123-142.

Brace W., Cheutet V.; (2012); A framework to support requirements analysis in engineering design; Journal of Engineering Design; Vol. 23, Iss. 12.

Bracewell R., Wallace K., Moss M., Knott D.; (2009) Capturing design rationale. *Computer-Aided Design*; 41:173–86.

Bregonje M. Patents: A unique source for scientific technical information in chemistry related industry?. *World Patent Information* 2005; 27:309–15.

Brown D.C; (2010); Creativity, Surprise & Design: *An introduction and investigation*; Proceedings of the International Conference on Design Creativity; Springer; Kobe, Japan.

Brunetti, G.; Golob, B.; (2000); A feature-based approach towards an integrated product model including conceptual design information, Computer-Aided Design, 32, 877-887. DOI:10.1016/S0010- 4485(00)00076-2

Buchler J., (1978); The philosophy of Peirce: selected writings, AMS press, New york.

Burki L., Cavallucci D., (2011); Measuring the Results of Creative Acts in R&D; in Building Innovation Pipelines through Computer-Aided Innovation, Cavallucci D., DeGuio R., Cascini G.(Eds.), CAI 2011; IFIP ACIT 355; pp. 163-177.

Cascini G.; (2004); State-of-the-art and trends of computer-aided innovation tools - towards the integration within the product development cycle; Building the information society; Kluwer Academic Publishers; p. 461-70.

Cascini, G., Rotini, F., Russo D.; (5-7 November 2008); “Networks of trends: systematic development of system evolution scenarios”, Proceedings of the 8th ETRIA TRIZ Future Conference, Twente, The Netherlands, pp. 31-40.

Cascini G, Russo D.; (2007); Computer-Aided analysis of patents and search for TRIZ contradictions. In: Creativity and innovation employing TRIZ. International Journal of Product Development;4(1/2):52–67 [special issue].

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

Cavallucci D., (2011); A research agenda for computing developments associated with innovation pipelines; Computers in Industry; Volume 62, Issue 4, May 2011, Pages 377–383

Caves, R. E., & Porter, M. E. (1977). From entry barriers to mobility barriers. Quarterly Journal of Economics, 91, 241–261.

Chechurin, L.S.; Wits, W.W.; Bakker, H.M.; Vaneker, T.H.J.; (2011); Introducing Trimming and Function Ranking to SolidWorks based on Function Analysis, In Proceedings of the 11th TRIZ Future Conference, 2011, 215-225.

Chiu I, Shu LH.; (2007); Biomimetic design through natural language analysis to facilitate cross-domain information retrieval. Artificial Intelligence for Engineering, Design, Analysis and Manufacturing;21:45–59.

Christensen C. M.; (1997). The Innovator’s Dilemma: When New Technologies Cause Great Firms to Fail. Boston: Harvard Business School Press.
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.

Collado-Ruiz D., Ostad-Ahmad-Ghorabi H.; (2010); Influence of environmental information on creativity, Design Studies. 31, 479-498.

Collins, H; (2010); Tacit and explicit knowledge; The University of Chicago Press; Chicago; ISBN-13: 978-0-226-11380-7

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

Danjou, S.; Koehler, P. (2007) Challenges for Design Management, Computer-Aided Design & Applications, Vol. 4, Nos. 1-4, 109-116. DOI: 10.3722/cadaps.2007.109-116

Dean, D. L., Hender, J. M., & Rodgers, T. L. (2006). Identifying Quality, Novel, and Creative Ideas: Constructs and Scales for Idea Evaluation. Journal of the Association for Information Systems, 7(10), 646–699.

Domb E.; (2005); How to deal with cost-related issues in TRIZ. In: 5th TRIZ future conference.

Dorst K., Cross N.; (2001); Creativity in the design process: co-evolution of problem–solution. Design Studies, 22(5), pp. 425–437.

Dorst K; (2006); Design Problems and Design Paradoxes; Design Issues; Elsevier; Volume 22, Number 3 Summer.

Eigner, M.; Mogo Nem, F.; (2010) On the Development of New Modeling Concepts for Product Lifecycle Management in Engineering Enterprises, DOI: 10.3722/cadaps.2010.203-212

Ericson Å., Müller P., Larsson T., Stark R., (2009); Product-Service Systems – From Customer Needs to Requirements in Early Development Phases, Proceedings of the 1st CIRP Industrial Product-Service Systems (IPS2) Conference, Cranfield University, 1-2 April 2009, pp62

Eris Ö.; (2003); Asking generative design questions: a fundamental cognitive mechanism in design thinking. In: 14th international conference on engineering design.

Ernst J.V., Clark J.C.; (2008); Students' Preferred Learning Styles in Graphic Communications, Engineering Design Graphics Journal. 72, 9-18.

Eynard, B.; Gallet, T.; Roucoules, L.; Ducellier, G.; (2006); PDM system implementation based on UML, Mathematics and Computers in Simulation, 70, 330–342. DOI: 10.1016/j.matcom.2005.11.012

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

Fiksel, J.; Hayes-Roth, F.; (1993); Computer-aided Requirements Management, Concurrent Engineering, Vol. 1, No. 2, 83-92. DOI: 10.1177/1063293X9300100201

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

French M.J.; (1999); Conceptual design for Engineers, Springer, London.

Füller J., Matzler K.; (2002); Virtual product experience and customer participation - A chance for customer-centred, really new products, Technovation27 (6-7) p. 378-387.

Gaines, B. R., (1987) An overview of knowledge-acquisition and transfer, in *International Journal of Man- Machine Studies*, 1987, 26(4) pp.453-472

Gero, J.S.; (1990); 'Design prototypes: a knowledge representation schema for design' AI Magazine Vol 11 No 4 p.26–36

Gero, J.S. and Rosenman, M.A.: (1990); “A conceptual framework for knowledge based design research at Sydney University’s Design Computing Unit”. Artificial Intelligence in Engineering, v.5(2), pp. 65-77.

Gero, J. S., Kannengiesser, U.; (2004); *The situated function-behaviour-structure framework*; Design Studies; Elsevier; 25, 373-391.

Grebici, K.; Goh, Y.M.; Zhao, S.; Blanco, E.; McMahon, C.; (2007) Information Maturity Approach for the Handling of Uncertainty Within a Collaborative Design Team. In Proceedings of the 11th International Conference on Computer Supported Cooperative Works in Design, 280-285. DOI:10.1109/CSCWD.2007.4281448

Hagen R.; (1968); Open top tank and covering for the contents thereof, Unites States Patent 3401818.

Hardré PL, Crowson HM, Xie K, Ly C.; (2006); Testing differential effects of computer- based, web-based and paper-based administration of questionnaire research instruments. British Journal of Educational Technology; 38:5–22.

Hassard S.T., Blanford A., Cox A.L.; (2010); Analogies in design decision-making. In: Proceedings of the 23rd British HCI Group Annual Conference on People and Computers: Celebrating People and Technology.

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.

Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S. and Wood, K. L.; (February 2002); “A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts”. NIST (National Institute of Standards and Technology) Technical Note 1447.

Howaldt, K., & Mitchell, A. (2007). Can segmentation ever deliver the goods? *Market Leader, 36* (Spring)

Johne A., (1999); "Successful market innovation", European Journal of Innovation Management, Vol. 2 Iss: 1 pp. 6 – 11 – doi: 10.1108/14601069910248838

Johnson G.M., Johnson J.A.; (2010); Dimensions of Online Behavior: Implications for Engineering E-Learning, in: M. Iskander, V. Kapila, M.A. Karim, Technological Developments in Education and Automation, Springer Dordrecht Heidelberg London New York, 61-66.

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

Kamara, J.M., Anumba, C.J. & Evbuomwan, N.F.O. (2000); Establishing and processing client requirements—a key aspect of concurrent engineering in construction; Engineering, Construction and Architectural Management 2000 7 (1), p. 15–28

Kano N.; Seraku N., Takahashi F., Tsuji S.; (1984); "Attractive quality and must-be quality" (in Japanese). Journal of the Japanese Society for Quality Control 14 (2): 39–48.

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.

Khomenko N., De Guio R., Lelait L., Kaikov I., (2007), "A framework for OTSM-TRIZ Based Computer Support to be used in Complex Problem Management", International Journal of Computer Applications in Technology, Volume 30, Number 1-2 / 2007, pp. 88-104

Kim, K.-Y.; Kim, Y.S.: Causal design knowledge: Alternative representation method for product development knowledge management, Computer-Aided Design, 43, 2011, 1137–1153. doi:10.1016/j.cad.2011.05.005

Kim W. C., Mauborgne R.; (2011); Strategia oceano blu, vincere senza competere, Harvard business review press, Etas.

Kitchenham B.A.; (1996); Evaluating software engineering methods and tool, part 1: The evaluation context and evaluation methods, ACM SIGSOFT Software Engineering Notes. 21, 11-15

Kokotovich V., (2005); Problem analysis and thinking tools: an empirical study of non-hierarchical mind mapping, *Design Studies*, 29(1), 2005, pp. 49-69.

Kruger C, Cross N. Solution driven versus problem driven design: strategies and outcomes. *Design Studies* 2006;27:527–48.

Kucharavy D., De Guio R., Gautier L., Marrony M.; (2007); Problem Mapping for the Assessment of Technological Barriers in the Framework Of Innovative Design; International Conference on Engineering Design, ICED'07, 28 - 31 AUGUST.

Kumar V., Reinartz W., (2012); Strategic Customer Relationship Management Today; Customer Relationship Managament; Springer texts in Business and Economics; pp 3-20.

Laghos A, Zaphiris P.; (2007); Evaluation of attitudes towards thinking and learning in a CALL website through CMC participation. In: Lambropoulos N, Zaphiris P, editors. User-centered design of online learning communities. Hershey: Information Science Publishing; p. 238–64.

Lee J.Y.; (2010); Implementing TRIZ at Samsung Electronics. In: Global TRIZ Conference in Korea.

Lemons G., Carberry A., Swan C., Jarvin L., Rogers C.; (2010); The benefits of model building in teaching engineering design, Design studies. 31, 288-309.

Leon Rovira N.; (2009); *The future of computer-aided innovation*; Computers in Industry; Elsevier; 60:539-50.

Liang Y.B., Ma Q.L., Liu S.T.; (2009); Applications of Computer Aided Instruction in Teaching of Survey Adjustment Course. In ICIECS 2009, International Conference on Information Engineering and Computer Science.

Linstone H.A., Turoff M.; (1975); The Delphi method: techniques and applications; Addison-Wesley Pub. Co., Advanced Book Program.

Liu, D.T.; XU, W.; (2001); A review of web-based product data management systems, Computers in Industry, Vol. 44, Issue 3, 251-262. DOI:10.1016/S0166-3615(01)00072-0

López de Mántaras R, McSherry D, Bridge D, Leake D, Smyth B, Craw S, et al.; (2006); Retrieval, reuse, revision and retention in case-based reasoning. The Knowledge Engineering Review; 20:215–40.

Maher M.L.; Poon J.; (1996); Modeling Design Exploration as Co-Evolution; Computer-Aided Civil and Infrastructure Engineering; Volume 11, Issue 3, pages 195–209, May 1996

Maher ML; (2010); *Evaluating Creativity in Humans, Computers, and Collectively Intelligent Systems*; Proceedings of the DESIRE10 Conference: Creativity and Innovation in Design; ACM International Conference Proceedings Series; 22-28.

March L.J.; (1984); The logic of design; In: Development in Design Methodology. Cross N. (ed.); John Wiley & sons; Ltd; Chichester.

Mareis C; (2012); The Epistemology of the Unspoken: On the Concept of Tacit Knowledge in Contemporary Design Research; Design Issues: Volume 28, Number 2 Spring 2012

Martín-Gutiérrez J., Saorín J.L., Contero M., Alcañiz M., Pérez-López D.C., Ortega M.; (2010); Design and validation of an augmented book for spatial abilities development in engineering students, Computers & Graphics. 34, 77-91.

Markides, C.; (2006); Disruptive Innovation: In Need of Better Theory; Journal of Product Innovation Management 2006; 23:19–25

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

Matzler K.; Hintertuber H.H.; (1998); How to make product development projects more successful by integrating Kano's model of customer satisfaction into quality function deployment; Technovation, 18(1) (1998) 25–38; Elsevier Science Ltd

Melgoza E.L., Serenó L., Rosell A., Ciurana J.; (2012); An integrated parameterized tool for designing a customized tracheal stent; Computer-Aided Design 44 (2012) 1173–1181

Mendicino M., Razzaq L., Heffern N.T.; (2009); A Comparison of Traditional Homework to Computer-Supported Homework, Journal of Research on Technology in Education. 41, 331-358.

McAdam R., Keogh W., Reid R.S., Mitchell N., (2007) "Implementing innovation management in manufacturing SMEs: a longitudinal study", Journal of Small Business and Enterprise Development, Vol. 14 Iss: 3, pp.385 - 403

McAdam R., McClelland J.; (2002); Sources of new product ideas and creativity practices in the UK textile industry, Technovation22 (2) p.113-121.

McBride M.F., Burgman M.A., (2012); What Is Expert Knowledge, How Is Such Knowledge Gathered, and How Do We Use It to Address Questions in Landscape Ecology? in Expert Knowledge and its Application to Landscape Ecology, Perera, Ajith H.; Drew, C. Ashton; Johnson, Chris J. (Eds.), Springer, ISBN 978-1-4614-1034-8

Miaskiewicz T., Kozar, K.A.; (2011); Personas and user-centered design: How can personas benefit product design processes?; Design Studies 32; p. 417-430

Myers, S. and Marquis, D.G. (1969) 'Successful industrial innovation: a study of factors under- lying innovation in selected firms', National Science Foundation, NSF 69–17, Washington, DC.

Nam T.J., Sakong K.; (2009); Collaborative 3D Workspace and Interaction Techniques for Synchronous Distributed Product Design Reviews, International Journal of Design. 3, 43-55.

Osborn AF, (1963) Applied imagination: Principles and procedures of creative problem solving (Third Revised Edition). Charles Scribner's Son: New York

Pahl G., Beitz W., Feldhusen J., Grote K.H; (2007) Engineering Design: a systematic Approach, 3rd Edition; Translation from German by Wallace K., Blessing L. (eds.) ; Springer-Verlag, London.

Perez-Araos A., Barber K.D., Munive-Hernandez J.E., Eldridge S., (2007) "Designing a knowledge management tool to support knowledge sharing networks", Journal of Manufacturing Technology Management, Vol. 18 Iss: 2, pp.153 - 168

Petrov V.; (2004); Logic of ARIZ. In: 4th TRIZ Future Conference.

Pil F.K., Cohen S.K.; (2006); Modularity: Implications for Imitation, Innovation, and Sustained Advantage; The Academy of Management Review, Vol. 31, No. 4 (Oct., 2006), pp. 995-1011

Polanyi M., (1967); Tacit dimension; Garden City, N.Y., Anchor Books.

Popescu V, Caelen J, Burileanu C.; (2007); Generic architecture for natural language generation in spoken human–computer dialogue. In: The 4th conference of speech technology and human–computer dialogue.

Porter, M. E. (1979). The structure within industries and companies' performance. Review of Economics and Statistics, 61, 214–227.

Pugh, S. (February 1991). Total Design: Integrated Methods for Successful Product Engineering. Addison-Wesley. ISBN 0-201-41639-5

Quarteroni S., Manandhar S.; (2008); Designing an interactive open-domain question answering system. Natural Language Engineering; 15:73–95.

Rawwas, M. Y. A., & Iyer, K. N. S. How do small firms possibly survive? A comparison study of marketing skills and logistics infrastructure of small and large wholesalers. International Business Review (2012), http://dx.doi.org/10.1016/j.ibusrev.2012.10.003

Rinderle S, Weber B, Reichert M, Wild W.; (2005); Integrating process learning and process evolution — a semantics based approach. In: 3rd international conference on business process management.

Rohde D, Pavkovi¢ N, Aurisicchio M.; (2008); Design knowledge indexing in relational database. In: 10th international design conference.

Röhner S., Breitsprecher T., Wartzack S; (2011); Acquisition of design-relevant knowledge within the development of sheet-bulk metal forming; International Conference On Engineering Design, ICED11, 15 - 18 August 2011, Technical University Of Denmark.

Rogers E.; (1983) *Diffusion of innovations,* 3rd ed.; New York: Free Press.

Rogers, E. and Shoemaker, R. (1972) *Communications of Innovations*, Free Press, New York.

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

Roth D., Binz H., Watty R.; (2010); Generic Structure Of Knowledge Within The Product Development Process - International Design Conference - DESIGN 2010 Dubrovnik - Croatia, May 17 - 20, 2010, pp. 1681-1690.

Rowley J.; (2007); The wisdom hierarchy: representations of the DIKW hierarchy; Journal of Information Science, 33 (2), pp. 163–180

Sarkar P., Chakrabarti A., (2011); Assessing design creativity; Design Studies; Volume 32, Issue 4, July 2011, Pages 348–383

Savransky SD.; (2000); Engineering of creativity: introduction to TRIZ methodology of inventive problem solving. Boca Raton: CRC Press.

Scaravetti, D.; Nadeau, J.P.; Pailhès, J.; Sebastian, P.; (2005) Structuring of embodiment design problem based on the product lifecycle; Int. J. Product Development, Vol. 2, Nos. 1/2, 47-70. DOI:10.1504/IJPD.2005.006668

Scheuer O., Loll F., Pinkwart N., McLaren B.M.; (2010); Computer-supported argumentation: A review of the state of the art, International Journal of Computer-Supported Collaborative Learning. 5, 43-102.

Schilling M.A., Strategic Management of Technology Innovation, 3rd Edition, McGraw Hill, 2010

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.

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

Simon, H. A.; (1973); *The structure of ill structured problems*; Artificial Intelligence; Elsevier; Volume 4, Issues 3-4, Winter, Pages 181-201.

Smith E.A.; (2001) The role of tacit and explicit knowledge in the workplace, Journal of Knowledge Management; Volume 5; Number 4; 311-321

Song, J.-S.; Lee, K.-M.; (2010); Development of a low-carbon product design system based on embedded GHG emissions, Resources, Conservation and Recycling, vol. 54, 547–556. DOI:10.1016/j.resconrec.2009.10.012

Sosnin PI, Sosnina EP.; (2005); Question–Answer system for object-oriented analysis and design. In: 22nd international conference on information technology in construction.

Spiegler I., (2003); Technology and knowledge: bridging a “generating” gap; Information & Management 40; 533–539

Streveler, R. A., Olds B. M., Miller R. L., Nelson M. A.; (2003). Using a delphi study to identity the most difficult concepts for students to master in thermal and transport science. In Proceedings, American Society for Engineering Education Annual Conference 2003. Nashville, TN.

Tay, F.E.H; Gu, J.; (2002); Product modeling for conceptual design support, Computers in Industry, 48, 143-155. DOI:10.1016/S0166-3615(02)00014-3

Trabelsi A.C., Rezgui M.A.; (2010); A multifactor ANOVA study for trainees performance measurement subjected to CADCAM and CAD courses, International Journal of Vocational and Technical Education. 2, 41-54.

Trott P. (2005); Innovation management and new product development — 3rd ed., FT Prentice Hall, Pearson Education Limited; Edinburgh. ISBN 0-273-68643-7

Tseng, M.M.; Jiao, J.: Computer-Aided Requirement Management for Product Definition: A Methodology and Implementation, Concurrent Engineering: Research and Applications Vol.6, No.3, 1998, 145-160. doi:10.1177/1063293X9800600205

Tushman M.L. Anderson P., (1986) Technological Discontinuities and Organizational Environments; *Administrative Science Quarterly*, Vol. 31, No. 3. (Sep., 1986), pp. 439-465

Ulrich, K.T., Eppinger, S.D. (2008). Product Design and Development. McGraw-Hill, Inc. Boston, Mass. USA.

Utterback J.M., Abernathy W.J., (1975); A Dynamic Model of Process and Product Innovation. OMEGA, the International Journal of Management Science, Vol. 3, No.6.

Vargas Hernandez N., Okudan Kremer G., Schmidt L.C., Acosta Herrera P.R.; (2012); Development of an expert system to aid engineers in the selection of design for environment methods and tools; Expert Systems with Applications 39 p. 9543–9553.

Vargas Hernandez N., Shah J.J., Smith S.M.; (2010); Understanding design ideation mechanisms through multilevel aligned empirical studies, Design Studies. 31, 382-410.

Vermaas PE.; (2009); The flexible meaning of function in engineering. In: 17th international conference on engineering design.

Veryzer R.W., (1998) Discontinuous innovation and the new product development process; Journal of Product Innovation Management, Volume 15, Issue 4, July 1998, Pages 304–321

Vincent JFV, Bogatyreva OA, Bogatyrev NR, Bowyer A, Pahl AK.; (2006); Biomimetics — its practice and theory. Journal of the Royal Society Interface; 3:471–82.

Von Hippel E., (1986); Lead Users: A Source of Novel Product Concepts; Management Science, Vol. 32, No. 7 (Jul., 1986), pp. 791-805

Wallace D.P.; (2007); Knowledge Management: Historical and Cross-Disciplinary Themes; Libraries Unlimited

Wang, L., Shen, W; Xie, H.; Neelamkavil, J.; Pardasani, A., (2002); Collaborative conceptual design - state of the art and future trends, Computer-Aided Design, Vol. 34, 981-996. DOI:10.1016/S0010-4485(01)00157-9

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

Wedel M., Kamakura W., (2000); Market Segmentation: Conceptual an Methodological Foundations 2nd edition; Springer, ISBN:0792386353.

Youmans R.J.; (2010); The effects of physical prototyping and group work on the reduction of design fixation, Design Studies. In press.

Zadeh M.H., Wang D., Kubica E.; (2010); The effect of sub-threshold forces on human performance in multi-modal computer-aided design, Computer-Aided Design. 42, 471-477.

Zelkowitz M.V., Wallace D.R.; (1998); Experimental Models for Validating Technology, Computer. 31, 23-31.

Zelkowitz M.V., Wallace D.R., Binkley D.W.; (1997) Experimental validation of new software technology, Information and Software Technology. 39, 735-743.

Zeng Y.; (2008); Recursive object model (ROM) — modelling of linguistic information in engineering design. Computers in Industry; 59:612–25.

Zhang X.; (2008); A multiscale progressive model on virtual navigation, International Journal of Human-Computer Studies, 66, 243-256.

Zwicky F., (1957); Morphological Astronomy; Springer, Berlin.

Appendix A – OPEN-IT Algorithm

This appendix contains all the Tables concerning the nodes of the original Algorithm presented along Section 3.3.

Text in square brackets represents variables that the user assigns by answering the questions. CNF and NIP mean respectively “Contradiction Not Formulated” and “Non-Inventive Problem”

Table A-1: Nodes, links and variables of the logical block “Initial situation”.

Node	Text	Type	Next	Yes	No	Variables
1	Type the name of the system that is under investigation. *(Use a substantive, without article, i.e. coffee machine, drill, car, dishwasher...)*	Assignment, Initial	2			[SYS]
2	Does the problem you want to face involve the whole [SYS]?	Decision		4	3	
3	Type the name of the system that undergoes the problem	Assignment	4			[SYS]
4	Now we have to define the overall goal of the [SYS], meaning the motivation of its/their existence. Think about the industry and the market of the [SYS], what the [SYS] is/are meant to achieve, the intentions of the users that exploit the [SYS] in terms of the desired modifications of a certain state/condition in the world. Could you then briefly describe the purpose of the [SYS]? *Write it in the infinitive form (i.e. inform a colleague, not be thirsty anymore, heal the patient, produce the chewing-gums, get entertained...)*	Assignment	5			[GOAL]
5	Which technical function is carried out by the [SYS] in order to [GOAL]? *Use the infinitive form of the verb (i.e. keep ink, dry the clothes, deliver a box...)*	Assignment	6			[GPF]
6	Is it possible to split the function "to [GPF]" into two subfunctions?	Decision		7	12	
7	Type the first subfunction *Use the infinitive form of the verb (i.e. keep ink, dry the clothes, deliver a box...)*	Assignment	8			[P1]

8	Type the second subfunction *Use the infinitive form of the verb (i.e. keep ink, dry the clothes, deliver a box...)*	Assignment	9			[P2]
9	Type again the subfunction that is more difficult to be delivered, or that is associated at a greater extent with undesired effects. If both the subfunctions are equally related to the problem, type again the overall function [GPF], or reformulate it with more appropriate terms. Choose one between to [P1] to [P2] to [GPF] to … (new formulation)? *Use the infinitive form of the verb without the preposition "to"*	Assignment	10			[GPF]
10	Now you have changed the primary function of the system. Thus, the [SYS] is/are meant to [GPF] in order to [GOAL]. Is it right?	Decision		6	11	
11	Type the name of the system that is meant to [GPF].	Assignment	4			[SYS]
12	Type who or what perceives the benefits generated by the [SYS], when it works in order to [GOAL].	Assignment	13			[BEN]
13	Describe what or who undergoes the modifications carried out through the action “to [GPF]”.	Assignment	14			[OBJ]
14	Describe and list (one per row): the kind of environment and conditions in which the [SYS] is required to [GPF] (i.e. vacuum, open space, rainy day, asphalt road…); the kind of user, who’s meant to make the [SYS] work correctly (i.e. old person, experienced truck driver, small cat…); the technical conditions that have to be respected in order to make the [SYS] work, or even needed tools. (i.e. high temperature, screwdriver…);	Assignment	15			[SSYS]

	the unchangeable different technical systems that can be influenced by the working of [SYS] (i.e. other [SYS], bigger gear, antenna tower…)					

Table A-2: Nodes, links and variables of the logical block "Negative Effect"

Node	Text	Type	Next	Yes	No	Variables
25	Which is the undesired effect that arises in the system? *Use a substantive without the article (e.g. noise, bone breaking, vibrations, obstructed view...)*	Assignment	26			[OE]
26	Which element of the [SYS], or related to the [SYS], causes the [OE]? Some suggestions follow: [COMP] [SSYS] [SYS] itself/themselves [OBJ] [BEN] *Use a substantive without the article (i.e. heater, lever, screw, bolt...)*	Assignment	27			[VOE]
27	Thus the [SYS] is related to and interacts with [BEN] [OBJ] [SSYS] [SYS] itself/themselves [PSSYS] Type which, among these elements (and/or whatever element not belonging to the [SYS]), undergo undesired modifications or is subjected to negative impacts as a consequence of the [OE] (one per row).	Assignment	28			[CRSS]
28	Does the [VOE] provide any useful effect?	Decision		29	37	
29	Define the instant or the initial condition in which the [VOE] starts/start to cause the [OE].	Assignment	30			[POTB]
30	Define the instant or the end condition in which the [VOE] stops/stop to cause the [OE].	Assignment	31			[POTE]
31	Thus the [VOE] causes the [OE] in the following delimited time interval	Decision		33	32	

	Beginning: [POTB] End: [POTE] Is it correct?					
32	We will define again the time boundaries in which the [VOE] causes the [OE]. Pay more attention on the mechanism and the boundary conditions that enables such problem.	Assignment	29			
33	Define the physical space in which the [OE] appears/appear. *Please describe this area/volume as precisely as possible..* *Use a substantive, without the article (i.e. external surface, intersection, space between X and Y...)*	Assignment	34			[POZ]
34	Are you aware of any parameter, influencing the [OE], and belonging to one of the following: [SYS] [OBJ] [BEN] [SSYS]	Decision		38	35	
35	Can you identify a different undesired effect, other than the [OE]	Decision		36	144	
36	Define the new undesired effect *(use a substantive without the article)*	Assignment	26			[OE]
37	Thus, the [VOE] can be removed without any particular consequences. Do you want to formulate a new problem focusing on how to embody the new system without the [VOE]?	Decision		1	129	

Table A-3: Nodes, links and variables of the logical block "ARIZ" (now "Contradiction")

Node	Text	Type	Next	Yes	No	Variables
38	Type a list of parameters (one per row) concerning the [VOE] and capable to impact/influence [OE] *Use substantives without the article (e.g. length, roughness of the external surface, pressure, thermal capacity...).*	Assignment	39			[LPVOE]
39	Choose one of the parameters belonging to the following list, focusing on what mostly, if any, influence the [OE]: [LPVOE]	Assignment	40			[PVOE]

40	In order to weaken the [OE], should I increase or decrease the [PVOE] of the [VOE]? Type "increase" or "decrease"	Assignment	41			[NOOE]
41	In order to enforce the [OE], should I increase or decrease the [PVOE]? Type "increase" or "decrease"	Assignment	42			[NUOE]
42	Do any bad consequences come out if you [NOOE] the [VOE]'s [PVOE]?	Decision		43	74	
43	When we [NOOE] the [VOE]'s [PVOE], does this result in the weakening or in the disappearing of any positive effect or useful function concerning any of the following items? [SYS] [OBJ] [BEN] [SSYS] [COMP]	Decision		44	67	
44	Type such positive effect *Use a substantive, without the article, or a verb in the -ing form (i.e. heating the gas, linking the components, control, deposition of salts...)*	Assignment	45			[PE]
45	Define the instant or the initial condition in which the [PE] start(s) to appear.	Assignment	46			[UOTB]
46	Define the instant or the end condition in which the [PE] stop(s) to appear.	Assignment	47			[UOTE]
47	Thus the [PE] appear(s) in the following delimited time interval Beginning: [UOTB] End: [UOTE] Is it correct?	Decision		49	48	
48	We will define again the time boundaries in which the [PE] appear(s). Pay more attention on the mechanism and the boundary conditions that enables such positive effect.	Assignment	45			
49	Delimitate the physical space in which the [PE] appears/appear. *Please describe this area/volume as precisely as possible..* *Use a substantive, without the article (i.e. external surface, intersection, space between X and Y...)*	Assignment	50			[UOZ]
50	If you [NOOE] the [PVOE] of the [VOE], the [OE] is weakened, but this results in the	Decision		51	62	

	diminishment of the [PE] too. Is it right?					
51	If you [NUOE] the [PVOE] of the [VOE], the [PE] increases, but the [OE] is enforced too. Is it right?	Decision		52	62	

Table A-4: Nodes, links and variables of the logical block "Performance"

Node	Text	Type	Next	Yes	No	Variables
77	Type now the name of the performance, feature or parameter, that is achieved at an unsatisfactory level for the [SYS]. *Use a substantive (e.g. capability of self-controlling, speed in changing the colour, range of possible applications...)*	Assignment	78			[PERF]
78	Do you know any ways to improve the [PERF] even if this may lead to any kind of drawbacks?	Decision		79	80	
79	Which is the undesired effect that arises in the system as a consequence of getting the satisfactory level of the [PERF]? *(use a substantive without the article, e.g.: high noise, overheating,...)*	Assignment	26			[OE]
80	Type why the [PERF] of the [SYS] needs to be improved/introduced. *Use the -ing form of the verb (e.g. reducing the user's involvement, accelerating the flow, respecting the standards about emissions in the environment...)*	Assignment	81			[RIM]
81	Thus, an enhancement in terms of [PERF] of the [SYS] should be carried out because of [RIM]. What or who would perceive these improvements? Some suggestions follow: [OBJ] [BEN] [SSYS] [PSSYS]	Assignment	82			[OBIM]
82	What or who doesn't currently allow the enhancements in terms of [PERF] of the [SYS] that the [OBIM] need(s)? Some suggestions follow: [SSYS] [OBIM] parts (present or missing) of the [SYS] itself/themselves technological and environmental boundaries	Assignment	83			[AGIM]

	[COMP] [PSSYS]					
83	Do you have any possibility of modifying something among/between [OBIM] [AGIM]?	Decision		84	85	
84	Type among/between [OBIM] [AGIM] what is easier to be modified.	Assignment	4			[SYS]
85	Reformulate the undesired effect in terms of the poor [PERF] of the [SYS]. *Use a substantive without the article (e.g. limited speed, insufficient heating, reduced controllability...)*	Assignment	144			[OE]
86	Type now, the name of the performance, feature or parameter, that is achieved at an unsatisfactory level for the [SYS]. *Use a substantive (e.g. capability of self-controlling, speed in changing the colour, range of possible applications...)*	Assignment	87			[PERF]
87	Is the [PERF] of the [SYS] determined during its design and manufacturing/delivering stage?	Decision		108	80	

Table A-5: Nodes, links and variables of the logical block "Resources"

Node	Text	Type	Next	Yes	No	Variables
88	Now we will focus more carefully on the components of the [SYS] and on the resources it/they require(s) in order to [GPF].	Assignment	89			
89	Do the costs of the [SYS] (to buy, to transport, to maintain, to make it work) represent a critical issue?	Decision		95	90	
90	Type the time that is required in order to [GPF], if it represents a critical issue for the [SYS].	Assignment	91			[CRTI]
91	Type the physical spaces that are required in order to [GPF], if they represent a critical issue for the [SYS].	Assignment	92			[CRSP]
92	Type the energy that is required in order to [GPF], if it represents a critical issue for the [SYS].	Assignment	93			[CREN]
93	Type the materials that are required in	Assignment	94			[CRMA]

	order to [GPF], if they represent a critical issue for the [SYS].					
94	Type the information, the know how and the skills that are required in order to [GPF], if they represent a critical issue for the [SYS].	Assignment	136			[CRIN]

Table A-6: Nodes, links and variables of the logical block "Costs"

Node	Text	Type	Next	Yes	No	Variables
95	Now we have to better define these incurred costs for user employing the [SYS]. We will carefully investigate when these costs mostly arise and what is responsible of the high expenditures.	Assignment	96			
96	Considering the main reasons for the expenditures, do the costs mostly occur when the [SYS] has to be disposed or, however, at the end of its lifecycle?	Decision		97	103	
97	Describe with further details the phase, during the lifecycle of the [SYS], that implies the most costs	Assignment	98			[CPHA]
98	During the [CPHA], are the costs due to aspects related to time consuming operations (e.g.: long interventions of personnel)? If yes, type the feature of the [SYS] resulting in high costs (e.g.: setup time, speed of process, ...)	Assignment	99			[CRTI]
99	During the [CPHA], are the costs due to aspects related to required room (e.g.: the rent of a big store, encumbrance, ...)? If yes, type the feature of the [SYS] resulting in high costs (e.g.: volume of transported stuff, ...)	Assignment	100			[CRSP]
100	During the [CPHA], are the costs due to aspects related to material consuming operations (e.g.: amount of components for maintenance)? If yes, type the feature of the [SYS] resulting in high costs (e.g.: number of substituted components, ...)	Assignment	101			[CRMA]
101	During the [CPHA], are the costs due to aspects related to energy consuming operations (e.g.: electrical power)? If yes, type the feature of the [SYS] resulting in high costs (e.g.: energy required to make the [SYS] work, ...)	Assignment	102			[CREN]

102	During the [CPHA], are the costs due to aspects related to operations that need information or particular skills (e.g.: skills for carrying out the setup)? If yes, type the feature of the [SYS] resulting in high costs (e.g.: complexity in repairing [SYS], ...)	Assignment	136			[CRIN]
103	Considering the main reasons for the expenditures, do the costs mostly occur when the [SYS] is being used (e.g. due to its consumptions)?	Decision		97	104	
104	Considering the main reasons for the expenditures, do the costs mostly occur before the [SYS] is being used (e.g. because of setup or fine-tuning)?	Decision		97	105	
105	Considering the main reasons for the expenditures, do the costs mostly occur when the [SYS] is purchased by the final user?	Decision		106	107	
106	It seems that we're dealing with high costs related to the production process of the [SYS]	Assignment	108			
107	Considering the main reasons for the expenditures, type the phase, during the lifecycle of the [SYS], that implies the highest costs.	Assignment	98			[CPHA]

Table A-7: Nodes, links and variables of the logical block "Process"

Node	Text	Type	Next	Yes	No	Variables
108	Thus, the [SYS] and its production process should be redesigned.	Assignment	109			
109	Type the required time to perform the design and/or some manufacturing/delivering phases for the [SYS], if it represents a critical issue.	Assignment	110			[PCRTI]
110	Type the required physical spaces to perform the design and/or some manufacturing/delivering phases for the [SYS], if they represent a critical issue.	Assignment	111			[PCRSP]
111	Type the required energy to perform the design and/or some manufacturing/delivering phases for the [SYS], if it represents a critical issue.	Assignment	112			[PCREN]
112	Type the required materials to perform the design and/or some manufacturing/delivering phases for the [SYS], if they represent a critical issue.	Assignment	113			[PCRMA]

113	Type the information, the know how and the required skills to perform the design and/or some manufacturing/delivering phases for the [SYS], if they represent a critical issue.	Assignment	114			[PCRIN]
114	Describe and list, one item per row: the kind of environment and conditions in which the [SYS] is designed and manufactured *(e.g.: vacuum, high temperature, ...);* the kind of designer, developer or worker who's meant to design or produce the [SYS] *(e.g.: high specialized working team, ...);* the kind of technologies, techniques or tools required to design or produce the [SYS] *(e.g.: 3D-CAD; CNC center, ...);* different systems with which the [SYS] has to interact during the design and production process *(e.g.: X-rays check, ...)*	Assignment	115			[PSSYS]
115	Thus the [SYS] is related to [PENV] [PUSER] [PTECH] [POSYS] Type (if any) the one(s), among these items, whose properties or requirements are affected or threatened by the [OE].	Assignment	116			[PCRSS]
116	The [SYS] is related to: [PENV] [PUSER] [PTECH] [POSYS] Type (if any) which, among these items, cause high costs.	Assignment	117			[PCRCO]
117	Is the following list empty? [PCRTI] [PCRSP] [PCREN] [PCRMA] [PCRIN] [PCRSS] [PCRCO]	Decision		144	118	

Table A-8: List of nodes connecting the main blocks of the algorithm

Node	Text	Type	Next	Yes	No	Variables
121	Thus, the [SYS] is meant to [GPF] between the instant/condition "[FOTB]" and the final instant/condition "[FOTE]". As well, the [VOE] causes/cause the [OE] between the instant/condition "[POTB]" and the final instant/condition "[POTE]". Do these two time intervals overlap?	Decision		123	122	
122	SUGGESTION: Think about the opportunities to redesign the [SYS], taking advantage of the circumstances that the performing of the function "to [GPF]" doesn't overlap with the [OE], since these actions occur in different moments.	Assignment	123			
123	The [SYS] is meant to [GPF] in the [FOZ]. As well, the [VOE] causes/cause the [OE] in the [POZ]. Do these two space regions overlap?	Decision		125	124	
124	SUGGESTION: Think about the opportunities to redesign the [SYS], taking advantage of the circumstances that the performing of the function "to [GPF]" doesn't overlap with the [OE], since these actions occur in different space regions.	Assignment	125			
125	Thus, the [VOE] produces the [PE] from the instant/condition "[UOTB]" to the final instant/condition "[UOTE]". As well, the [VOE] causes/cause the [OE] between the instant/condition "[POTB]" and the final instant/condition "[POTE]". Do these two time intervals overlap?	Decision		127	126	
126	SUGGESTION: Think about the opportunities to redesign the [SYS], taking advantage of the circumstances that the [PE] doesn't overlap with the [OE], since these actions occur in different moments.	Assignment	127			
127	The [VOE] produce(s) the [PE] in the [UOZ]. As well, the [VOE] causes/cause the [OE] in the [POZ]. Do these two space regions overlap?	Decision		129	128	
128	SUGGESTION: Think about the opportunities to redesign the [SYS], taking advantage of the circumstances that the [PE] doesn't overlap with the [OE], since these actions occur in different space	Assignment	129			

	regions.					
129	SUGGESTIONS 1) You can reformulate the problem, paying attention on what surrounds the [SYS] with a particular focus on the [CRSS] 2) You can reformulate the problem, focusing on the components of the [SYS]; choose one of the following items: [COMP] 3) Reformulate the problem, thinking about the opportunities to turn the [OE] into a useful effect for some of the following elements: [BEN] [SYS] itself/themselves [OBJ] [COMP] [SSYS] [PSSYS] 4) Reformulate the problem introducing a different system in order to [GOAL], as requested by the [BEN]	Assignment	130			
130	Following the previous suggestions, do you think that you can advantageously reformulate the problem?	Decision		1	131	
131	Do you want to further investigate and characterize the underlying problems of the [SYS], thus revealing some aspects that haven't been yet elicited?	Decision		132	144	
132	Does the [OE] occur when the [SYS] is manufactured, prepared or delivered?	Decision		108	133	
133	Does the [OE] arise during the use of the [SYS] and/or between stops and restarts?	Decision		88	134	
134	Does the [OE] characterize the whole lifecycle of the [SYS]?	Decision		135	144	
135	It seems that we are dealing with a problem that should be faced during the design of the [SYS]	Assignment	108			
136	We have tried to investigate the relevant problems of the [SYS] during its use. Is the following list empty? List: [CRTI] [CRSP]	Decision		137	138	

	[CREN] [CRMA] [CRIN]					
137	Is the [OE] related to some unsatisfactory performances of the [SYS]?	Decision		79	144	
138	Thus, we know that we have [OE] mostly affecting [CRSS] Moreover, in order to [GPF], the [SYS] requires, in its lifecycle: time: [CRTI] space: [CRSP] energy: [CREN] material: [CRMA] information: [CRIN] By this checklist, do you still think that is correct to focus on the [OE]? Otherwise we can redefine the problem considering the resources, the requirements and the costs related with the [SYS] lifecycle.	Decision		144	139	
139	Type among: [CRTI] [CRSP] [CREN] [CRMA] [CRIN] what represents the most critical issue.	Assignment	140			[CRRE]
140	Our new problem is: during the [SYS] lifecycle, the [SYS] itself/themselves or some of its/their component require(s) [CRRE] in order to [GPF] and/or to fulfill some subtask. Now reformulate the undesired effect. *Use a substantive without the article (e.g. requirement of too much fuel, need of excessive space...)*	Assignment	141			[OE]

Node 206 in Table A-9 represents just an example of the nodes from which the user can skip the System Operator branch in order to reformulate the main problem (line 23 of Figure 3) or refine the problem model according to OTSM-TRIZ contradiction model (line 24 of Figure 3). There is a total of 9 nodes (number 206-198) that allows the user to skip the procedure, each of them shares the same formulation of node 206; the only difference stands in the variable in square brackets proposed to user's attention, according to the screen from where the analysis of the system operator gets skipped.

Table A-9: Detail of the new branch of the algorithm for problem analysis. Nodes pertaining to the System Operator block.

Node Id	**Text**	**Type**	Next	Yes	No	**Variab.**
228	You are close to the final question, but it seems that the problem formulation is not going to result in a successful outcome. It could be worth to further detail the technical system "[SYS]" by answering a new set of questions which are viable to formulate alternative or bypass problems. Do you want to proceed with this kind of analysis?	D		227	CNF	
227	Before the investigation please confirm that the main issue concerning the [SYS] is related to the [OE]. If yes, click on the "save and continue" button; otherwise correct it and then "save and continue".	A	226			[OE]
226	You are going to start an analysis of potentially available resources within your technical system and its surroundings. During the following steps you will be asked to reformulate your original problem in order to identify a new alternative problem whose solution could be easier and fulfils the same requirements.	A	225			
225	You identified the technical system under investigation as "[SYS]" and the whole analysis has been focused on the delivery of its function "to [GPF]" during the time interval from [FOTB] to [FOTE]. Answer the following set of questions by taking into account the whole time interval in which the [SYS] is working. Type, in the blank space pertaining to SYSPR, a set of properties of the [SYS] that characterizes it when it is delivering the function "to [GPF]", regardless the influence of such properties on the delivery of the function. *Example: "Encumbrance of the [SYS], length of the [SYS], friction factor of the wheel,..."* Type, in the blank space pertaining to OBJPR, a set of properties of the [OBJ] that characterizes it when the [SYS] delivers the function "to [GPF]", regardless the influence of such properties on the delivery of the function by the [SYS]. *Example: "mean size of grains, paper color, ..."*	A	224			[SYSPR, OBJPR]
224	"*What should the [SYS] or the [OBJ], or one of the below mentioned properties, [SYSPR] [OBJPR] do in order to reduce the [OE]?"* Can you mentally answer such question? If you	D		206	223	

	can't, please press "No"; otherwise keep reading, since you may have an alternative problem formulation. Is the new problem formulation easier to be faced than the original one?					
223	You identified the technical system under investigation as "[SYS]" and the whole analysis has been focused on the delivery of its function "to [GPF]" during the time interval from [FOTB] to [FOTE]. Answer the following question by taking into account the whole time interval in which the [SYS] is working. Type, in the blank space, a set of properties of the components of the system that characterize it during the time interval after [FOTB] and before [FOTE], also specifying the component the property belong to, regardless the influence of such properties on the delivery of the function "to [GPF]". In order to help you in answering this question, this is the list of components belonging to the [SYS] you previously typed. [COMP] *Example: "maximum pressure of the coffee brewer; diameter of the feeding pipe, ..."*	A	222			[COMPPR]
222	[COMP] [COMPPR] *"What should one of the above reported items, or a combination of them,do in order that the [OE] doesn't appear or affect significantly the [SYS], one of its components or something in the immediate surroundings?* Can you mentally answer such question? If you can't, please press "No"; otherwise keep reading, since you may have an alternative problem formulation. Is the new problem formulation easier to be faced than the original one?	D		205	221	
221	You identified the technical system under investigation as "[SYS]" and the whole analysis has been focused on the delivery of its function "to [GPF]" during the time interval from [FOTB] to [FOTE]. Answer the following set of questions by taking into account the whole time interval in which the [SYS] delivers its function. At last, you identified the following items [SSYS] as elements that surround the system. What properties characterize such elements during the time interval during the [SYS] works in order to [GPF]? Type them in the blank space, regardless the	A	220			[SSYSPR]

	influence of such properties on the delivery of the function by the [SYS], also specifying the element the property belong to. *Example: "Speed of conveyors, voltage and frequency of electric current, ..."*					
220	[SSYS] [SSYSPR] *"What should one of the above reported items, or a combination of them, do in order that the [OE] doesn't appear or affect significantly the [SYS], one of its components or something in the immediate surroundings?* Can you mentally answer such question? If you can't, please press "No"; otherwise keep reading, since you may have an alternative problem formulation. Is the new problem formulation easier to be faced than the original one?	D		204	219	
219	You identified the technical system under investigation as "[SYS]" and the whole analysis has been focused on the delivery of its function "[GPF]" during the time interval from [FOTB] to [FOTE]. Answer the following set of questions by taking into account the whole time interval that comes before the instant [FOTB]. Type, in the blank space pertaining to SYSP, a set of properties of the [SYS] that characterizes it before it start to [GPF] (since it is assumed that some properties of the system may change during the delivery of its function). *Example: "Position during the transport, encumbrance of the box, … "* Type, in the blank space pertaining to OBJP, a set of properties of the [OBJ] that characterizes it before the [SYS] starts to [GPF]. *Example: "Roasting degree (of coffee beans), quantity of caffeine, …"*	A	218			[OBJP, SYSP]
218	*"What should be done in advance, exploiting the following properties [SYSP] [OBJP] in order to prevent the [OE]?* Can you mentally answer such question? If you can't, please press "No"; otherwise keep reading, since you may have an alternative problem formulation. Is the new problem formulation easier to be faced than the original one?	D		203	217	

217	You identified the technical system under investigation as "[SYS]" and the whole analysis has been focused on the delivery of its function "[GPF]" during the time interval from [FOTB] to [FOTE]. Answer the following set of questions by taking into account the whole time interval that comes before the instant [FOTB]. Type, in the blank space, a set of properties of the components of the system that characterize them during the time interval before [FOTB], also specifying the component the property belong to. In order to help you in answering this question this is the list of components belonging to the [SYS] you previously typed. [COMP] *Example: "Volume of the drum of the washing machine, radius of the steering wheel, height of the door of the refrigerator, ..."*	A	216			[COMPP]
216	[COMPP] *"What should be done by one of the above reported items, or a combination of them, in order that the [OE] gets prevented?* Can you mentally answer such question? If you can't, please press "No"; otherwise keep reading, since you may have an alternative problem formulation. Is the new problem formulation easier to be faced than the original one?	D		202	215	
215	You identified the technical system under investigation as "[SYS]" and the whole analysis has been focused on the delivery of its function "[GPF]" during the time interval from [FOTB] to [FOTE]. Answer the following set of questions by taking into account the whole time interval that comes before the instant [FOTB]. At last, you identified the following items [SSYS] as elements that surround the system. What properties characterize such elements during the time interval before the [SYS] starts to [GPF]? Type them in the blank space, also specifying the element the property belong to. *Example: "air composition; direction of wind; water salinity,..."*	A	214			[SSYSP]
214	[SSYSP] *"What should be done by one of the above reported items, or a combination of them, in order that the [OE] gets prevented?* Can you mentally answer such question? If you	D		201	213	

	can't, please press "No"; otherwise keep reading, since you may have an alternative problem formulation. Is the new problem formulation easier to be faced than the original one?					
213	You identified the technical system under investigation as "[SYS]" and the whole analysis has been focused on the delivery of its function "[GPF]" during the time interval from [FOTB] to [FOTE]. Answer the following set of questions by taking into account the whole time interval that comes after the instant [FOTE]. Type, in the blank space pertaining to SYSF, a set of properties of the [SYS] that characterizes it after it ends to [GPF] *Example: "Temperature of the coffee machine; shape of the ice-maker, ..."* Type, in the blank space pertaining to OBJF, a set of properties of the [OBJ] that characterizes it after the [SYS] has ended to [GPF]. *Example: "Temperature of the coffee, volume of the ice cube, ..."*	A	212			[OBJF, SYSF]
212	[SYSF] [OBJF] *"What should the above properties should do in order to mitigate the undesired effects caused by the [OE]?* Can you mentally answer such question? If you can't, please press "No"; otherwise keep reading, since you may have an alternative problem formulation. Is the new problem formulation easier to be faced than the original one?	D		200	211	
211	You identified the technical system under investigation as "[SYS]" and the whole analysis has been focused on the delivery of its function "[GPF]" during the time interval from [FOTB] to [FOTE]. Answer the following set of questions by taking into account the whole time interval that comes after the instant [FOTE]. Type, in the blank space, a set of properties of the components of the system that characterize them during the time interval after [FOTE] , also specifying the component the property belong to. In order to help you in answering this question this is the list of components belonging to the [SYS] you previously typed. [COMP] *Examples: "thickness of the table top, stiffness of*	A	210			[COMPF]

	table top, flow ratio of the pump, number of holes in pump inlet,..."					
210	[COMPF] *"What should one of the above reported items, or a combination of them, do after the [OE] in order that its/their effects become negligible?* Can you mentally answer such question? If you can't, please press "No"; otherwise keep reading, since you may have an alternative problem formulation. Is the new problem formulation easier to be faced than the original one?	D		199	209	
209	You identified the technical system under investigation as "[SYS]" and the whole analysis has been focused on the delivery of its function "[GPF]" during the time interval from [FOTB] to [FOTE]. Answer the following set of questions by taking into account the whole time interval that comes after the instant [FOTE]. At last, you identified the following items [SSYS] as elements that surround the system. What properties characterize such elements during the time interval after the [SYS] ends to [GPF]? Type them in the blank space, also specifying the element the property belong to. *Example: "density of the air; temperature of the environment, viscosity of water, noise level ...."*	A	208			[SSYSF]
208	[SSYSF] *"What should one of the above reported items, or a combination of them, do after the [OE] in order that its/their effects become negligible?* Can you mentally answer such question? If you can't, please press "No"; otherwise keep reading, since you may have an alternative problem formulation. Is the new problem formulation easier to be faced than the original one?	D		198	CNF	
207	Unfortunately it seems that you didn't identify any formulation of alternative problems that may result easier to be solved. Is the following list empty? [LPVOE]	D		NE	CNF	
206 (198)	It seems that you find some useful inspiration among the below mentioned resources in order to solve or to formulate an alternative problem. You are now kindly asked to specify what is the resource you just identified among	A	197			[PVOE, VOE]

	[SYSPR] [OBJPR]. Please write, in the blank space pertaining to PVOE, the property you want to exploit in order to reduce the [OE] and in the blank space pertaining to VOE the element it belongs to. (Example: PVOE= diameter; VOE= ball; PVOE=speed; VOE= pump; ....)					
197	Do you think that the [PVOE] of the [VOE] may positively impact on the [OE]? If you think so, please click on the "yes" button and you will be directed to a path that may help you in deepening the problem analysis and finding some useful solutions. Otherwise, if you think it's worth to formulate a new alternative problem, click on the "no" button and you will be supported in its new analysis	D		196	IS	
196	If you properly modify the [PVOE] of the [VOE] in order to, at least, reduce the effects of the [OE], this results in the worsening of some useful effects already delivered by the [SYS] or by one of the following elements? [COMP]	D		CTD	195	
195	It seems that the [PVOE] of the [VOE] is an appropriate resource capable to solve the original problem, since its modification doesn't imply any worsening in the functioning or in the structure of the [SYS]. Does the required modification of [PVOE] somehow negatively impact on the following elements? [SSYS]	D		CTD	194	
194	Since the [PVOE] of the [VOE] can be properly modified in order to remove or limit the [OE] without worsening any useful effect, being it functional or structural, you may have a powerful direction of solution for your problem. Do you want to investigate further negative effects pertaining to the [SYS]?	D		NE	NIP	

Appendix B - Checklists

Pugh's checklist

- *Performance*
Which function(s) does the product has to fulfil? What are the parameters by which the functional characteristics will be assessed (speed, power, strength, accuracy, capacity, etc.)?

- *Environment*
To which environmental influences is the product subjected during manufacturing, storing, transportation and use (temperature, vibrations, humidity, etc.)? Which effects of the product on the environment should be avoided?

- *Life in service*
How intensively will the product be used, how long does it have to last?

- *Maintenance*
Is maintenance necessary and available? Which parts have to be accessible?

- *Target product cost*
How much may the product cost, considering the prices of similar products?

- *Transportation*
What are the requirements of transport during production, and to the location of use?

- *Packaging*
Is packaging required? Against which influences should the packaging protect the product?

- *Quantity*
What is the size of run? Is it batch or continuous production?

- *Manufacturing facilities*
Should the product be designed for existing facilities; are investments in new production facilities possible? Is (a part of) the production going to be contracted out?

- *Size and weight*
Do production, transport, or use put limits as to maximum dimensions or weight?

- *Aesthetics, appearance and finish*
What are the preferences of the consumers, customers? Should the product fit in with a product line or house style?

- *Materials*
Are special materials necessary? Are certain materials not to be used (for example in connection with safety or environmental effects)?

- *Product life span*
How long is the product expected to be produced and marketable?

[continues]

- *Standards*

Which standards (national and international) apply to the product and its production? Should standardization within the company or industrial branch be taken into account?

- *Ergonomics*

Which requirements, with regard to perceiving, understanding, using, handling, etc., does the product have to meet?

- *Quality and reliability*

How large may 'mean times before failure' and 'mean times to repair' be? Which failure modes, and resulting effects on functioning, should certainly not occur?

- *Shelf life and storage*

Are there during production, distribution, and use (long) periods of time in which the product is stored? Does this require specific 'conservative' measures?

- *Testing*

To which functional and quality tests is the product submitted, within and outside the company?

- *Safety*

Should any special facilities be provided for the safety of the users and non-users?

- *Product policy*

Does the current and future product range impose requirements on the product?

- *Social and political implications*

What is the public opinion with regard to the product?

- *Product liability*

For which unintended consequences of production, operation and use can the manufacturer be held responsible?

- *Installation, operation*

Which requirements are set by final assembly and installation outside the factory, and by learning to use and operate the product?

- *Re-use, recycling, disposal*

Is it possible to prolong the material cycle by re-use of materials and parts? Can the materials and parts be separated for waste disposal?

Pahl & Beitz's checklist for conceptual design

Main headings	Examples
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension
Kinematics	Type of motion, direction of motion, velocity, acceleration
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, inertia forces, resonance
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversion.
Material	Flow and transport of materials. Physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials (food regulations etc)
Signals	Inputs and outputs, form, display, control equipment.
Safety	Direct safety systems, operational and environmental safety.
Ergonomics	Man-machine relationship, type of operation, operating height, clarity of layout, sitting comfort, lighting, shape compatibility.
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances, wastage.
Quality control	Possibilities of testing and measuring, application of special regulations and standards.
Assembly	Special regulations, installation, siting, foundations.
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of despatch.
Operation	Quietness, wear, special uses, marketing area, destination (for example, sulphurous atmosphere, tropical conditions).
Maintenance	Servicing intervals (if any), inspection, exchange and repair, painting, cleaning.
Recycling	Reuse, reprocessing, waste disposal, storage
Costs	Maximum permissible manufacturing costs, cost of tooling, investment and depreciation.
Schedules	End date of development, project planning and control, delivery date

Pahl & Beitz's checklist for embodiment design

Headings	Examples
Function	Is the stipulated function fulfilled? What auxiliary functions are needed?
Working principle	Do the chosen working principles produce the desired effects and advantages? What disturbing factors may be expected?
Layout	Do the chosen overall layout, component shapes, materials and dimensions provide: adequate durability (strength) permissible deformation (stiffness) adequate stability freedom from resonance unimpeded expansion acceptable corrosion and wear with the stipulated service life and loads?
Safety	Have all the factors affecting then safety of the components, of the function, of the operation and of the environment been taken into account?
Ergonomics	Have the human–machine relationships been taken into account? Have unnecessary human stress or injurious factors been avoided? Has attention been paid to aesthetics?
Production	Has there been a technological and economic analysis of the production processes?
Quality control	Can the necessary checks be applied during and after production or at any other required time, and have they been specified?
Assembly	Can all the internal and external assembly processes be performed simply and in the correct order?
Transportt	Have the internal and external transport conditions and risks been examined and taken into account?
Operation	Have all the factors influencing the operation, such as noise, vibration, handling, etc. been considered?
Maintenance	Can maintenance, inspection and overhaul be easily performed and checked?
Recycling	Can the product be reused or recycled?
Costs	Have the stipulated cost limits been observed? Will additional operational or subsidiary costs arise?
Schedules	Can the delivery dates be met? Are there design modifications that might improve the delivery situation?

Appendix C - TRIZ Laws of Engineering Systems Evolution

From the English handbook of the TETRIS Project – Teaching TRIZ at School (http://www.tetris-project.org). Further and more in-depth details in (Altshuller, 1984).

The laws of development of technical systems were firstly published by G. S. Altshuller in his book *Creativity as an Exact Science: the Theory of the Solution of Inventive Problems* in 1979:

1. The law of the completeness of parts of the system.
2. The law of "energy conductivity".
3. The law of harmonizing the rhythms of parts of the system.
4. The law of increasing of the degree of idealness of the system.
5. The law of uneven development of parts of a system.
6. The law of the transition to a super-system.
7. The law of the transition from a macro to a micro level.
8. The law of increase of the S-field involvement.

If to speak about TRIZ as about the system, it is important to mention that it is very harmonious. The tools which are included in its structure make the system work. They are interconnected, and the basis is formed by the Laws of Development of Technical Systems. Laws are divided into 3 groups: laws of statics (1-3), laws of kinematics (4-6); laws of dynamics (7, 8). In such a division there is a certain analogy with mechanics – the section of physics. By consideration of «a life line » of development of the technical system *the S-shaped curve*, the following is observed. The Laws of statics are characteristic for the appearance stage of the technical system; laws of kinematics – for the development stage of the technical system; laws of dynamics – for the closing stage of development and transition to a subsystem.

LESE #1 - Definition

"A necessary condition for the living capability in principle of technical systems is the presence and minimal functioning power of the basic parts of the system."

The consequence:

"For a technical system to be controllable it is necessary for at least one of its parts to be controllable. "To be controllable" means changing its properties in a way required by the controller."

The law is related to the chapter "Static", to be more precise, to the laws which define the life beginning of technical systems. However, it is important to understand that the law refers not only to such ancient technical systems as a bow, a stone axe, a catapult. Any technical system changes during its evolution. There is very often a full replacement of one or several basic parts in the technical system. At the moment of such a change of parts a new system actually appears and the law of the completeness of parts of the system is applicable to it as well as for the essentially new technical system.

Minimal Technical System Model

A model includes the main parts of the technical system: the engine, the transmission, the tool, the control unit (for further reference about its use, please refer to Appendix D).

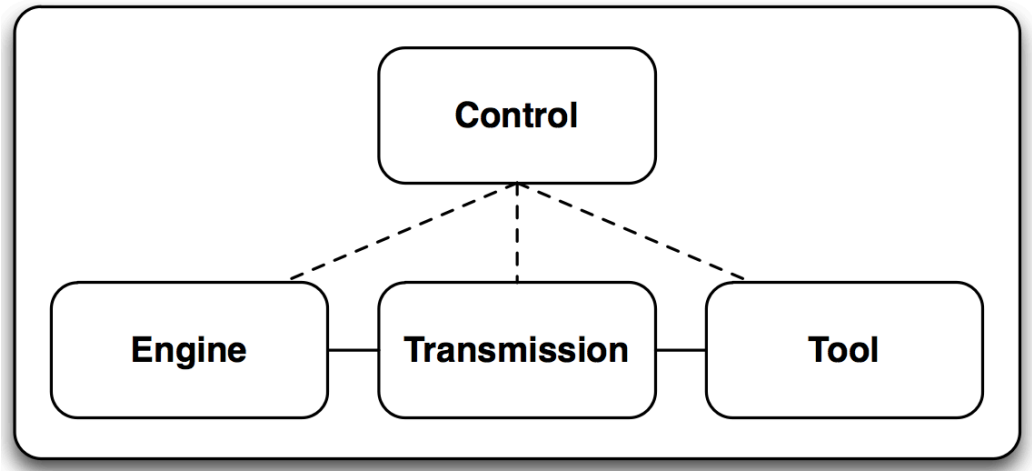


Figure C-1: The minimum kind of parts composing a Technical System

LESE #2 - Definition

"The law of "energy conductivity" of the system: A necessary condition for the life capability in principle of a technical system is the unhindered passage of energy through all parts of the system".

"The corollary of Law 2 is also significant: It is necessary to ensure conductivity of energy between this part and the controlling organs in order to control the part of the technical system."

The law refers to the section "Static", to be more precise, to the laws which define the beginning of life of technical systems.

LESE #3 - Definition

An essential condition for the living viability in principle of a technical system is the harmonization of the rhythms (frequencies of vibration, periodicity) of all parts of the system.

LESE #4 - Definition

The development of all systems proceeds in the direction of increasing the degree of Ideality.

Model of Ideality with S-curve

The life of the technical system (as well as of other systems, for example, the biological systems) can be illustrated with the image of dependency of the main parameters of the system on time. Such model of the technical system in the form of a S-curve (Figure C-2) is widely used in OTSM-TRIZ. The S-curve shows clearly how the main parameters (speed, capacity, productivity, etc.) of the technical system are changed during its life. Each system has its own peculiarities, its own «portrait» of the S-shaped curve. But there is something common in each «portrait», which is characteristic for all systems. 1 – «Childhood»; 2 – «Maturity»; 3 – «Old age» are such areas.

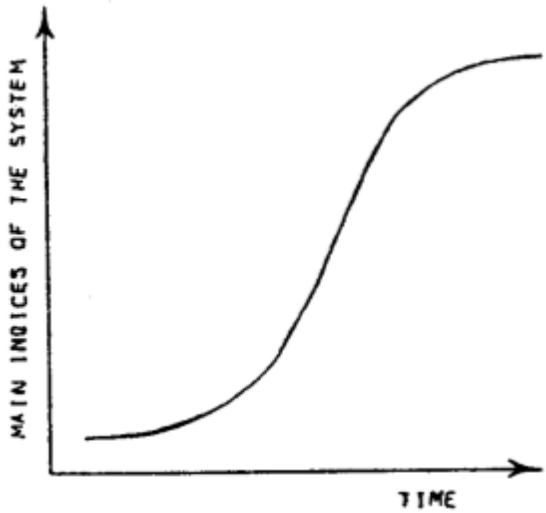
In the course of development of the technical system its main parameters are increased, the system becomes better, more ideal. It is necessary to construct the scheme of change in time of one of the main indicators of the system, using the patent fund and other sources about the previous development of the analysed system. Further, using the received S-shaped curve to draw conclusions about that stage of development on which the technical system is found.

There are several stages, steps of increase of Ideality:

- improvement of parameters of a system (1-2 main) at the increase of costs;
- improvement of parameters of a system (1-2 main) at the unchanged costs;
- improvement of parameters of a system (the appearance of new functions) at the increase of costs;
- improvement of parameters of a system (the appearance of new functions) at the unchanged costs;
- improvement of parameters of a system at the decrease of costs;
- improvement of parameters of a system (the appearance of new functions) at the decrease of costs;

The significant decrease of expenses which are used to support the existence of the system and the appearance of new functions, and which extend significantly the application of the system takes place by the complete disappearance (by the rollback) of the technical system, for example, by its connection with another system or its transition to the sub-system with the transfer of its main functions to the new system.

Figure C-2: S-Curve



LESE #5 - Definition

The development of a system's parts proceeds unevenly; the more complicated the system, the more uneven the development of its parts is.

LESE #6 - Definition

Having exhausted all development possibilities, a system is included in a supersystem as one of its parts; in doing so further development takes place at supersystem level.

LESE #7 - Definition

The development of working organs (“Tools”) proceeds at first at macro and then, at a micro level.

LESE #8 - Definition

“The development of technical systems proceeds in the direction of increasing the S-Field involvement”.

Appendix D – Steps from Cascini's Modeling Technique

Modeling technique as presented in Cascini (2008).

1. *Preliminary analysis of the Technical System*
   1.1. *Identify the Main Useful Function of the Technical System, its characterizing parameters and expected values*
      - *Identify the Evaluation Parameters defining the performance of the Main Useful Function*
      - *Decompose the Main Useful Function, according to the Functional Basis (Hirtz, 2002), into elementary functions needed to impact those Evaluation Parameters*
      - *Identify constraints and minimum performance values (e.g. due to standards, certification systems etc.)*

   1.2. *Analyze the goal of the Technical System and the role of its Main Useful Function at a super-system level; identify all the functions acting on the same object of the Main Useful Function*

- E.g.: Let's consider a sterilization module in a machinery for aseptic filling of beverage containers; its function is reducing the amount of pathogenic organisms (Evaluation Parameter) in the container, e.g. a bottle, before to fill it, until a sealed cap will be applied; in this case it is important to identify further functions acting on the bottle, e.g. handling, because they can interfere with the Technical System under study.

   1.3. *Identify the alternative Behavioral Models of the Technical System capable to produce the expected Main Useful Function*
      - *This task should be performed taking into account also out-of-date configurations of the Technical System*
      - *Only different Behaviour Model of the Main Useful Function should be mapped, while other differences between possible embodiments (structures) of the Technical System can be neglected at this stage*

- E.g.: Let's consider a machine for rubber pulverization (Main Useful Function): alternative Behaviour Models are cryogenic milling, high-speed cutting, high compression and shear milling, waterjet cutting etc.

   1.4. *Identify the Auxiliary Functions requested by each specific Behaviour Model of the Main Useful Function*

- E.g.: in the example of bottle sterilization, if the elimination of bacteria is obtained through a chemical substance like peracetic acid, an auxiliary function to be delivered is bottle rinsing, since even small drops of the sterilizer could negatively impact the taste of the beverage.

Each Behavioural Model can be described in terms of the Minimal Technical System Model, as presented in (Becattini, 2011-c):

Then the Behaviour of each elementary function is represented by means of the TRIZ model of Minimal Technical System as follows:

a. *identify the Product, i.e. the object of the function which determines a transformation of the input flow into the output;*
b. *identify the Tool, i.e. the element which acts directly on the Product;*
c. *determine which properties characterize the Tool's capability to deliver the function to the Product;*
d. *for each of the properties defined at step c, identify the "Engine" from where the properties derives;*
e. *complete the model of the minimal technical system, by adding the transmission from the Engine to the Tool, the control and its interactions with the other subsystems and the external supply of the engine.*

Appendix E - OTSM-TRIZ models of the problem solving processes

Description of the three models as presented in Becattini (2012-a):

Hill model

In order to avoid a trial and error approach to idea generation and psychological inertia biases, the problem solving process (Figure E-1) should start with an abstraction phase aimed at transforming a specific inventive situation into a general typical situation (left part of the hill). Then, once an inventive problem is transformed into a typical one, i.e., it is described in terms of unsatisfactory functional interactions or in terms of contradictions, it is possible to apply some general solving instruments and identify the most appropriate model of the solution. Such an ideal solution must then be embodied into a concrete one through a convergence process, which must be focused on the most fruitful exploitation of the available resources (right slope of the hill). The Hill model acquires a more comprehensive meaning through the integration with the Tongs model (see below) which represents the approach to be used during the problem generalization phase: at the beginning of the problem-solving process the problem is reformulated several times according to the rules of the Tongs model, but each time the level of generalization increases. This abstraction process leads to a more general description of the problem itself and, as a result of this generalization, it is easier to find a direct analogy between problems that look very different from each other.

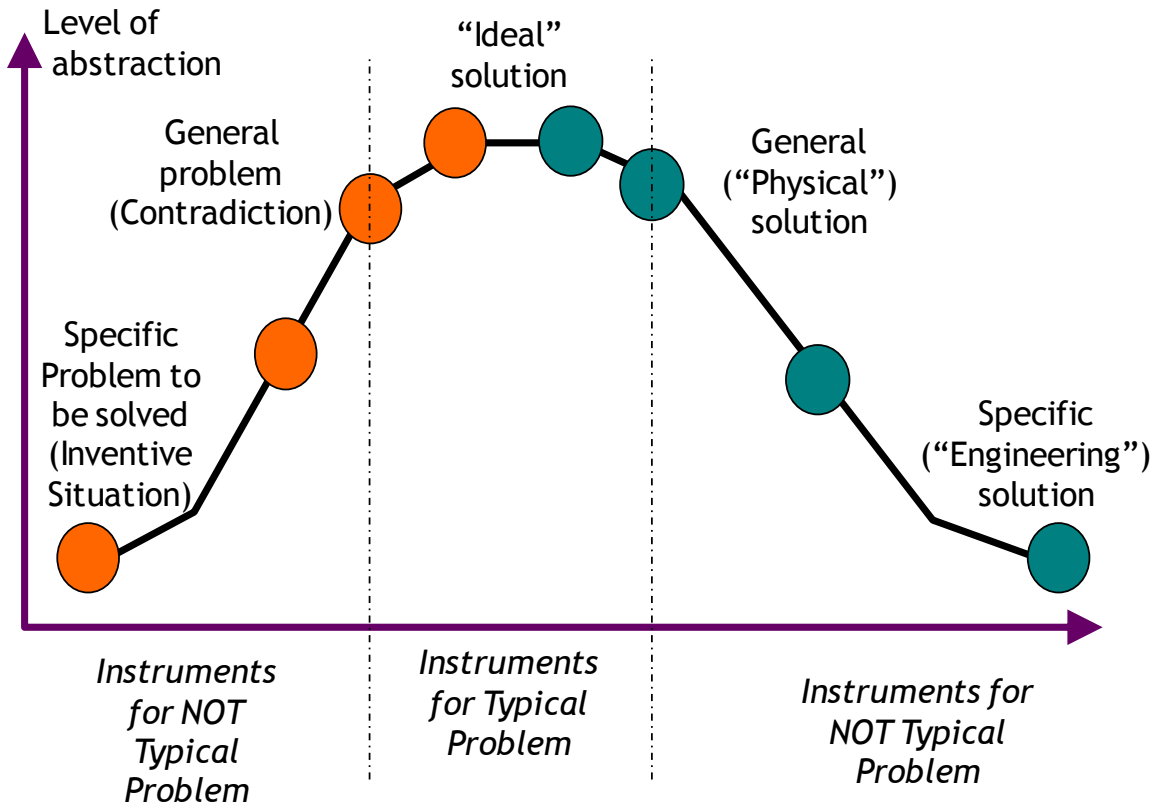


Figure E-1: Hill Model

Funnel Model

Most of the techniques supporting creativity suggest the adoption of a divergent approach, according to the assumption that within a larger set of ideas there is a higher probability to get a successful solution. TRIZ starts from a firm refusal of trial and error and recommends following a convergent approach in order to increase the efficiency of the overall process, i.e., the ratio between effective solutions and the resources involved for their development.

The Funnel model depicts a convergent process by taking into account natural laws and personal needs with consequent steps aimed at the definition of the profile of the final solution, i.e., a set of characteristics until its description is unique. At the beginning of the problem-solving process the solution space must be large in order to avoid falling in the traps of psychological inertia. Then, within the problem analysis phase, the solution space is progressively narrowed until just satisfactory solutions remain. The problem-solving process should be located inside this Funnel and prevent a problem solver from useless trials and error.

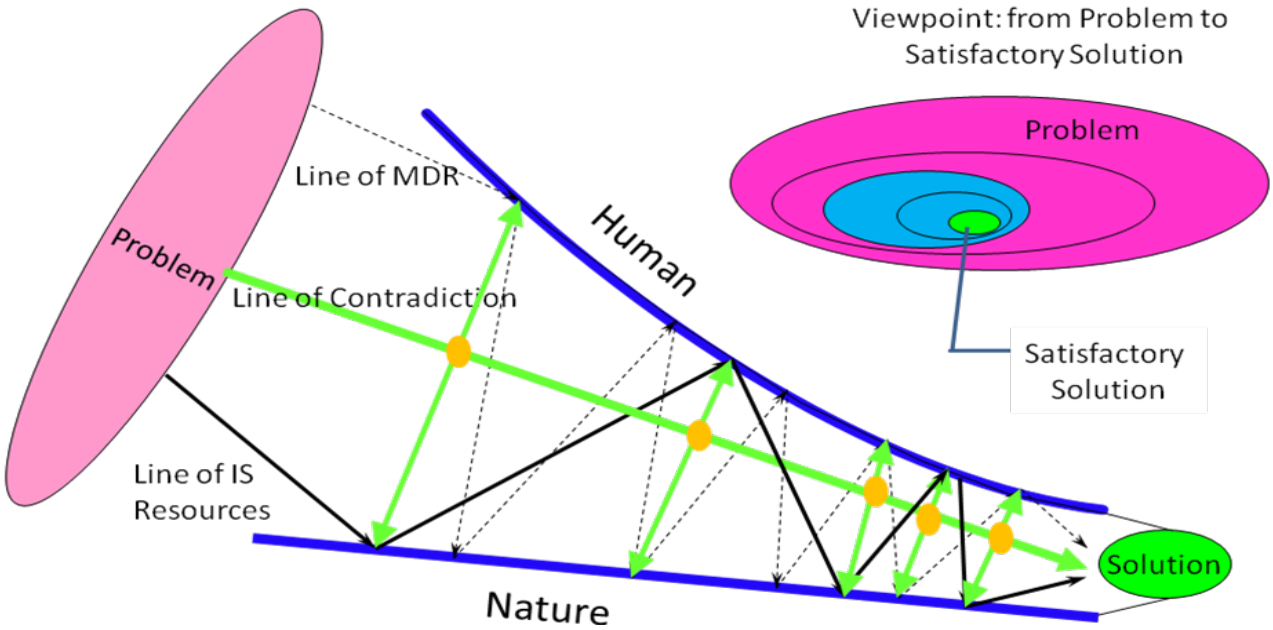


Figure E-2: Funnel Model

Tongs Model

The Tongs model provides further details about the analysis stage of a TRIZ problem solving process (Figure E-1, left slope). It is important to avoid the generation of ideas starting from the actual technical system in order to overcome psychological inertia. Besides, it is suggested to depict the characteristics of the Most Desirable Result (MDR); then a comparison between the Most Desirable Result and the current situation is the key to identifying the barriers impeding the achievement of the expected results. Such a barrier hides one or more contradictions to be elicited and overcome through the TRIZ instruments.
Moreover, the identification of contradictions and the application of the solving principles highlight the possible lacks of knowledge and consequently determine a direction to integrate new competences and technologies systematically.

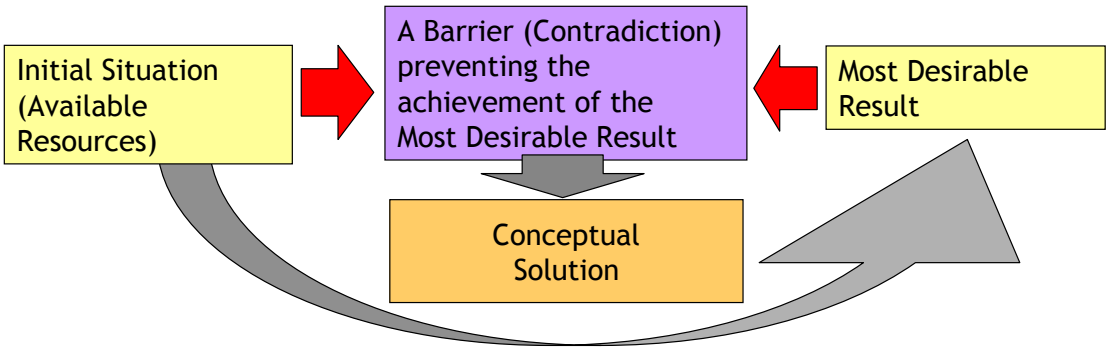


Figure E-3: Tongs Model

Appendix F – ARIZ85-C

This appendix present an excerpt (all the steps, few details) of the whole algorithm proposed in 1985 by Altshuller. It has not been published in English. The following sequence of steps is the translation of Kucharavy available, with further details and comments, at the website http://www.seecore.org

PART 1. ANALYZING THE PROBLEM

1.1. formulate the mini-problem
1.2. define the conflicting elements
1.3. describe graphic models for technical contradictions
1.4. select a graphic model for further analysis
1.5. intensify the conflict
1.6. describe the problem model
1.7. apply the inventive standards

The main purpose of Part 1 is the transition from an indefinite initial problem situation to the clearly formulated and extremely simplified description (model) – Problem Model.

PART 2. ANALYZING THE PROBLEM MODEL

2.1. define the Operational Zone (OZ)
2.2. define the Operational Time (OT)
2.3. define the Substance-Field resources (SFR)

The main purpose of Part 2 is to identify available resources (space, time, substances, and fields) that may be useful for solving the problem.

PART 3. DEFINING THE IDEAL FINAL RESULT (IFR) AND PHYSICAL CONTRADICTION (PhC)

3.1. formulate IFR-1
3.2. intensify the definition of IFR-1
3.3. identify the Physical contradiction for the Macro-level
3.4. identify the Physical contradiction for the Micro-level
3.5. formulate IFR-2
3.6. apply the Inventive Standards to resolve the Physical contradiction

As result of applying Part 3 the image of the Ideal Final Result (IFR) should be formulated. The Physical Contradiction (PhC) that prevents the achievement of the IFR should be identified too. The ideal solution is not always achievable, but the IFR indicates the direction of the most powerful solution.

PART 4. MOBILIZING AND USING SUBSTANCE-FIELD RESOURCES (SFR)

4.1. simulation with little creatures
4.2. take a "step back" from the IFR

4.3. using a combination of substance resources
4.4. using "voids"
4.5. using derived resources
4.6. using an electrical field
4.7. using a field and field-sensitive substance

At step 2.3, the available resources, which can be used "free of charge", were identified. Part 4 of ARIZ includes systematic procedures to increase the availability of resources. One considers the derivative SFRs that can be obtained almost free of charge through slight modification of the already available resources. Steps 3.3-3.5 began the transition from the problem to the solution based on the application of physics; Part 4 continues in this direction.

PART 5. APPLYING THE KNOWLEDGE BASE

5.1. applying the System of Standard solutions for Inventive problems
5.2. applying the problems-analogue
5.3. applying Principles for Eliminating Physical Contradictions
5.4. applying the Pointer to Physical Effects and Phenomena

In many cases, Part 4 of ARIZ helps to achieve a solution concept, so it is possible to go to Part 7 of ARIZ. If no solution is achieved after step 4.7, Part 5 is recommended.

The purpose of Part 5 of ARIZ is to mobilize all experience accumulated in the TRIZ knowledge base. The problem is significantly clearer at this point so it is very likely that direct utilization of the knowledge base will be successful.

PART 6. CHANGING OR SUBSTITUTING THE PROBLEM

6.1. transition to the technical solution
6.2. checking the problem formulation for a combination of several problems
6.3. changing the problem
6.4. reformulation of the mini-problem

Simple (typical) problems can be solved through direct elimination of the Physical Contradiction, for instance, by separating conflicting properties in space or in time. Solving complex (non-typical) problems is usually associated with changing the problem statement, that is, with removing the initial restrictions created by mental inertia – those that seem obvious from the beginning.

For instance, to resolve a problem about increasing the speed of an "icebreaker" it is necessary to transit to an "iceNObreaker". Infinity "paint" can be obtained by the transition to "NOpaint" - electrolysis, gas bubbles were created. The bubbles themselves provide an adequate marker. Mental inertia had dictated that "painting" the model's trail is improved with the use of actual paint rather than another type of marker.

To correctly understand a problem it has to be solved; inventive problems cannot be precisely formulated at the outset. The process of problem solving is the process of correcting (reformulating) the problem statement.

PART 7. ANALYZING THE METHOD OF RESOLVING THE PHYSICAL CONTRADICTION

7.1. checking the solution concept
7.2. preliminary estimation of the solution concept
7.3. checking the priority of the solution concept through patent funds
7.4. estimation of sub-problems for implementing the obtained solution concept

The main purpose of Part 7 of ARIZ is to check the quality of the obtained solution concept. The Physical Contradiction should be resolved almost ideally, "without nothing". It is better to spend an additional two or three hours to obtain a new, more powerful solution concept than to fight half a lifetime with a weak, difficult to implement idea.

PART 8. APPLYING THE OBTAINED SOLUTION

8.1. estimate the changes to the super-system
8.2. find a new application for the obtained solution
8.3. apply the solution concept to other problems

A true innovative idea not only solves the particular problem, but also provides a universal "key" to many other analogous problems. The purpose of Part 8 of ARIZ is to maximize the utilization of resources unveiled by the obtained solution concept.

PART 9. ANALYZING THE PROBLEM SOLVING PROCESS

9.1. compare the proposed and the real process
9.2. compare the obtained solution concept and knowledge from TRIZ

Every problem solved using ARIZ has to increase the creative potential of the person. To achieve that, however, a thorough analysis of the solution process is required. This is the main purpose of the final part of ARIZ, Part 9.

Appendix G - Mapping of Customer Attributes as emerged from a review about Blue Ocean Strategy cases.

This Appendix collects the mapping of *create*-type customer requirements, as emerged from a literature investigation, according to the classes proposed together with the criteria of Section 3.2. The next table collects the mapping as it has been presented in Section 4.2.2.

Legend to read the results:
TA – Threshold achievement
VE – Versatility
ROB - Robustness
SENS – Sensitivity to External Conditions
CO- Controllability

OBJ – Harmful action against the object of the function
ENV- Harmful function against the environment
SYS- Harmful function against the System

SPACE- Resources of Space
TIME- Resources of Time
INFO- Resources of information
MATERIAL- Resources of Material
ENERGY - Resources of Energy

Case study	Parameter definition	Classification	Subclassification
[Yellow Tail] wines	Fun and adventure	UF	TA
[Yellow Tail] wines	Ease of drinking (i.e. because of sweetness)	HF	OBJ
[Yellow Tail] wines	Ease of selection	RES	INFO
Amphicar	multifunctionality-all in one (car-boat)	UF	VE
Amphicar	fun and adventure (first car-boat)	UF	SENS
Apple iPod	Possibilty of performing direct purchases	RES	TIME
Apple iPod	Automatic synchronization with computer	RES	TIME
Apple iPod	Variety of lines and sizes	UF	VE
Apple iPod	Aesthetics	UF	TA
Apple Lisa	innovative functions	UF	TA
Apple Lisa	user-friendliness (country	RES	INFO

	language)		
Apple Newton	freedom of use (orientable screen)	UF	VE
Apple Newton	fun and adventure through touch drawing	UF	VE
Barnes & Noble booksellers	New hardcover classics and working papers	UF	VE
Barnes & Noble booksellers	Safety of not buying an unlikely book due to reviews and further information available	HF	OBJ
Barnes & Noble booksellers	Environment for reading	UF	VE
Bert Claeys Kinepolis	Comfortness of seats	HF	OBJ
Bert Claeys Kinepolis	Ensured unobstructed view	HF	OBJ
Bert Claeys Kinepolis	Abscence of sound vibrations	HF	OBJ
Bloomberg	Analytical capability on historical data	RES	INFO
Bloomberg	Additional information about financial operators	RES	INFO
Bloomberg	Additional information (from a different sphere)	RES	INFO
Bloomberg	Ease of use (i.e. simple keyboards and jargon)	RES	INFO
BMW C1 motorbike	Elimination of equipment (i.e. helmet)	HF	OBJ
BMW C1 motorbike	Visibility with rain (wiper)	HF	OBJ
Body Shop cosmetics	Representation of a healty living	RES	INFO
Body Shop cosmetics	Ethics in business through promotion of social and political causes	HF	OBJ
Body Shop cosmetics	Emotionality due to the feminine values	UF	TA
Bratton's New York Transit Police	Perceived safe atmosphere in the trains (i.e. trough cleanliness)	HF	OBJ
Bratton's New York Transit Police	Processes speed (through bust buses)	RES	TIME
Bratton's New York Transit Police	Night-time arrests	UF	CONT
Bratton's New York Transit Police	Mapping the hot spots	RES	SPACE
Cadillac Cimarron	environmental friendliness	HF	ENV
Callaway Golf "Big Bertha"	Ease of playing	UF	ROB
Campbell's Souper Combo	expected quickness and speed in performing the function (microwave)	RES	TIME
Canon copiers	Ease of refilling	RES	MATERIAL
Cirque du Soleil	Pleasure production (i.e. by	UF	TA

	refinement of the watching environment, brightly-colored, fantastical world characterized by the harmonious play of an international cast of circus performers)		
Cirque du Soleil	Artistic shows with theme or plot	RES	INFO
Cirque du Soleil	Differentiation of shows	UF	VE
Cirque du Soleil	Exhibitions in meaningful locations (because of the art, the history, the meeting of different people and cultures)	RES	INFO
Cirque du Soleil	Respect of animal rights	HF	ENV
CNN	Real-time news	RES	TIME
CNN	Eye-catching forms of communication (i.e. graphics, sidebars, boxes)	RES	INFO
CNN	Information reliability, avoided information manipulation to generate political consensus	RES	INFO
Compaq in Server Industry (1992-1994)	Serviceability	RES	MATERIAL
Compaq in Server Industry (1992-1994)	Configurability	RES	MATERIAL
Compaq in Server Industry (1992-1994)	Manageability	RES	SPACE
Compaq in Server Industry (1992-1994)	Storability	RES	SPACE
Croc's	Fun, emotional appeal	UF	TA
Croc's	Odor elimination	HF	OBJ
CueCat	creation of automatic database	RES	INFO
CueCat	availability of certain magazine contents	RES	INFO
Curves fitness company	Fun atmosphere	UF	TA
Curves fitness company	Non-threatening environment	HF	OBJ
Curves fitness company	Speed in performing the workout	RES	TIME
Dell’s Web PC	customer care and ease of solving related problems	RES	TIME
Digital Audio Tape	possibility of modifying recorded tracks	UF	VE
Direct Line	Quickness in delivering the insurance policy (instant insurance)	RES	TIME
Dive Restaurant	fun and adventure (theme, vip, periscopes)	UF	TA
Dive Restaurant	availability of accessories	UF	VE

Dive Restaurant	distinction and recognition for his shape	RES	INFO
Dreamcast	multiplayer option (via internet)	UF	VE
DuPont's Corfam	Use of non-animal sources	HF	ENV
Earring Magic Ken	distinction and recognition (no tuxedos)	RES	INFO
EFS - Corporate Foreign Exchange	Confirmation	RES	INFO
EFS - Corporate Foreign Exchange	Tracking	RES	INFO
Evilla Sony	screen quality (best one, new technology)	UF	TA
Facebook	Sharing positive emotions about entertainment (through public communication)	UF	TA
Facebook	Ease of finding and predicting people links	RES	INFO
Ford Edsel	Self adjusting brakes	HF	SYS
Ford Edsel	Ease of opening the hood, by electronic release	RES	ENERGY
Ford Edsel	People involvement (choice of the name and pathos through TV show)		???
Ford Edsel	Innovative features ("rolling dome" speedometer, Teletouch transmission shifting system)	UF	VE
Ford Model T	Suitability to poor road conditions	UF	VE
Ford Model T	Ease of manteinance	RES	MATERIAL
Geox	Eliminating humidity from the inside of the shoe	HF	OBJ
Geox	Keeping the feet correctly heated	HF	OBJ
Gerber Singles	storability and trasportability	RES	SPACE
Hermann Miller Aeron Chair	Ease of shifting position without getting out the chair	RES	ENERGY
Hermann Miller Aeron Chair	Mantainance of an even heat distribution in the front and back	HF	OBJ
Home Depot	Social responsibility	HF	ENV
Home Depot	Friendliness of advices	RES	INFO
IBM PC jr	manegeability (wireless keyboard)	RES	SPACE
IBM PC jr	controllability of applications (page flipping)	RES	INFO
IBM PC jr	video stability (no video tremling)	HF	SYS
IKEA	Swedish food and drink availability	UF	TA
IKEA	Free gadgets	UF	TA
IKEA	Swedish identity		????
Intuit Quicken ™ (compared with financial softwares)	Customization	UF	VE
iTunes (compared with CD stores)	Additional information (i.e. about songs and BPM)	RES	INFO
iTunes (compared with CD stores)	Flexibility of choice	UF	VE

iTunes (compared with CD stores)	Safety of choice (through 30s streaming preview)	HF	OBJ
JCDecaux	Opportunities of maintaining public spaces	UF	TA
Joint Strike Fighter F-35	Maintainability	RES	MATERIAL
Joint Strike Fighter F-35	Durability	HF	SYS
Kellog's Cereal Mates	Integration of complementary products (milk and spoon for all-in-one breakfast)	RES	TIME
La Femme	accessories	UF	TA
Lynx barber shop	entertainment services (Lynx products, penny arcade)	UF	TA
Mc Donalds' Arch Deluxe	Suitability for exigent customer (sophistication)	UF	VE
Microsoft BOB	Social interaction with humanlike agents (anthropomorphic interfaces)	RES	INFO
Microsoft BOB	Nontechnical interface, computer as a room: metaphor lives on	RES	INFO
Motorola Iridium	Possibility to talk wherever (geographically) in the world	UF	SENS
NetJets	Time saving aircraft administration	RES	TIME
NetJets	Simple aircraft management	RES	TIME
NetJets	Savings on deadhead costs	HF	OBJ
New Coke	distinction and recognition (“new”)	RES	INFO
Nintendo Virtual Boy	3D gaming	UF	VE
Nintendo WII	Wireless joypad integrated with movement sensor	UF	VE
Nintendo WII	Videogames suitable for both sexes and any age	UF	VE
Nintendo WII	Player identification through Avatar creation	UF	TA
Nintendo WII	Integration between videogames and home daily life	UF	VE
Nokia N-Gage	multiplayer wireless	UF	VE
Nokia N-Gage	multifunctionality-all in one(mobile phone, consolle, hard disk, video, mp3, internet)	UF	VE
Nokia N-Gage	fun	UF	TA
Novo Nordisk Novopen®	Use for blind people	UF	VE
Novo Nordisk Novopen®	Ease of use	RES	INFO
Novo Nordisk Novopen®	Reusability of items	RES	MATERIAL
OK Soda	ethics (manifesto of generation X)	HF	ENV
OK Soda	customer care (toll-free number)	HF	OBJ
OS/2	os stability	HF	SYS
Outlet Villages	Perceived environment refinement	HF	OBJ

	of the shopping malls		
Outlet Villages	"Shopping tourism" initiatives	HF	TA
Outlet Villages	Accessibility to the mall (through closeness to highways, abundant road indications)	RES	SPACE
Pepsi Crystal	sense of purity	HF	OBJ
Pfizer Viagra	Lifestyle enhancement	HF	OBJ
Pfizer Viagra	Usage for people with any degree of erectile dysfunction problems	HF	OBJ
Philips Alto bulbe	Environment friendliness	HF	ENV
Philips Alto bulbe	Uniformity of illumination	UF	ROB
Philips CD-i	entertainment functions	UF	TA
Pink taxi	Safety against sex crimes	HF	OBJ
Pink taxi	Concerted effort for women (offer advice, share gossip, lift passengers' spirits)	HF	OBJ
Planet Hollywood	fun and adventure (vip, theme)	UF	TA
Polaroid Polavision	Instant movie playing	RES	TIME
Polo Ralph Lauren (compared with haute couture)	Classical and lasting look (imported in fashion world)	UF	VE
Polo Ralph Lauren (compared with haute couture)	Lifestyle image (offer of a complete range of lifestyle products, link with home items)	UF	VE
Polo Ralph Lauren (compared with haute couture)	Use for less sophisticated and "fit" people	UF	VE
QB House barbershops	Readiness of chair	RES	TIME
Quadraphonic Sound	realistic sound (3D)	UF	CONT
Rasna Limited's Oranjolt	Effervescence, fizz	UF	TA
RedBull	Performance Increment: physical endurance, reaction speed and concentration, mental alertness, overall feeling of well-being, metabolism, stamina	UF	TA
RedBull	Link with youngsters lifestyle, following up on new tendencies in music, fashion and sport	UF	TA
Rim's Blackberry	Secure corporate multiple e-mail access for roaming employees	UF	VE
Rim's Blackberry	Simple easy-to-use device: full QWERTY keyboard, scroll and click thumb trackwheel	RES	INFO
RJ Reynolds Premier smokeless cigarettes	ethics (less smoke and ash)	HF	OBJ
SAP R/2	Real-time data exchange	RES	TIME
SAP R/2	Possibility of use by multinational companies	UF	VE

SAP R/2	Order tracking capability	RES	INFO
Sony Minidisc	comfortness (antishock)	HF	SYS
Sony Minidisc	customizability (possibility of modifying the tracks)	UF	VE
Sony Walkman	Usability during movement (i.e. joggers or commuters)	UF	SENS
Sony Walkman	Avoiding to annoy surrounding people when listening music	HF	ENV
Sony Walkman	Avoiding to be disturbed in urban environments	HF	OBJ
Southwest Airlines	Connectivity and connections frequency	UF	VE
Southwest Airlines	In flight friendly approach, fun and humour	HF	OBJ
Southwest Airlines	Cheapness	HF	OBJ
Southwest Airlines	Customer care in case of incurring problems (i.e. lost flights, health problems, pets…); responsiveness	HF	OBJ
Swatch	Appeal, originality, fantasy	UF	TA
Swatch	Adaptation to styles and states of mind	UF	VE
Telecom Italia FIDO - (compared with competitor GSM)	Outdoor use of home number	UF	VE
Thirsty Cat! and Thirsty Dog!	storability and transportability	RES	SPACE
Toyota Prius	Style embedded of eco-friendliness	HF	ENV
Virgin Atlantic	Cheapness of transportation to the departing airport	HF	OBJ
Virgin Atlantic	Cheapness of transportation from the landing airport	HF	OBJ
Virgin Atlantic	Flair, style	UF	TA
Virgin Atlantic	In-flight entertainment services	HF	OBJ
Virgin Atlantic	Services for children	HF	ENV
Voice Pod	multifunctionality- all in one (memo, mail)	UF	VE
Voice Pod	audio quality	UF	TA
YouTube	Ease of use technology for uploading and sharing/displaying video files	RES	INFO
YouTube	Ready-made websites	RES	TIME
YouTube	Video Tags and Search Functions	RES	INFO
YouTube	Social Networking	RES	INFO