Functions and failures.
How to manage technological promises for societal challenges

Riccardo Apreda, Andrea Bonaccorsi, Gualtiero Fantoni, Donata Gabelloni

Faculty of Engineering, University of Pisa, Italy

Largo Lazzarino 1, Pisa, 56100, Italy

apreda.riccardo@gmail.com

a.bonaccorsi@gmail.com

g.fantoni@ing.unipi.it

d.gabelloni@gmail.com

Riccardo Apreda is research associate at the University of Pisa. With a background in theoretical physics, his research interests concern the models for the abstract representation of technologies and artefacts.

Andrea Bonaccorsi is professor of economics and management at the University of Pisa. His research interests include: the economic analysis of the dynamics of scientific knowledge, the functional theory of technology, and empirical analyses of higher education.

Gualtiero Fantoni is assistant Professor in mechanical engineering at the University of Pisa. His main interests are in the fields of micromanipulation, microassembly and design methods.

Donata Gabelloni is a PhD student in management engineering at the University of Roma Tor Vergata. She also holds a research position at the University of Pisa. She is working on product and process design methodologies.

Functions and failures.
How to manage technological promises for societal challenges

ABSTRACT. Technological promises are becoming part of the way in which scientific and technological communities try to attract the attention of stakeholders, aiming at legitimation, reputation, and funding. Not all promises, however, become reality. With the increase in the use of promises comes the risk of disillusion and cynicism, which may affect negatively policy makers and the public opinion. The paper suggests the introduction in the field of S&T and innovation policy of a tool commonly used in engineering fields, aimed at identifying and measuring all possible failures of a proposed technology. Instead of focusing on the magnitude of promises, it suggests that a useful perspective can be gained by placing systematic attention to the negative side, i.e. all reasons why a given technology may fail to deliver the promises. The paper develops the methodology, presents a case study, and illustrates the benefits of using it in policy making.

Keywords: technology foresight; functional analysis; FMECA.

1. Introduction

The idea that technologies are crucial ingredients for addressing problems that plague modern societies has been accepted since long time. However, with the acceleration of technological progress, and particularly after the emergence of technologies of information, materials and life, this belief has been associated with rising expectations and with the purposeful management of technological promises by scientists and technologists.

As an interesting stream of literature in sociology of technology has recently emphasized (Brown and Michael, 2003; Hedgecoe and Martin, 2003; Borup et al., 2006; Sung and Hopkins; 2006), proponents of new technologies have learnt how to manage the expectations of society, building compelling narratives about the promises of current developments that mobilize social and political support and help to ensure public funding. This literature has showed that, in some sense, the building of promises is endogenous to the unfolding of technologies, so that the social construction of promises and the actual, material development of technological achievements are mutually determined. They develop through cycles of legitimation, construction of promises, social support, public and private funding, technology development- but also, and more often than expected, disappointment. Therefore creating high expectations is a double-edge sword: on one hand, it may help to mobilize more support, raise more money and accelerate the delivery of promises; on the other hand, the higher the expectations, the stronger the disappointment should the delivery fall short of them. Even worse, the disappointment on poor delivery of technology may feed back adversely on society, since the next promises may be addressed with a more cynical attitude.

These issues have become even more crucial because many governments have started to base their S&T policies on the notion of societal challenges- a theme that underlies both the recent US policy

towards energy and sustainability proposed by President Obama, the European Union Green Paper approved in 2011 and the ambitious plan Europe 2020.
This paper addresses these issues from a quite technical, but hopefully useful, perspective, by reversing the point of view commonly adopted. Instead of focussing on what can be achieved with technologies, or on the delivery of new functions that address societal challenges, we suggest to focus also on failures - how it is possible that the new solutions fail to deliver their promise.
A systematic analysis of failures requires a structured approach, for which we advocate the adaptation to the context of S&T policies of a method originally developed and largely used in engineering, called FMEA (Failure Modes and Effects Analysis). The paper discusses a full-fledged case study of failure analysis of a new technology, and offers suggestions on how to use this approach on a large scale in a policy context.

2. Technological promises, hype cycles and the danger of excess expectations

In recent years, several scholars started to investigate the role of technological promises. A promise is, by definition, a projection into the future of a desired state of affairs, associated to a commitment to deliver this state. Scientists and technologists make a promise when they claim that, if their research is adequately funded, their discoveries will deliver some specified benefit to society. Such promises are not generic - gene therapy will address diseases for which there is currently no known solution, or nanotechnology will bring new materials that make solar energy cheap and clean.
The tendency to shift to the future the realization of desires is considered an integral part of the experience of modernity, while visions of the future carry with them expectations of improvements in the material conditions of people (Koselleck, 2004).
However, in the case of science and technology, more than in other spheres of human history, the visions of the future have a powerful effect on the present. In the case of technological promises, in fact, the projection into the future may be self-fulfilling. In trying to influence the vision of the future held by society, scientists and technologists may obtain more resources and actually determine the course of technology. This is even more so when technologies are new, because of the "deeply fluid character of new emerging technologies in their first stages" (Van Merkerk et *al*., 2005). Thus what retrospectively may appear as a linear and deterministic development of the technology is instead the result of a complex interplay between technological expectations, purposefully fostered by technological promises, and the internal dynamics of technology. As the literature on technological determinism has shown, retrospective interpretations tend to obscure the role of earlier representations, i.e. promises and expectations, in shaping technology (Roe Smith and Marx, 1994).

However, while technological promises may build up representations of the future that help to raise more resources, there is also the possibility of excess promises, or promises that do not materialize even in a state of abundant resources. If this is the case, the promise produces perverse effects.
As pointed out by Borup et al. (2006), "expectations and the frequent disappointments to which they lead are accompanied by serious costs in terms of reputations, misallocated resources and investment". In general, disappointment is a function of the distance between the promise (or the expectation) and the realization. Pushing technological promises high may result in larger disappointment in the future.
Yet, the tendency to commit to important promises seems to be an integral part of the dynamics of scientific and technological communities.
In the field of nanotechnology, Maestrutti (2011) has offered an impressive reconstruction of the way in which a new technology becomes legitimated, referring to authoritative pioneering sources, while technological promises are constructed using grand visions and prophecies. She shows how technological promises, embedded into these visions of the future, have been systematically used to leverage consensus and funding. At the same time, the same visions of the future may paradoxically

generate fears, negative reactions and irrational behavior, as it happens when the themes of invisible worlds, manipulation of the body at nanoscale, or even immortality, are proposed.

The literature discussed above seems to suggest that, if the dynamics of promises and expectations is left to itself, it tends to generate cycles of hype and disappointment. In the long run, this may threaten the credibility of scientific and technological communities and make the dialogue with society more difficult.

Brown and Michel (2003) suggested that this effect might come from the tendency of scientists and technologists to ignore, or underestimate, the degree to which the delivery of promises depends also on human behaviour, or more generally, on the interaction and co-evolution between technology and society.

Therefore, there is clearly a need for developing methods aimed at mitigating the possibility of disappointment and negative reactions.

3. How to manage technological promises: methods and gaps

It is not our goal to offer a full-scale review of methods, but only to highlight some recent directions of the literature and to identify gaps.

The first area of methods has been developed under the broad category of technology foresight. Here recent developments are participative and networking methods that try to involve prospective users of technologies in the foresight and policy building process. These developments were pioneered in the 1990s by the so-called Constructive Technology Assessment (Rip et al., 1995). Such approach was intended to “anticipate on societal aspects in an early stage of technological developments to get better societal embedded technology” (van Merkerk et al., 2005). More recent developments include scenario workshops, groupware, semantic tools to analyse user requirements (e.g. mindmapping), and various deliberative tools. The main direction here is to transform technology foresight into a social process, rather than using it as an expert support to high level, relatively insulated, policy decisions. However, “increasingly sophisticated methodologies of futures analysis and planning may be hard to integrate with more participative activities” (Miles et al., 2008).

Participation of prospective users, if not managed appropriately, may even worsen the technology promise cycle, because it may lead to unrealistic and exaggerated expectations. Since technological scenarios are produced with the validation of users, their disappointment may be even larger.

As stated by a European Commission Expert Group (2010): “The point is that simply “asking society” is not adequate. When asked, society does not tell you what you need to drive policies. There is often a naïf argument in recent debates, according to which consultative, open, bottom up methods of society involvement into technology policy making are *the* solution. There is still a gulf between what society asks, and what should be done in technology and innovation policy making […]. By contrasting to the military complex or the notion of user-innovation proposed by von Hippel (e.g. von Hippel, 2005), this Report calls the attention to the fact that technology and society speak very different languages, and simply putting them into relation is not an adequate solution.”

Other fields in which the issue of technological promises has been recently addressed include scientometrics and technometrics. In the former, a crucial question is whether a given scientific development has a potential for generating technological opportunities in the short-medium term, or rather whether it is oriented towards fundamental understanding of natural processes. Jovanovic (2007) developed a method, called Footprint Analysis, which combines the analysis of the nature of the institutions that publish paper or grant patents (e.g. academic research, companies), with the allocation of substantive matters into one of the four quadrants of the Stokes matrix (Stokes, 1997). In the latter field, a recent example of the implications of long term technological decisions aimed at addressing societal needs can be found in sustainable mobility. There is still significant uncertainty over the relative advantages of hydrogen, fuel cell, and electric propulsion for vehicles.

In this area the role of technological promises has been enormous, since proponents of respective technologies have used the argument of societal challenges in order to obtain funding. Based on patent analysis and industry specialization analysis, Beaudet et *al*. (2010) have argued that Europe has over-invested in fuel cell technology, while Japan has invested heavily in battery technology, benefitting from spillover from the consumer electronics industry, and is better placed to exploit the expected transition to electric vehicles based on batteries.

Third, new methods have been proposed to manage social conflicts. In this direction, Hard (1993) developed the notion that innovation is intrinsically divisive, so that it is pointless to look for methods that give a consensual view of the future. Rather, it is important to identify the conflicts that new technologies will bring about, and to manage them. More recently, Sung and Hopkins have developed a method to define the uncertainty associated to technological promises. Uncertainty depends on the potential conflict between frames adopted by different social groups, and on the difference between past experiences and future expectations (Sung and Hopkins, 2006).

Let us examine some weaknesses of the current toolbox.
First of all, in advocating the need to combine technical expertise and social involvement, existing methods underestimate the difference in languages between experts and lay people. It is not enough to open a dialogue between these communities, if there is not adequate methodology to translate the languages and make the two parts understand each other. Moreover, mastering a language means to exert power over a certain domain, and no social group accepts to give up its own language without something in exchange. This may require the development of a language, which is not owned by any specific group, but rather a *lingua franca*. Although these limitations are clearly understood by the technology assessment community, there is surprising little research in trying to address the language and associated power issues.

Second, existing methods do not demand a deep engagement into the substantive content of technology. This may be understood as a demand for parsimony: at the end of the day, it is not realistic to require that in order to design and manage S&T policies the specificities of fields of scientific research and domains of technology are mastered. Nevertheless, understanding at least the basic aspects of research is fundamental in order to effectively deal with it.
There is a need to infuse more technical content inside existing methodologies. Participatory methods that produce broad scenarios and storyboards, or use visual techniques based on ethnographic design methods provide a useful starting point, but they should be integrated with methods that have a closer relation to the technical content. This remark is also consistent with the criticism by Könnölä et *al*. (2007), who note that the open-ended consultation of stakeholders tends to produce "relatively unstructured pools of 'signals'".
Therefore the challenge is to develop methods that can be managed by both experts and stakeholders, add information to the process, and help to face the uncertainty associated to new technologies.
We suggest the adaptation to the management of technological promises of techniques originally developed in engineering. In the next sections we first introduce the notion of function and of Functional Analysis; second, we describe failures, and the technique called FMECA is advocated as a powerful tool to examine technological promises; finally, a case study is presented.

4. Address functions, not only performance. A short introduction to Functional Analysis

In suggesting technological promises, communities of scientists and technologists usually refer to the expected performance of future technologies. In many cases the promised performance is associated to quantitative measures, so that several competitive technologies can be compared

systematically. The emphasis on performance is understandable since it is associated to the promise to address and solve concrete issues: cure for diseases, clean energy and so on.
Furthermore, it is clear that many technological promises are not fulfilled because of performance issues, including the highly relevant dimension of cost. For example, the promise of RFID technology of providing a large-scale support in logistics is far from being achieved due to the inability of such technology to reduce manufacturing costs significantly. At a broader systemic scale, technological promises may fail due to the inability to provide complementary technologies, or to arrange for supply chain, logistics and after sales services appropriately.

However, an exclusive focus on performance has two negative implications. First, the emphasis on performance inhibits a full-scale consideration of potential technological alternatives. They are only considered at the beginning, and then disregarded in the course of technology development.
Second, it locks the dialogue between society and technology. Faced with the promise of delivering a given performance, it seems that there is no further room for interaction: what is needed is only to fund research adequately, and wait. Thus the emphasis on performance results in passivization of society. Consideration of systemic effects of technology and of interaction with users and their social context tends to be overlooked, or postponed at a later, implementation stage.
Consequently, we suggest that focusing on performance is *not* the appropriate way to manage technological promises and to establish a dialogue between scientific communities and stakeholders. Rather, we propose that the appropriate level of analysis is the abstract *function* of a technology, and the appropriate language is then the *functional language*.
In a classical engineering approach (Pahl and Beitz, 1984) each function is defined as an "operation on flows" and it is represented using a verb+object form. The verb describes the action (the operation) that can be performed on three fundamental types of objects (flows): material, energy and signal. A function is an abstract description of the behavior of an artifact in a given context of use, which is also informative about the overall reasons for the artifact itself.
To describe functions, however, a language that makes abstraction from any specific technical solution is needed. This turns out to be quite difficult, since a good functional description must encompass *all* technical solutions (existing or potential), but at the same time must be comprehensible for the users. Luckily enough, recent developments in the literature make new functional languages reasonably user-friendly.

Many research works have been aimed at the definition of standardized taxonomies of all the possible functions and flows, resulting both in large databases (Bonaccorsi and Fantoni 2007) or restricted sets (Hirtz *et al.* 2002, Fantoni *et al.* 2009). Among the latter, the so-called Reconciled Functional Basis (Hirtz *et al.* 2002) has become one of the most widely accepted, although some critical remarks (Vermaas 2007), additions (Ahmed and Wallace 2003) and further refinements (Fantoni *et al.*, 2009) have been proposed. These databases offer a rich language, which can be used to construct formally correct functional descriptions at any level of resolution, and for many technological fields.
Without entering in an in-depth discussion about the concept of function (see Fantoni *et al.* 2011 for further details), the notion of function assumed in this paper is that functions are nothing other than the result of the user's interpretative process about the product's physical behaviors, conditioned by the goal he wants to achieve.
Such formulation underlines both the cognitive aspects of a function and the physical level related to the object's behavior. Functions capture the main purpose of existence of a product together with its essential characteristics and therefore they constitute a powerful tool to represent and study artifacts and technologies.
Indeed, Functional Analysis (FA) has proven extremely useful in many fields of engineering design, from the conceptual design of new products to the mapping and sharing of knowledge. All these areas of application support the notion that a functional representation may be a fundamental

element for the theory of technological change (Bonaccorsi 2011).
Recently, we have applied it to an exercise of technology foresight in the biomedical industry, with surprising results (Apreda et al. 2013). After having built an appropriate functional representation for the technology, the dialogue between technologists and stakeholders became much more concrete and creative. The functional language offers a fully developed *lingua franca* to people who otherwise would not understand the language of the counterpart. Technologists would insist on the achievement of technical performance, while stakeholders would ask for the resolution of problems that are extremely urgent, but also ill-defined and vague. We suggest this problem will impair significantly any effort to guide research policy through the notion of societal challenges, as many governments, and more recently the European Commission, are prepared to do in the future.
With respect to the issue of technological promises, the distinction between function and performance is crucial.
As for the focus on functions, it is well known that a certain technology is generally characterized by performing a specific function, presumably in a better way than other existing technologies. So if the FMECA proves that the technology does not perform the "promised" functions, a potential and serious failure can be present.
Clearly the boundary between function and performance is not sharp-cut and the two entities are intertwined. When there is no function the concept of performance is meaningless; on the other hand if the level of performance is too low no function can be fulfilled. Therefore we are not devaluing the importance of performances in the analysis. What we state is that failures in achieving performance do not necessarily mean that the promise is bound to be broken: further research may still lead to achieving the expected performance levels. However, if the functional promise is severely ill conceived, there is no way for the promise to be fulfilled, even with additional investment. Therefore the analysis of functions already embeds an assessment of the performances. Thus this constitutes one more reason to start from a functional perspective rather than from the other side of the chain.

In this paper we extend the use of FA by showing how a systematic application of a negative version of it (i.e. the analysis of failures) may contribute to address technological promises.

5. Address failures, not promises. Introducing a venerated engineering method in the policy making context

Failure Modes and Effects Analysis (FMEA) is the main standardized methodology for failure analysis in industry. Its close relative Failure Modes Effects and Criticality Analysis (FMECA) was first developed by US military engineers and then adopted by NASA. In the seventies the automotive industry introduced FMEA as more suitable to the industrial context; later it spread to many other sectors and was further refined.
FMEA is intended to: a) recognize and evaluate the potential failures of a product or a process and the effects of each failure; b) identify actions that can eliminate or reduce the chance of the potential failure occurring and c) document the entire process.
We define a failure as the loss of an intended function of a product. Such loss can present itself in more than one realization, each called failure mode. To each failure mode it is possible to associate the *failure causes*, i.e. those defects in design or in realization that generated it, and the *failure effects*, i.e. its immediate consequences on the system. Of course there can be more than one cause and more than one effect. Failure cause, failure mode and failure effect are therefore linked by a causal relationship that is called the *failure chain.*

Each failure mode, identified within the analysis, is studied by assessing three parameters: Severity

(S), Non Detectability (ND) and Occurrence (O). The first quantifies the importance of the fault, the second its likelihood to be detected and therefore prevented or fixed, and the third the probability of the fault to actually happen.
The values assigned to S, ND and O (ranging from 0 to 10) are then used to compute a Risk Priority Number (RPN) value expressing the gravity of the potential failure. The RPN is simply calculated by multiplying S, ND and O.

Analyzing a product or a process with FMEA has two main goals in the present context: to study its uses and misuses, and to assess either its positive potential, either its likelihood to fail before or immediately after entering the market.

The functional interpretation of a failure is rather straightforward: a failure is no more than either a desired function that is not performed as expected by the product, or an unforeseen and unwanted negative consequence. The negative connotation of the latter is clearly related to the human's perspective and therefore can be called a function as well, though a harmful one. To sum up, from the point of view of FA a failure is either the negation of a positive function or a negative function. In this sense failure analysis is just the other, "darker" side of standard Functional Analysis. The two approaches actually strengthen each other and this fact underlines once more the power of FA as an interpretative and predictive tool: rather than costly learning by mistakes, once they have happened and it is often too late, a proper analysis of possible failures allows to prevent or fix them, avoiding false promises, disappointments, lack of use or commercial flop.

While FMEA has been developed as a technique to be applied at the level of individual products, it is possible to extend the domain of analysis to entire product families, sometimes declined through different contexts of use. This extension is made possible by applying FA in order to identify higher level types of failures, that are associated not just to individual products, but to large classes of potential products. The specific failure modes, as well as their measurable parameters, will usually be different, depending on the design of individual products.

In addition, while the application of FMEA to individual products results in the need for detailed plans to overcome failures through re-engineering and re-design, that is, activities that take place downstream in the development cycle, the application to broad technologies may result in re-orientation of research activities. In this case the outcome of failure analysis is not necessarily to emit a definitive verdict on a technology, because there will normally be room for further development, but to direct the evolution towards a better satisfaction of user needs.

In addition, we would like to extend even further the approach to include all aspects related to the product.
Why not considering other phases as for example communication, advertising, reuse, recycle, and the like? For example a product can function perfectly during its useful life but be extremely polluting when disposed of.
Our definition of failure is consequently broader than in standard FMEA, encompassing not just the situations when the product stops functioning properly during the phase of usage, but any and all negative or unwanted behaviors happening during any stage of the entire lifecycle of the product.
Broadening the view even further, it is possible to investigate also the "failures" related to the wider market context, as for example changes in the demand, presence of cheaper alternatives and competitors, effects of government policies, etc.
In the following we discuss four short examples to illustrate the impact of failures occurring in as much non-standard phases of the life cycle or market-related factors.

Example 1. Electrical cars are expected to reduce carbon emissions and pollution. A main component of such vehicles is the battery. At the current state of the technology however, batteries create serious environmental problems both during the production and the disposal phases, due to the heavy metals they contain. Indeed a recent study showed that, considering the entire lifecycle of an electrical car, its ecologic balance is not favorable (Hawkins et al. 2013).

Example 2. Rare earths permanent magnets are used in a variety of products in order to achieve higher performances. As of today, the most relevant applications are hybrid cars and wind turbines. However rare earths are now becoming too expensive (and their production is very polluting, too - another relevant failure considering that the main applications are in the green technology sector) (Alonso et al. 2012). The key point is that it is precisely the very success of such technology that has entailed a rise in price, due to the shortage and the concentration of rare earths in only one country. Therefore such failure in the supply chain could have been foreseen, at least in principle. The problem is becoming so important, also for its geopolitical implications, that the US government has launched a research program specifically to substitute the technology with new ones (program REACT - Rare Earth Alternatives in Critical Technologies).

Example 3. Carbon nanotubes are considered a potentially revolutionary technology due to their outstanding technical performances. For instance, they may be used to produce very resistant and light mechanical frames, very efficient water purification filters or ultrafast computer chips. However they also present the risk of a potential big failure of non-technical nature, since many studies indicate they could cause cancer (e.g. Poland et al. 2008).

Example 4. Sometimes the threat to health or environment does not even need to be a real one. As a foresight study we performed in 2010 has revealed, many Italian manufacturers hesitate to adopt basalt fiber in the textile industry, despite its good performances, because of the *fear* of a potential risk, given the analogy with asbestos fiber. Although basalt fibers measure on average two times the respiratory limit of 5 nanometers and should therefore be safe, research is not conclusive and above all the public opinion is still suspicious; hence, as an entrepreneur said: “nobody wants to be associated to the new asbestos”. In this case the failure is not in the product itself, but in something quite intangible as the *perception* that the technology induce in the user or, as in the above case, in the producers themselves, that do not want to run the risk of a market fiasco.

The idea of combining function and failure analysis is relatively recent, but various research works have already been undertaken. Nagel *et al.* (2009) propose a process analysis to investigate the propagation of faults that can compromise the successful usage of a product; Hutcheson *et al.* (2006) define a method for studying the critical sequences of events that can occur in a complex system; Del Frate (2011) presents a life cycle approach to product failures that extends FMEA to manufacturing, maintenance and retirement.

While such contributions offer various extensions to the classical use of FMEA, the idea to apply it to technological promises, considering the entire product lifecycle, and to adopt it as a tool for innovation policy is, to the best of our knowledge, pretty new.

6. Applying failure analysis to technological promises.

6.1 A structured approach to failures

As already mentioned, the technology foresight method proposed here relies on FA, which is used first to map the product functioning and then to perform a FMEA. Figure 1 represents the sequence of steps for its application.

Figure 1 should ideally go here

For any given product, the first step is the life cycle analysis that identifies the various stages of its life, from the gathering of raw materials to disposal. At a second, further level of detail each stage is subdivided into phases (for example the disposal stage implies collection, transport and proper disposal or recycle). In the third step, each phase is realized through one or more functions. The output of these first steps is then a full-scale functional map, associated to a rich textual description.

The next step identifies all the potential failure modes in order to assess the more critical ones (process FMEA). As discussed, a failure can be considered as (i) the real lack of capacity to perform a certain action, or (ii) the presumed/perceived inability to perform it.
The FMEA then proceeds taking into account for each failure its effects (thus setting a numerical value for the Severity parameter), its causes (thus defining a value for the Occurrence parameter) and the current controls that can detect the failure (thus assessing the Non Detection parameter). The consequent RPN permits to prioritize the failure modes and to devise actions to improve the product.
This investigation allows also mapping the failure sequence in terms of cause-effect relationships: a failure cause can be considered directly responsible for a failure mode and a failure mode for a failure effect. The existence of such causal chains can generate dangerous domino effects, negating too many useful functions.
A main characteristic of the FMEA is its bottom-up nature: it provides failure description at different levels of detail (e.g. the failure of a system can be represented as being caused by the failure of its subsystems and so on), and enables a temporal/causal study of what happens before and after a certain failure sequence.

6.2 A case study in the textile industry

The method described has been applied to the analysis of the textile industry, a large low-medium tech sector that is meeting considerable problems in Europe. The study was conducted in 2010, in the context of a Technology Foresight exercise, covering also a high technology sector (biomedical engineering), commissioned by the Regional authority in Tuscany, Italy.
The study was multi-sided and touched different aspects of the sector, from the evolution of the logistic chain to environmental issues, and used traditional methods of analysis, such as expert panels or consensus building, as well. However, since of the many claims made by interested parties to leverage public support, that new fibers or materials could greatly contribute to restore the competitiveness of the Tuscan textile industry, we were authorized to apply FMEA to test some of these technological promises. In the same exercise we also experimented new methods for technology foresight from patent analysis, for which we refer to Apreda et al. (2013).

First, we gathered information from experts and by processing industry publications, newsletters, websites etc. This activity led to the selection of a list of products and technologies, considered most innovative or at least very promising for the textile industry. We then performed both functional decomposition and failure analysis for each one of them.
We illustrate the method using as an example a recent technology where a network of optical fibers is embedded in fabrics. Luminosity is generated by integrated electronics supplied by an electric battery. Such technology allows creating a family of textile products that can emit their own light, with application both in interior design and in clothing.
This class of products received lot of media coverage and generous R&D funding, so it can be considered a good example of a technological promise.
At the time of the analysis, the technology had few applications and the first one was a jacket; market data were preliminary and did not allow any projection on the success of the family of products.
We chose the jacket as an example of the methodology, valid for the whole range. The first step is to identify all the functions performed by the jacket, starting from the various phases that occur

during the use of the product (Figure 2).

Figure 2 should ideally go here

Among the main functions there are the capability to allow the passage of air and sweat or to allow the movement of the user.
In addition to these functionalities that all clothes should have, the peculiarity of this jacket is to export a luminous signal towards the external environment.
The first six functions in Figure 2 can therefore be considered the primary functions, because they are connected to the reason why the user buys that particular jacket. The jacket performs them in an "active" way. Functions from 7 to 9 concern instead the ordinary maintenance of the jacket, washing, drying and ironing, and are performed *on* the jacket rather than *by* it. Functions occurring during the maintenance phase can have an impact on the functions occurring during the next phase of usage/wearing.
To sum up, what the product needs to do is to emit light and adapt to the shape of the human body, plus other auxiliary functions. Failing to deliver any of those tasks compromises its success.
A list of possible failures can be associated to "active" functions and can be represented simply in the form "not+functional verb+object".
Each failure can be connected to a failure mode describing the way in which it can occur (Figure 3). For example, the failure *not allow flow of air* is associated to the failure mode *flow of air blocked.*
In the same way, the failure modes are generated by the failure causes, which are the origin of the problems. Continuing with the example, the failure mode *flow of air blocked* is generated by the cause *optical fibers are joined to the jacket through glue*, because the glue makes the jacket non breathable.
One failure can be linked to more than one failure modes (Figure 3), because there can be several ways to realize the same failure. Likewise one failure mode can be caused by more than one failure causes.
For example the effect *not export signal* may occur either because different points of light emerge, or because the jacket reduces its light in time. In turn, the first failure mode, due to the breaking of fibers, can be generated either by wearing or during washing.
Finally, in Figure 3 the expression "*breaking of fibers*" appears several times, followed by different numbers. The number distinguishes between the possible ways in which the fibers can break.

Figure 3 should ideally go here

The following step is the assessment of *Severity*, *Occurrence* and *Detection* by the technicians. The resulting RPN indicates the criticality of each failure (Figure 4).

Figure 4 should ideally go here

For example the failure cause "*the stiffness of the glass reduces the flexibility*" presents the highest value of RPN. This failure cause is associated to the essential function that a jacket should follow the movement of the body ("to adapt").
As a consequence of the many critical failures, the technological promise underlying the development of light emitting clothes presented serious drawbacks, at least in the existing realization of the technology. This was clearly no good news to the Regional government, but was received as an important lesson for the future.

Is this result relevant only at the level of individual products, or does it extend to the entire technology? Here we can see the power of the methodology. The failures identified above carry over to all existing textile applications of optical fibers. The same conclusions can be derived at a higher level of generality by studying physical properties of optical fibers and controlling whether

they can deliver the desired functions.
The use of the entire technology in the textile industry can be justified because of its typical functions that are "to adapt" to surfaces of different shapes and "to emit" light. If it does not perform these characteristic functionalities obviously the technology loses most of its value for that family of applications. In the case study we have discussed only one product, but the same analysis is applicable to all other analogous artifacts, since they all present the same problems. For example in a curtain the flexibility may be less important than in a T-shirt but during the washing phase it remains an important feature. The particular failure detected on a specific product may be less relevant for another product but a complete analysis of the technology failures can lead to identify the weak points of each product in that range, since they are often strictly connected.
For what concerns the relationship between functions and performances, it is true that sometimes the fulfillment of a function is hindered by a low performance. However, an incremental improvement of performance will hardly solve a big failure (its "gravity" is highlighted by the RPN value) related to the total absence of a promised function. On the other hand, if the change in performance is truly radical so that it will deliver a new function, actually it probably implies a totally different and innovative technical solution as well; therefore a new technology is created altogether. Referring to the case study, the optical fiber is made of glass but a very flexible glass does not exist. If an alternative optical fiber would be found, it will definitely be a new technology, with many useful applications beyond the textile industry.
Of course, this is not necessarily the conclusion of the analysis, since in other cases it may well be that the current product is bound to fail, while other developments of the underlying technology could do better. Using FMEA, decision makers are in a better position to decide whether the risk profile of the technology is worth the effort. Considering the broader product-user-market system, and applying FA, decision makers may take risks in a more informed way. More importantly, they do not fail victim of the fascination of technological promises. On the other hand, if technologies pass the test of FMEA, they largely gain in credibility. Applying FMEA to technological promises is a win-win game, in which decision makers gain in robustness of decisions, and technologists gain in legitimation.

In the technology foresight described above it was possible to classify a large number of emerging technologies in the textile industry in two categories:

- *Low risk*, when RPN values were low for all the failure modes of the product;
- *High risk*, for products characterized by high RPN values, at least in some important function-failure relationship.

In the first class there are the emerging products and technologies presenting few problems and which are potentially successful on the market. Therefore it should be desirable for the Regional government to invest in them, helping when possible the reorganization of declining segments of the textile industry towards the more profitable new directions.
In the second class there are the products or technologies that present one or more severe criticalities, either of technical nature or in the wider context of their introduction into the market, which can affect negatively their success. Therefore the government should either not invest on them or, if a certain product presents nevertheless desirable benefits, support further research in order to improve it. In certain cases it can also be a sensible strategy to look for different sectors of application for the technology, maybe by exploiting its ability to perform functions different from the original one.

7. Implications and policy lessons

The application of FA and FMEA to technology foresight looks promising. We have suggested two important departures from existing methods. First, address functions, not only performance. This requires that technological promises are not discussed at face value, focusing on the presumed expected results that may solve societal issues at some point in the future. Rather, it is important to build up functional representations of the proposed technology and to open a dialogue between technologists and stakeholders that take place *within* this representation. Sharing a common language is extremely powerful in order to establish shared visions of the future. Second, address failures, not promises. We suggest that failure analysis is applied systematically in all cases where there are technological promises, or when there is conflict over a technology. It might even become a standard policy tool, for example by requiring that it is carried out in proposals submitted for research funding. For a technological promise, it must become a reference the fact that it has been submitted to a structured FMEA and has survived!

Two objections to our methodology can be raised. On one hand, one may wonder whether our approach requires that the product is already instantiated, so that technologies in their early stage cannot be examined. It is true that, traditionally FMEA is mostly associated to existing products, but FA and FMEA can be applied successfully at any level of development of a technology, even in the conceptual stage. Of course it has to be possible to provide at least an abstract description of the functioning of a certain technology or product. If a product is just a vague idea without a series of conceptual steps to implement it, no FMEA is possible, but we are dealing with a wish rather than with a real technological potential. On the other hand, one may be worried about the costs of such methodologies, but newly developed functional databases allow a relatively fast learning and application.

We believe that future S&T policies, aimed at creating strong connections between research and the resolution of societal challenges, will greatly benefit from a large scale application of such approach.

8. References

Ahmed S., Wallace K.M. (2003) Evaluating a functional basis, in ASME 2003 *Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Chicago, IL, USA.

Alonso, E., Sherman, A. M., Wallington, T. J., Everson, M. P., Field, F. R., Roth, R. and Kirchain, R. E. (2012) Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. *Environmental science & technology*, 46(6), 3406-3414.

Apreda R., Bonaccorsi A., Fantoni G. (2013) Functional Technology Foresight. A new methodology for the era of societal challenges. Submitted to *Technological Forecasting and Social Change.*

Beaudet A., Archambault E., Campbell D. (2010) Fuel cell and battery technology in the age of electric vehicles: Have Europe and North America bet on the wrong horse?, *11th International Conference on Science and Technology Indicators*, Leiden, Netherland.

Bonaccorsi, A. (2011) A functional theory of technology and technological change. In *Handbook on the economic complexity of technological change*. Cheltenham, Edward Elgar.

Bonaccorsi, A., Fantoni, B. (2007) Expanding the Functional Ontology in Conceptual Design. ICED’07 Paris, France.

Borup M., Brown N., Konrad K., van Lente H. (2006) The sociology of expectations in science and technology. *Technology Analysis and Strategic Management*, vol.18, no.3-4, 285-298.

Brown N., Michael M. (2003) A sociology of expectations: retrospecting prospects and prospecting retrospects. *Technology Analysis and Strategic Management*, vol.15, pp.3-18.

Del Frate, L., (2011), Product failure: a life cycle approach, ICED'11, Copenhagen, Denmark.

European Commission- Directorate General for Research and Innovation (2010) *The role of community research policy in the knowledge-based economy.* Expert group report. Luxembourg: Publications Office of the European Union.

Fantoni G., Apreda R., Bonaccorsi A. (2009) Functional Vector Space. ICED’09, Stanford, CA, USA.

Fantoni G., Apreda R., Gabelloni D., Bonaccorsi A. (2011) Do Functions Exist?, ICED’11, Copenhagen, Denmark.

Hard M. (1993) Beyond harmony and consensus. A social conflict approach to technology. *Science, Technology and Human Values*, vol.18, 408-432.

Hawkins, T. R., Singh, B., Majeau-Bettez, G. and Strømman, A. H. (2013) Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*, 17: 53–64.

Hedgecoe A., Martin P. (2003) The drugs don’t work: expectations and the shaping of pharmacogenetics. *Social Studies of Science*, vol.33,. 327-364.

Hirtz J., Stone R., McAdams D., Szykman S. and Wood K. (2002) A Functional Basis for Engineering Design: reconciling and evolving previous efforts, *Research in Eng. Des*. 13, 2002, 65-82.

Hutcheson R.S., McAdams D.A., Stone R.B. and Tumer I.Y. (2006) A function based methodology for analyzing critical events, *Proceedings of Detc/Cie ASME* 2006, Philadelphia, USA.

Jovanovic M. (2007) Footprints through science. Using citations to assess the path towards applicability. *ISSI Newsletter*, vol.10, no.16.

Könnölä T., Brummer V., Salo A. (2007) Diversity in foresight: insights from the fostering of innovation ideas. *Technological Forecasting and Social Change*, vol.74, no.5, 608-626.

Koselleck R. (2004) *Futures past. On the semantics of historical time*. New York, Columbia University Press.

Maestrutti M. (2011) *Imaginaires des nanotechnologies. Mythes et fictions de l’infiniment petit.* Paris, Vuibert.

Miles I., J.C. Harper, L. Georghiou, M. Keenan, R. Popper (2008) New frontiers: Emerging foresight. In *The Handbook of technology foresight*. Cheltenham, Edward Elgar, PRIME Series on Research and innovation policy.

Nagel R.L., Stone R.B., Greer J.A. and McAdams D.A. (2009) Investigation of system sensitivity to propagated configuration faults, ICED’09, Stanford, CA, USA.

Pahl G., Beitz W. (1984) *Engineering Design: A Systematic Approach*, London, Design Council.

Poland, C. A., Duffin, R., Kinloch, I., Maynard, A., Wallace, W. A., Seaton, A., ... and Donaldson, K. (2008). Carbon nanotubes introduced into the abdominal cavity of mice show asbestos-like pathogenicity in a pilot study. *Nature nanotechnology*, 3(7), 423-428.

Rip A., Misa T.J., Schot J. (1995) *Managing technology in society. The approach of Constructive Technology Assessment.* London, Pinter Publishers.

Roe Smith M., Marx L. (1994) *Does technology drive history? The dilemma of technological determinism.* Cambridge, Mass., The MIT Press.

Stokes D.E. (1997) *Pasteur's quadrant: Basic science and technological innovation*. Washington, D.C., Brookings Institute.

Sung J.J., Hopkins M.M. (2006) Towards a method for evaluating technological expectations. Revealing uncertainty in gene silencing technology discourse. *Technology Analysis and Strategic Management*, vol.18, no.3, 345-359.

van Merkerk R.O., van Lente T.H. (2005) Tracing emerging irreversibilities in emerging technologies. The case of nanotubes. *Technological Forecasting & Social Change* vol.72, 1094-1111.

Vermaas P. (2007) The Functional Modelling Account of Stone and Wood: Some Critical Remark, ICED'07 Paris, France.

Von Hippel E. (2005) *Democratizing innovation*. Cambridge, Mass. The MIT Press.